Review | Received: 07-06-2013 | Accepted: 04-12-2013

Quality Assessment and Comparison of Global Digital Elevation Models for Croatia

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Abstract: Users of digital elevation models must be aware of their main characteristics in order to judge better their suitability for a specific application. In this study, a comparison and evaluation of the characteristics of seven publicly available global digital elevation models were made for territory of the Republic of Croatia. The models chosen were: ASTER, SRTM, SRTM30+, ACE2, GMTED2010, GTOPO30 and ETOPO1. For each digital elevation model, the most important characteristics are given: construction methods, resolution, horizontal and vertical datum, and estimated accuracy. In addition, in relation to Croatia as a whole, differences between digital elevation models at identical points were determined and analysed, after the models had been adjusted to the same resolution. The model differences yielded information on the mutual correspondence between the models and areas of disagreement, and allowed an evaluation of the presence of major, systematic errors indicating the existence of significant differences between the various global elevation models. The causes of differences between digital models are numerous, and users need to recognize the relevance of errors to the final results of a particular scientific or expert task.

Keywords: global digital elevation models, ASTER, SRTM, SRTM30+, ACE2, GMTED2010, ETOPO1, GTOPO30, Croatia

1 Introduction

Digital elevation models (DEM) provide basic, quantitative information about the Earth's surface. Most data providers and professional users use the term DEM for both the digital terrain model (DTM) and digital surface model (DSM). A DTM usually refers to the physical surface of the Earth (elevations of the bare ground surface) without objects such as vegetation or buildings, while a DSM describes the upper surface of the landscape, includes the height of vegetation, man-made structures and other surface features, and only gives elevations of the terrain in areas where there is little or no ground cover (Maune, 2007). Though most of the models in this research paper are originally DSMs, we use the generic term digital elevation model (DEM) for them all.

In a digital elevation model, elevation data are stored, distributed and represented as a grid, triangulated irregular network (TIN), or contour lines. Because of their ease of use and computer efficiency, in this research DEMs are used as regular grids.

Elevation data sets, from which DEMs are generated, are obtained by a broad range of measurement techniques, such as ground survey (GPS, total station, terrestrial laser scanner), airborne photogrammetric imagery, airborne laser scanning (LiDAR), radar altimetry and interferometric synthetic aperture radar (InSAR). Today, satellite spaceborne techniques (photogrammetric imagery, LiDAR and InSAR) are extensively used for global DEM (GDEM) generation. Their advantage over traditional terrestrial methods is that height data can be produced relatively cheaply over large and inaccessible areas. Besides global DEMs, the only available elevation data in many countries are topographic maps at different scales (Mukherjee et al. 2013, Liu and Bian 2008).

Digital elevation models provide basic information on heights, from which different additional geomorphological attributes can be derived, such as terrain

Pregledni znanstveni rad | Primljeno: 07-06-2013 | Prihvaćeno: 04-12-2013

Procjena kvalitete i usporedba globalnih digitalnih modela reljefa na ozemlju Republike Hrvatske

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Sažetak: U svrhu bolje procjene iskoristivosti za konkretni zadatak korisnici digitalnih modela reljefa moraju biti svjesni njihovih glavnih karakteristika. U ovome se radu navode i uspoređuju karakteristike sedam javno dostupnih globalnih digitalnih modela reljefa na širem ozemlju Republike Hrvatske. Izabrani modeli su ASTER, SRTM, SRTM30+, ACE2, GMTED2010, GTOPO30 i ETOPO1. Za svaki od digitalnih modela reljefa navode se najvažnije karakteristike: metoda izrade, razlučivost, horizontalni i visinski datum i procijenjena točnost. Osim toga, za šire područje Republike Hrvatske određene su i analizirane razlike između digitalnih modela reljefa, nakon što su modeli prethodno usklađeni u istu razlučivost. Određene razlike dale su informaciju o međusobnom slaganju između modela, otkrivanju područja velikih neslaganja te procjenu prisutnosti grubih i sustavnih pogrešaka. Razlike upućuju na postojanje znatnih razlika između različitih globalnih modela reljefa. Uzroci nastajanja razlika između digitalnih modela su mnogobrojni te je pri korištenju modela potrebno spoznati relevantnost utjecaja pogrešaka modela reljefa na konačne rezultate pojedine znanstvene ili stručne zadaće.

Ključne riječi: globalni digitalni modeli reljefa, ASTER, SRTM, SRTM30+, ACE2, GMTED2010, ETOPO1, GTOPO30, Hrvatska

1. Uvod

Digitalni modeli reljefa (DMR) pružaju osnovne kvantitativne informacije o površini Zemlje. Većina pružatelja podataka i profesionalnih korisnika rabe izraz digitalni model reljefa i za digitalni model terena (eng. *digital terrain model, DTM*) i za digitalni model površine (eng. *digital surface model, DSM*). Digitalni model terena najčešće se odnosi na fizičku površinu Zemlje (visinu stvarne površine), dok digitalni model površine opisuje gornju plohu koja uključuje i visine vegetacije, izgrađene objekte i ostale površinske objekte, a visine fizičke površine opisuje jedino u područjima gdje nema navedenih objekata (Maune 2007). Iako većina modela korištenih u ovom istraživanju spada u kategoriju digitalnih modela površine (DSM), za sve modele upotrebljava se općeniti izraz digitalni model reljefa (DMR).

Visinski podaci u digitalnim modelima reljefa pohranjuju se, distribuiraju i upotrebljavaju u obliku pravilne mreže (eng. *grid*), nepravilne mreže trokuta (eng. *triangulated irregular network, TIN*) ili izohipsa. Zbog jednostavnosti korištenja u računalnom okruženju u ovom su istraživanju digitalni modeli reljefa korišteni u obliku pravilnih mreža.

Skupovi visinskih podataka, iz kojih se izrađuju digitalni modeli reljefa, mogu se dobiti velikim brojem mjernih tehnika: terestričkim mjerenjima (GPS, totalna stanica, laserski skener), aerofotogrametrijskim snimanjem, zračnim laserskim skeniranjem (LiDAR), radarskom altimetrijom, sintetičkim interferometrijskim radarom (InSAR) i dr. U današnje se vrijeme za prikupljanje podataka za izradu globalnih digitalnih modela reljefa uvelike primjenjuju satelitske i aero tehnike (fotogrametrijsko snimanje, LiDAR i InSAR). Njihova je prednost pred tradicionalnim terestričkim metodama u tome što je podatke o visinama površinom velikih i neprohodnih područja moguće prikupiti relativno jeftino. Osim globalnih digitalnih modela reljefa, za mnoge

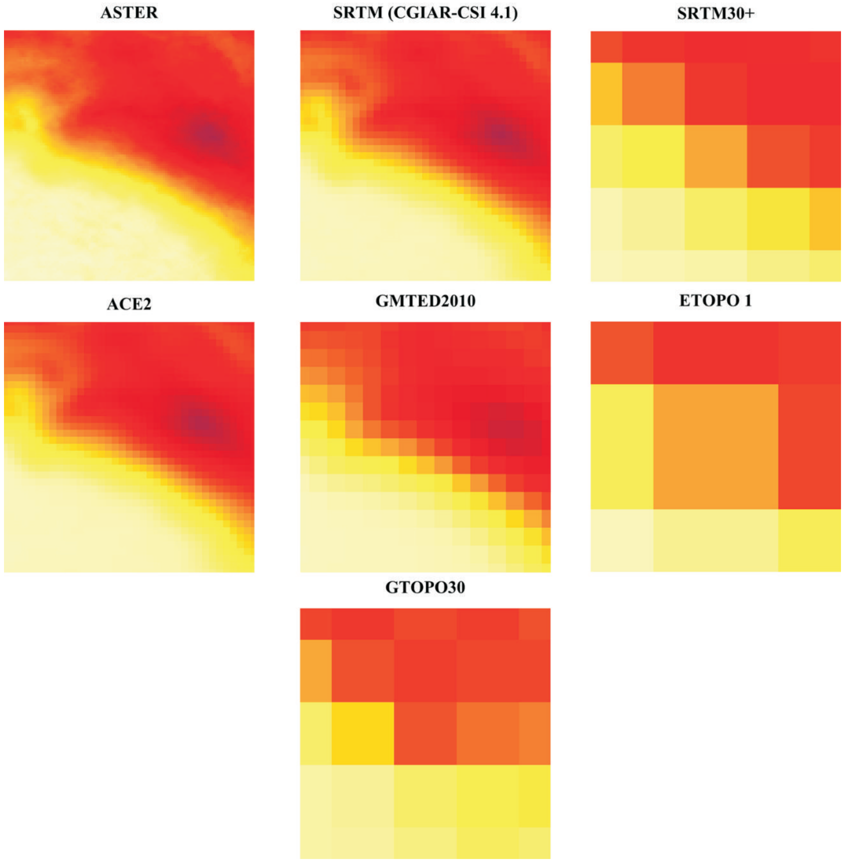

Figure 1 Examples of the topography detail displayed by the selected digital elevation models
Slika 1. Primjer detalja topografije prikazanog različitim digitalnim modelima reljefa

slope (size and direction), index of soil curvature, soil moisture index, etc. (Beven and Kirkby 1979, Hirt et al. 2010). Elevations and geomorphological attributes are used for a large range of applications in earth and environmental sciences, such as hydrological studies (modelling water flow, drainage networks, flood simulation and management), land use planning, climate studies, geomorphology, landform analysis, volcanic eruption, archaeology, terrain visualization and mapping (creation of relief maps, topographic cartography, orthorectification of aerial imagery), flight planning, gravity field modelling and many more (Bishop et al. 2001, Mukherjee et al. 2013).

As several applications utilize DEMs, the critical need for and use of high-quality, accurate terrain data is evident (Hirt et al. 2010). DEM quality refers to how well elevations from a DEM model represent the physical surface of the Earth (bare earth). According to Wechsler (Wechsler 2003), the effects of DEM errors are often ignored by DEM users, however some recognise that DEM uncertainty affects the outcome of their results.

The accuracy of DEM is affected by a variety of factors, such as the measurement technique, quality of source data, sampling or interpolation method, DEM resolution, terrain complexity, etc. Quality and errors in DEM data are generally composed of two components, the vertical and horizontal components, which cannot be interpreted separately (Mukherjee et al. 2013, Nikolakopoulos et al. 2006). Accuracy and errors in the data of digital elevation models are usually estimated by comparison with independent data of greater accuracy, such as benchmarks (stable geodetic points with known orthometric heights). Reference independent data (true or real values of bare earth) for comparison with DEM are usually collected from terrestrial surveys, laser scanning, photogrammetric measurements, levelling, or a combination of these methods. In this study, no reference data were used for comparison, so models were only compared relatively to each other.

In this research, global DEMs ASTER, SRTM, SRTM30+, ACE2, GMTED2010, GTOPO30 and ETOPO1 were examined. Examples of topographic detail shown by the selected DEMs are given in Figure 1.

2 Global Digital Elevation Models

In the past, high-resolution DEMs were only available at the local or national level, while high-resolution global DEMs have become freely accessible in the last decade. Fully global DEMs in coarse resolution (ETOPO5 in 5 arcminutes resolution) were made available from zemlje svijeta jedini podaci o visinama reljefa dobivaju se iz topografskih karata u različitim mjerilima (Mukherjee i dr. 2013, Liu i Bian 2008).

Digitalni modeli reljefa daju visine kao osnovni podatak, a iz njih se mogu dobiti različiti geomorfološki parametri poput nagiba terena (iznosa i smjera), indeksa zakrivljenosti tla, indeksa vlažnosti tla i dr. (Beven i Kirkby 1979, Hirt i dr. 2010). Visine i geomorfološki parametri imaju velik broj primjena u geoznanstvenim i ekološkim aplikacijama poput izradbe hidroloških studija (modeliranje vodotoka, simuliranje i upravljanje poplavama), planiranju korištenja zemlje, studijama o klimi, geomorfologiji, analizi oblika reljefa, vulkanskim erupcijama, arheologiji, kartiranju terena (izrada karata reljefa, topografska kartografija, ortorektifikacija aerosnimaka), planiranju leta, modeliranju ubrzanja sile teže i mnogim drugima (Bishop i dr. 2001, Mukherjee i dr. 2013).

S obzirom na primjene digitalnih modela reljefa velika je potreba za korištenjem visokokvalitetnih i točnih podataka o reljefu (Hirt i dr. 2010). Kvaliteta digitalnog modela reljefa očituje se u točnosti kojom podaci iz modela opisuju fizičku površinu Zemlje. Prema Wechseru (2003) pogreške visina u digitalnim modelima reljefa među korisnicima se često zanemaruju iz praktičnih razloga, uz svjesnost o njihovu utjecaju na rezultate.

Na točnost digitalnog modela reljefa utječu mnogi čimbenici poput tehnike mjerenja, kvalitete izvornih podataka, uzorkovanja ili metoda interpolacije, razlučivosti, razvedenosti terena i dr. Točnost digitalnih modela reljefa općenito se sastoji od visinske i položajne komponente, koje se ne mogu interpretirati odvojeno (Mukherjee i dr. 2013, Nikolakopoulos i dr. 2006). Točnost i pogreške u podacima digitalnih modela reljefa najčešće se procjenjuju u odnosu na neovisne podatke veće točnosti kao što su primjerice reperi (stabilne geodetske točke s poznatom nadmorskom visinom). Neovisni podaci (stvarne vrijednosti oblika površine Zemlje) za usporedbu s digitalnim modelima reljefa najčešće se prikupljaju terestričkim metodama izmjere poput laserskog skeniranja, fotogrametrijskog snimanja, nivelmana i slično. U ovom prikazu nisu korišteni neovisni podaci, već su analizirani relativni odnosi između odabranih digitalnih modela reljefa.

U radu su obrađeni globalni digitalni modeli reljefa ASTER (eng. *Advanced Spaceborne Thermal Emission and Reflection Radiometer*), SRTM (eng. *Shuttle Radar Topography Mission*), SRTM30+, ACE2 (eng. *Altimeter Corrected Elevations*), GMTED2010 (eng. *Global Multi-resolution Terrain Elevation Data*), GTOPO30 i ETOPO1. Primjer topografskog detalja prikazanog izabranim modelima reljefa dan je na slici 1.

2. Globalni digitalni modeli reljefa

U prošlosti su digitalni modeli reljefa u visokoj razlučivosti bili dostupni samo za lokalno područje ili državu, dok su globalni digitalni modeli reljefa visoke razlučivosti postali dostupni tek u posljednjem desetljeću. Potpuno globalni digitalni model reljefa ETOPO5 u gruboj razlučivosti 5 lučnih minuta dostupan je od 1988. godine. Era globalnih digitalnih modela reljefa u visokoj razlučivosti počela je publiciranjem modela SRTM (3 lučne sekunde) 2007. godine, a nastavila se ASTER-om (1 lučna sekunda) 2009. i GMTED2010 (7,5 lučnih sekundi) 2010. godine.

2.1. ASTER

ASTER je napredni višespektralni optički senzor lansiran na NASA-inoj (eng. *National Aeronautics and Space Administration*) svemirskoj letjelici Terra. Senzor ASTER pokriva 14 spektralnih područja (od vidljivog do infracrvenog), i to tri spektralna područja u vidljivom blisko infracrvenom području (VNIR), šest u kratkovalnom infracrvenom području (SWIR) i pet u termalnom infracrvenom području (TIR). Dodatni senzor koji pokriva blisko infracrveno područje i prikuplja podatke s razlučivošću 15 m dodan je na stražnji dio letjelice za prikupljanje podataka o reljefu (Abrams i dr. 2008).

Za izradu globalnog DMR-a ASTER primijenjena je tehnika stereokorelacije 1,3 milijuna stereoskopskih slika koje su prikupljene u razdoblju od 7,5 godina (2000–2007). Globalni DMR ASTER pokriva područje Zemlje između 83°S i 83°J u razlučivosti od 1 lučne sekunde. Visine iz globalnog DMR-a ASTER dane su u geografskom koordinatnom sustavu i referencirane na horizontalni datum WGS84 (eng. *World Geodetic System 84*), dok su s poljem ubrzanja sile teže povezane preko vertikalnog datuma EGM96 (eng. *Earth Gravitational Model*) (Abrams i dr. 2008).

Do danas su javno publicirane dvije inačice globalnog DMR-a ASTER. Inačica 1 publicirana je 2009., kada su svi prikupljeni podaci objedinjeni i konvertirani u jednostupanjske datoteke s razlučivošću 1 lučne sekunde (oko 30 m na ekvatoru). Iako je taj skup bio koristan zbog visoke razlučivosti, imao je manjkavosti u obliku nedostatka stereosnimaka, rupa, artefakata i drugih anomalija u različitim područjima (Nikolakopoulos i dr. 2006). Inačica 2 publicirana je u studenome 2011. i poboljšana s dodatnih 260 000 stereosnimaka, maskom za vodena područja i dodatnim podacima obrađenim s nadograđenim algoritmom.

Broj korištenih stereosnimaka za izračunate vrijednosti visina izrazito varira i u većini slučajeva s većim

1988 onwards. The era of high-resolution global DEMs began with SRTM (3 arc-seconds) in 2007, continuing with ASTER (1 arc-second) in 2009 and GMTED2010 (7.5 arc-seconds) in 2010.

2.1 ASTER

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) is an advanced multispectral optical imager on board NASA's (National Aeronautics and Space Administration) Terra spacecraft. ASTER covers a spectral region of 14 bands (from visible to thermal infrared): three spectral bands in the Visible Near-Infrared (VNIR), six bands in the Shortwave Infrared (SWIR), and five bands in the Thermal Infrared (TIR) regions. An additional backward-looking near-infrared band provides stereo coverage with a 15 m ground sampling distance used to collect relief data (Abrams et al. 2008).

In constructing ASTER GDEM, a stereo-correlation technique of 1.3 million stereoscopic image scenes (stacks or images used for extracting elevations) was used, collected during an observation period of 7.5 years (2000-2007). The ASTER GDEM covers the Earth between 83°N and 83°S in 1 arc-second resolution. The ASTER GDEM elevations are projected to a geographic coordinate system (GCS) referenced to the WGS84 (World Geodetic System 84) horizontal datum and the gravity-related vertical datum EGM96 (Earth Gravitational Model 96) (Abrams et al. 2008).

Up to now, two versions of ASTER GDEM have been released publicly. Version 1 was released in 2009, when all the collected data were merged and portioned to 1 degree tiles (granules) with a ground sampling of 1 arc-second (approximately 30 m at the Equator). Although this dataset was very useful because of its high resolution, it suffered from a lack of stereo models, voids, artifacts and different anomalies in several areas (Nikolakopoulos et al. 2006). Version 2 was released in October 2011, enhanced by 260,000 additional scenes and improved water masking, and was reproduced using an updated algorithm.

The number of stacks (image scenes) used per calculated elevation point varies, and in most cases, as the number of stacks increases, ASTER shows improved vertical accuracy. For example, in areas with low cloud coverage and higher priority, a high number of scenes is used, while in cloudy and mountainous areas, only 2 scenes may be used. The global vertical accuracy of version 1 is ±20 m, while that of version 2 is ±17 m (URL1).

ASTER is distributed in granules (tiles), in which each tile accommodates a DEM and Quality Assessment (QA) file. Each granule describes a 1 degree area (3601 by 3601 elevations). Quality Assessment files give the number of scenes for each elevation value, or indicate the source of external DEM data used to fill voids.

2.2 SRTM and SRTM30+

The Shuttle Radar Topography Mission (SRTM) mission was the first satellite mission to produce a near-global, high-resolution DEM with coverage between 60°N and 56°S latitude. The mission was a partnership between NASA and the Department of Defense's National Imagery and Mapping Agency (NIMA), along with German Aerospace Centre (DLR). The SRTM radar flew on board the space shuttle Endeavour at an altitude of 233 km from 11 to 22 February 2000. The SRTM DEM was developed from Interferometric Aperture Radar with the Spaceborne Imaging Radar-C/X-band Synthetic Aperture Radar (SIR-C/X-SAR) (Farr et al. 2007).

Two official versions of C-band SRTM GDEMs were released by NASA for the entire globe in 3 arc-seconds resolution in 2003 and 2009. Two additional versions derived from the basic SRTM dataset are (URL2):

- SRTM30 DEM, which is the result of combining two data sets; one from the SRTM and the other from the global GTOPO30 DEM.
- SRTM30+ global topography/bathymetry DEM, which was developed from SRTM30 and ICESat datasets for the continents. Bathymetry datasets were derived from different sources (NOAA, SIO, NGA, GEBCO) for ocean areas.

The global absolute vertical height accuracy of SRTM is estimated at ±16 m, affected by vegetation, though some independent regional studies have shown that there are significant differences (e.g. Denker 2004). According to these studies, there are many regions where the vertical accuracy of the SRTM dataset is high (particularly in flat, continental areas). The quality of the SRTM DEM may suffer due to gaps and voids (data holes), especially on high, steep mountains, rough terrain, dry sand deserts and areas of water. In datasets, small gaps are filled by post-processed interpolation from the surrounding area using known heights, though larger gaps are filled using other data, for example from SPOT-5 HRS. This leads to varying reliability (Farr et al. 2007).

The SRTM DEM elevations are projected to a geographic coordinate system referenced to the WGS84 horizontal datum and EGM96 vertical datum. Data are distributed with a spatial resolution of 1 arc-second for the USA and 3 arc-seconds (approximately 90 m at the Equator) for the rest of the world.

In this research, two versions of DEMs derived from brojem korištenih stereosnimaka ASTER pokazuje veću vertikalnu točnost. Primjerice, u područjima s malom prekrivenošću oblacima i visokog prioriteta korišten je veći broj stereosnimaka, dok su se u područjima jake naoblake i planina koristile samo dvije snimke. Globalna vertikalna točnost inačice 1 iznosi ±20 m, a inačice 2 iznosi ±17 m (URL 1).

ASTER se distribuira u obliku tzv. granula, koje sadrže dvije datoteke: visine i ocjenu točnosti. Svaka granula opisuje područje 1 stupnja (3601 x 3601 vrijednosti visina). Datoteka s ocjenama točnosti sadrži informacije o broju stereosnimaka za svaku vrijednost visine.

2.2. SRTM i SRTM30+

Misija SRTM bila je prva satelitska misija koja je rezultirala izradom globalnoga digitalnog DMR-a visoke razlučivosti s pokrivenošću od 60°S do 56°J geografske širine. Misija je nastala partnerstvom NASA-e i NIMA-e (eng. *National Imagery and Mapping Agency*, SAD) s DLR-om (eng. *German Aerospace Center*). SRTM-radar postavljen je na svemirsku letjelicu Endeavour, koja je letjela na visini 233 km 11.–22. veljače 2000. godine. SRTM DMR izrađen je iz radarskih interferometrijskih mjerenja instrumentom SIR-C/X-SAR (eng. *Spaceborne Imaging Radar-C/X-band Synthetic Aperture Radar*) (Farr i dr. 2007).

NASA je 2003. i 2009. godine objavila dvije službene inačice SRTM globalnog DMR-a razlučivosti 3 lučne sekunde. Osim njih, javno su dostupne i dodatne inačice (URL 2):

- SRTM30 DEM: kao rezultat kombiniranja dva skupa podataka: podataka SRTM-a i globalnog DMR-a GTOPO30.
- SRTM30+: globalni topografski/batimetrijski DMR dobiven iz SRTM30 DMR-a i ICESat skupova podataka za kontinente. Batimetrijski podaci za područja oceana i mora dobiveni su iz različitih izvora (NOAA, SIO, NGA, GEBCO).

Globalna apsolutna vertikalna točnost SRTM-a procijenjena je na ±16 m, iako su neke neovisne regionalne studije pokazale znatne razlike (npr. Denker 2004). Prema tim studijama postoje mnoga područja gdje je visinska točnost SRTM podataka vrlo visoka (pogotovo u zaravnjenim kopnenim područjima). Kvaliteta SRTM DMR-a narušena je u područjima bez podataka visine (tzv. rupe, eng. *void*), prije svega u visokim i strmim planinama, neravnim terenima, pustinjama i vodenim površinama. Prilikom obrade, popunjavanje manjih područja izvodi se interpolacijom iz okolnih područja s poznatom visinom, dok se veća područja bez visina popunjavaju drugim podacima, primjerice iz misije SPOT-5 HRS. To vodi varijabilnoj pouzdanosti modela reljefa (Farr i dr. 2007).

Visine SRTM DMR-a dane su u geografskom koordinatnom sustavu i referiraju se na horizontalni datum WGS84 i vertikalni datum EGM96. Podaci se distribuiraju u prostornoj razlučivosti 1 lučne sekunde za područje SAD-a i 3 lučne sekunde (otprilike 90 m na ekvatoru) za ostatak svijeta.

U ovom su se istraživanju upotrebljavale dvije inačice digitalnih modela reljefa napravljenih iz podataka SRTM-a; inačica 4.1 (publicirana od CGIAR-CSI, eng. *Consortium for Spatial Information*) i inačica SRTM30+. Inačica CGIAR-CSI SRTM 4.1 znatno je poboljšanje u odnosu na službene NASA-ine inačice. Pri izradi su korišteni novi algoritmi za interpolaciju i dodatni DMR-ovi tako da se trenutačno smatra najkvalitetnijim globalnim DMR-om dobivenim iz podataka SRTM-a (URL 9).

2.3. ACE2

Ideja je projekta ACE pod vodstvom Europske svemirske agencije (eng. *European Space Agency, ESA*) proizvesti najopsežniji i najtočniji globalni digitalni model reljefa u razlučivosti 3 lučne sekunda kombinacijom podataka iz SRTM misije sa satelitskim, radarskim i altimetrijskim visinskim podacima iz drugih izvora (ERS-1 misija, ERS-2, EnviSat, itd.). Očekuje se znatno poboljšanje kvalitete globalnog DMR-a jer satelitska i altimetrijska mjerenja omogućavaju korekcije mnogih pogrešaka vertikalnog datuma u različitim skupovima podataka uključenim u izradu globalnih modela GTOPO30 i GLOBE, kao i transformacija iz digitalnog modela površine u digitalni model terena (Berry i dr. 2008).

Glavni skup podataka za izradu ACE2 DMR-a dobiven je SRTM misijom, dok su izvan područja obuhvata korišteni podaci ACE-a i GLOBE-a (Hastings i Dunbar 1999). Osnovni skup altimetrijskih podataka je iz geodetske misije ERS-1, dok su po potrebi uključeni podaci ERS-2 i EnviSat Ku-band misije. ACE2 je horizontalno referenciran na WGS84, a vertikalno na srednju razinu mora ovisno o izvoru podataka (Berry i dr. 2008). ACE2 se distribuira u datotekama u kojima se nalaze podaci s visinama, izvorima podataka, točnosti i pouzdanosti.

2.4. GMTED2010 i GTOPO30

Model GMTED2010 izradilo je Američko geološko društvo (eng. *US Geological Society*) i Nacionalna geoprostorna agencija (eng. *National Geospatial-Intelligence Agency, NGA*) 2011. godine kombiniranjem jedanaest različitih skupova podataka o visinama. Neki su od glavnih izvora: popunjeni SRTM (inačica: Digitalni terenski visinski podaci 2; DTED2), kanadski digitalni podaci o visinama, podaci misija SPOT-5 HRS i ICESat te

SRTM data were used; SRTM version 4.1 (published by CGIAR-CSI) and SRTM30+ version. CGIAR-CSI SRTM 4.1 represents a significant improvement on previous NASA versions. Using new interpolation algorithms and auxiliary DEMs, it is considered the highest quality SRTM GDEM available (URL9).

2.3 ACE2

The idea of the European Space Agency (ESA) Altimeter Corrected Elevations-2 (ACE2) project is to provide the most comprehensive and accurate global digital elevation model in 3 arc-seconds resolution, by combining the SRTM dataset with satellite radar altimeter datasets from a variety of sources (ERS-1 Geodetic Mission, ERS-2, EnviSat, etc.). Considerable enhancement in the quality of global DEM is expected, because precise altimeter measurements enable the correction of many vertical datum errors in the various datasets included in GTOPO30 and GLOBE, including the transformation from DSM to DTM (Berry et al. 2008).

The main dataset for generating ACE2 was from the SRTM mission, while outside this region, ACE and GLOBE datasets were used (Hastings and Dunbar 1999). The main altimetry dataset was the ERS-1 Geodetic mission, and data from ERS-2 and EnviSat Ku-band were included where appropriate. ACE2 is horizontally georeferenced to the WGS84 and vertically to mean sea-level, depending on the source data (Berry et al. 2008). ACE2 is distributed in file combinations including height, source data, accuracy and confidence.

2.4 GMTED2010 and GTOPO30

Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010) was produced in 2011 by the U.S. Geological Survey (USGS) and the National Geospatial-Intelligence Agency (NGA), by combining eleven raster elevation datasets. Some of the main resources are void-filled SRTM (version: Digital Terrain Elevation Data 2; DTED2), Canadian digital elevation data, SPOT-5 HRS data, ICESat data and updated Antarctica and Greenland elevation models. This DEM has been generated as a replacement for and upgrade to the GTOP030 dataset (Danielson and Gesch 2008).

GTOPO30 is a global DEM in 30 arc-seconds resolution, developed in 1996. The quality of the elevation data in GTOPO30 varies widely, because it was derived from limited and heterogeneous data. Despite its coarse resolution and limited quality, it was extensively used many years in a various scientific fields such as geomorphology, hydrology, climatology, etc. (Danielson and Gesch 2011).

GMTED2010 provides coverage from 84°N to 56°S in three resolutions (7.5, 15 and 30 arc-seconds). Geographic coordinates are referenced to WGS84 horizontal datum and elevations are in most cases referenced to the EGM96 geoid as the vertical datum (where data sources are from SRTM). Where datasets differ from SRTM, the vertical datum varies according to the source data, because no adjustments were performed (Danielson and Gesch 2008).

For each resolution (7.5, 15 and 30 arc-seconds), several sub-samples were created and distributed, such as minimum, maximum and mean height, median, standard deviation, etc. The absolute vertical accuracy of GTOPO30 varies, depending on the data source. According to (Danielson and Gesch 2011) the standard deviation between GMTED2010 and GTOPO30 at 30 arc-seconds resolution is about 4.3 m. In this research, a 7.5 arc-seconds sub-sample of "mean height" was used for which (Danielson and Gesch 2008) calculated an accuracy of ±5 m at 1.6 million points.

2.5 ETOPO1

ETOPO1 is a model which includes both land topography and ocean bathymetry. It was published in August 2008 by the USA National Geophysical Data Center (NGDC). It provides global coverage from 90°N to 90°S in 1 arc-minute resolution. ETOPO1 was generated in geographic WGS 84 horizontal datum and in vertical mean sea-level datum (Amante et al. 2009).

The height model was built from numerous global and regional shoreline, bathymetric, topographic, integrated bathymetric–topographic, and bedrock datasets. Topographic datasets were mainly taken from GLOBE and SRTM30 (provided by NASA), while bathymetric datasets were collected from the Japan Oceanographic Data Center (JODC). The vertical accuracy of the ETOPO1 is dependent upon the datasets used to determine corresponding DEM elevation values (Amante et al. 2009).

The basic characteristics of the DEMs described are given in Table 1.

3 Methods

The area of determining differences between the selected digital elevation models is located between 42.0° < φ < 46.5° and 13.0° < λ < 19.5°, and covers the land area of Croatia, Bosnia and Herzegovina, with parts of Slovenia, Hungary, Serbia, Montenegro and Italy (Figure 2). It represents all terrain types from plains and low hills to hills, mountains, high mountains and very complex terrain.

dopunjeni digitalni modeli za područje Antarktike i Grenlanda. Taj DMR izrađen je kao zamjena i nadogradnja digitalnog modela reljefa GTOPO30 (Danielson i Gesch 2008).

GTOPO30 je globalni DMR u razlučivosti 30 lučnih sekundi izrađen 1996. godine. Kvaliteta visinskih podataka GTOPO30 modela znatno varira jer je napravljen iz ograničenih i heterogenih podataka. Unatoč gruboj razlučivosti i ograničenoj kvaliteti iznimno se često primjenjivao u različitim znanstvenim poljima poput geomorfologije, hidrologije, klimatologije itd. (Danielson i Gesch 2011).

GMTED2010 model pokriva područje od 84°S do 56°J i dostupan je u trima razlučivostima. Geografske koordinate referencirane su na horizontalni datum WGS84, dok se visine na većini područja odnose na geoid EGM96 kao vertikalni datum. U područjima podataka različitih od SRTM, vertikalni datum varira ovisno o samom izvoru (Danielson i Gesch 2008).

GMTED2010 je izrađen u trima razlučivostima: 30, 15 i 7,5 lučnih sekundi. Za svaku razlučivost izrađeno je i distribuirano nekoliko poduzoraka (eng. *subsample*) DMR-a, npr. minimalna, maksimalna i srednja visina, medijan, standardno odstupanje itd. Apsolutna vertikalna točnost GTOPO30 varira ovisno o izvoru podataka. Prema (Danielson i Gesch 2011) srednje odstupanje između GMTED2010 i GTOPO30 u razlučivosti 30 lučnih sekundi je oko 4,3 m. U ovome se istraživanju primjenjuje 7,5 sekundni poduzorak „srednja visina“, za koji je na 1,6 milijuna kontrolnih točaka izračunata točnost ±5 m (Danielson i Gesch 2008).

2.5. ETOPO1

Model ETOPO1 sadrži i topografiju i oceansku batimetriju, a publicirao ga je u kolovozu 2008. Nacionalni geofizički centar (eng. *National Geophysical Data Center, NGDC*) iz Sjedinjenih Američkih Država. Omogućuje globalnu pokrivenost između 90°S i 90°J u razlučivosti 1 lučne minute. ETOPO1 je napravljen u horizontalnom datumu WGS84 i odnosi se na srednju razinu mora u visinskom smislu (Amante i dr. 2009).

Model je izrađen iz globalnih i regionalnih podataka o obalnim linijama, batimetrijskim, topografskim i integriranim batimetrijsko-topografskim podacima. Topografski prostorni podaci većinom su preuzeti iz modela GLOBE i SRTM30, dok su batimetrijski skupovi podataka dobiveni od Japanskog oceanografskoga podatkovnog centra (JODC). Vertikalna točnost ETOPO1 varira ovisno o različitim skupovima podataka korištenih za određivanje pripadnih vrijednosti visina u modelu (Amante i dr. 2009).

Figure 2 Study area (visualised in Google Earth)

Slika 2. Testirano područje (prikaz u Google Earthu)

Osnovne karakteristike prethodno opisanih digitalnih modela reljefa navedene su u tablici 1.

3. Metode

Područje određivanja razlika između odabranih digitalnih modela reljefa nalazi se između 42,0° < φ < 46,6° i 13,0° < λ < 19,5°, a obuhvaća kopneno područje Republike Hrvatske, Bosnu i Hercegovinu te dijelove kopna Slovenije, Mađarske, Srbije, Crne Gore i Italije (slika 2). Područje je reprezentirano svim vrstama terena, od nizina, niskih brda, gora do visokih planina i veoma razvedenog reljefa.

S obzirom na veliki raspon od najdetaljnijeg DMR-a ASTER, razlučivosti 1 lučne sekunde, do najgrubljeg modela ETOPO1, razlučivosti 60 lučnih sekundi, za usporedbu u identičnim točkama potrebno ih je međusobno uskladiti u jednoj razlučivosti. Modeli su se iz razlučivosti 1, 3 i 7,5 lučnih sekundi (ASTER, SRTM, ACE2 i GMTED2010) preračunavali u krupniju razlučivost (30") iz dva razloga. Prvi je razlog taj što je matematički pouzdanije predicirati osrednjavanjem (određivanje modela grublje razlučivosti iz modela finije razlučivosti), nego razlaganjem podataka (određivanje modela finije razlučivosti iz modela grublje razlučivosti). Drugi je razlog taj da je poznato horizontalno neslaganje digitalnih modela reljefa, odnosno tzv. geolokacijska pogreška, koja za pojedine modele reljefa iznosi do jedne sekunde (oko 30 m) (npr. Hirt i dr. 2010, URL1). Usklađenjem modela u grubljoj rezoluciji manji je utjecaj geolokacijske pogreške na određivanje razlika između modela, nego što bi bio u slučaju da se određuju razlike u finijoj razlučivosti.

Table 1 Summary of basic characteristics of Global Digital Elevation Models (GDEM)

Tablica 1. Pregled osnovnih karakteristika globalnih digitalnih modela reljefa

Model	ASTER	SRTM	SRTM30+	ACE2	GMTED2010	ETOPO1	GTOPO30
Generation and distrib. Izrada i distribucija	USGS/NGA/METI*	NASA/NGA/JPL	NASA/NGA/JPL	EAPRS**/ESA	USGS/NGA	NOAA	USGS
Data collection Prikupljanje podataka	2000–2008 (ver. 1) 2000–2010 (ver. 2)	2000	2000	-	-	-	-
Published versions Publicirane inačice	ver. 1: 2009 ver. 2: 2011	ver. 1: 2003 ver. 4.1: 2009	ver. 8.0: 2011	2009	2010	2008	1996
Surface type (DSM/DTM) Tip površine (DSM/DTM)	DSM	DSM	DSM	DSM/DTM	DSM	DSM	DTM
Coverage, N S, E W [°] Pokrivenost, S J, I Z [°]	83–83, 180–180	60–56, 180–180	90–90, 180–180	90–90, 180–180	90–90, 180–180	90–90, 180–180	90–90, 180–180
Resolution [arc-seconds] Razlučivost ["]	1	1, 3	30	3, 9, 30, 300	7,5, 15, 30	60	30
Horizontal system Horizontalni sustav	geographic geografski	geographic geografski	geographic geografski	geographic geografski	geographic geografski	geographic geografski	geographic geografski
Horiz./vert. datum Horiz./vert. datum	WGS84/EGM96	WGS84/EGM96	WGS84/EGM96	WGS84/MSL	WGS84/EGM96	WGS84/MSL	WGS84/MSL
Horiz./vert. unit Horiz./vert. jedinica	arc-second/m lučna sekunda/m	arc-second/m lučna sekunda/m	arc-second/m lučna sekunda/m	arc-second/m lučna sekunda/m	arc-second/m lučna sekunda/m	arc-minute/m lučna minuta/m	arc-second/m lučna sekunda/m
Official website Službena web-stranica	URL1	URL2	URL3	URL4	URL5	URL6	URL7
Distribution format Format distribucije	GeoTiff	GeoTIFF, ArcASCII	JPEG tiles, ER Mapper	netCDF	GeoTiff	Geotiff, netCDF, g98, binary, xyz	Geotiff
Download link Link za preuzimanje	URL8	URL9	URL10	URL4	URL11	URL 12	URL11

*METI - Japan's Ministry of Economy, Trade and Industry

** EAPRS - Earth and Planetary Remote Sensing Laboratory

Stoga su modeli preračunati iz svojih početnih razlučivosti u razlučivost 30 lučnih sekundi. Model GTOPO30 izvorno je dan u razlučivosti 30 lučnih sekundi te je kao takav korišten za usporedbu. Modeli koji su dani u razlučivostima detaljnijima od 30 lučnih sekundi, ASTER DMR, SRTM DMR modeli, ACE2 i GMTED2010, osrednjeni su metodom pokretne sredine (eng. *moving average filter*) u razlučivost 30 lučnih sekundi. ETOPO1 DMR običnom Krigeovom interpolacijom razmnožen je iz izvorno dane razlučivosti 60 lučnih sekundi u razlučivost 30 lučnih sekundi.

Nakon usklađenja razlučivosti modela, apsolutne vrijednosti razlika visina izračunate su razlikom visina modela u identičnim točkama, i to u svim kombinacijama modela. Apsolutne vrijednosti razlika između modela promatrane su jer je cilj bio spoznati iznos i mjeru neslaganja, a ne predznak. Pritom su kao statistički pokazatelji korišteni minimum (min.), maksimum (maks.), medijan (med.) i srednje apsolutno odstupanje od medijana (MAD). Prema (Höhle i Höhle 2009) za procjenu i analizu točnosti digitalnih modela reljefa potrebno se koristiti robusnim statističkim pokazateljima poput medijana i srednjeg apsolutnog odstupanja od medijana, umjesto sredine i standardnog odstupanja. Razlog tomu je, što su sredina i standardno odstupanje statistički pokazatelji koji se baziraju na pretpostavci da su pogreške u uzorku raspodijeljene prema Gaussovoj (normalnoj, simetričnoj) razdiobi, što kod digitalnih modela reljefa najčešće nije slučaj. Iz dosadašnjih analiza točnosti globalnih digitalnih modela reljefa (npr. Bašić i Buble 2007, Denker 2004, Hirt i dr. 2010, Nikolakopoulos i dr. 2006) poznato je kako u modelima postoje mnogobrojne sustavne i grube pogreške koje uzrokuju asimetričnu distribuciju pogrešaka te time neupotrebljivost statističkih pokazatelja sredine i standardnog odstupanja. Medijan (eng. *median*) definira sredinu skupa podataka; pola vrijednosti skupa nalazi se iznad medijana, a pola ispod. Srednje apsolutno odstupanje od medijana (eng. *median absolute deviation, MAD*) definirano je kao medijan apsolutnih odstupanja podataka od medijana uzorka. Računa se po izrazu $MAD = medijan_i(|X_i - medijan_j(X_j)|)$, gdje se prvo računaju apsolutne vrijednosti reziduala (razlika) podataka skupa (X_i) u odnosu na medijan $medijan_j(X_j)$ cijelog uzorka, te se potom između tih vrijednosti odredi medijan.

4. Rezultati i diskusija

Statistički pokazatelji testiranih digitalnih modela reljefa koji su na već opisani način pretvoreni u razlučivost 30 lučnih sekundi dani su u tablici 2. Maksimalna visina u svim modelima, osim SRTM30+ i

Table 2 Characteristics of GDEMs for the defined study area at 30 arc-second resolution

Tablica 2. Statistika globalnih modela reljefa u 30 sekundnoj razlučivosti na području testiranja

Model	Min. [m]	Max. [m]	Median [m]	MAD [m]
ASTER	0	2648	323	360
SRTM (CGIAR-CSI 4.1)	0	2645	341	360
SRTM30+	0	2579	334	358
ACE2	0	2647	340	359
GMTED2010	0	2627	322	360
GTOPO30	0	2689	332	359
ETOPO1	0	2586	329	358

ETOPO1 iznosi približno 2650 m. Medijan i apsolutno odstupanje medijana u svim modelima sličnih je vrijednosti; medijan približno 330 m, a apsolutno odstupanje medijana približno 360 m.

Nadalje, osim statističkih pokazatelja razlika između modela reljefa, definirani su intervali u koje su razvrstane dobivene apsolutne vrijednosti razlika između modela. Određen je postotak razlika koje se nalaze u pojedinom intervalu (manje od 20 m, od 20 m do 100 m i više od 100 m). Statistički pokazatelji i distribucija razlika digitalnih modela reljefa po intervalima sumirani su u tablici 3.

Općenito, najveće su razlike između modela u slučajevima razlike ETOPO1 ili GTOPO30 modela i svih ostalih modela. Primjerice, najveći medijan dobiven je razlikom ASTER i GTOPO30 modela i iznosi 32 ±61 m. Čak 22% razlika visina između ta dva modela veće su od 100 m. Najmanji medijan dobiven je razlikom SRTM i ACE2 modela i iznosi 3 ±4 m, uz 98% razlika manjih od 20 m. Na slici 3 prikazane su razlike modela ASTER i GTOPO30 s najvećim medijanom te razlike modela SRTM i ACE2 s najmanjim medijanom.

Slaganje dvaju, trenutačno vjerojatno najkorištenijih digitalnih modela reljefa, ASTER i SRTM, prema medijanu je 5 ±8 m, dok je 94% razlika manje od 20 m. Zanimljivo je slaganje modela SRTM30+ s modelima GTOPO30 (medijan 5 ±7 m) i ETOPO1 (medijan 3 ±5 m).

Uzrok nastajanja razlika između modela koje su manje od 20 metara vjerojatno je sustavnog karaktera i povezan je s horizontalnim neslaganjem modela, tipom površine (bez vegetacije ili s vegetacijom) i definicijom vertikalnog datuma (model geoida ili srednja razina mora). Područja u kojima su razlike između modela veće

Given the wide range, from the most detailed DEM resolution of ASTER in 1 arc-second resolution, to the largest ETOPO1 model in 60 arc-seconds resolution, in order to compare the models at identical points, they need to be reconciled in the same resolution. The models with 1, 3 or 7.5 arc-seconds resolution (ASTER, SRTM, ACE2 and GMTED2010) were recalculated to the coarser 30 arc-seconds resolution for two reasons. Firstly, it is mathematically more reliable to predict data by averaging (calculating a model of coarser resolution from a model of finer resolution), rather than by the data decomposition (calculating a model of finer resolution from a model of coarser resolution). Secondly, horizontal disagreement may occur between digital elevation models, known as geolocation error, which for some elevation models is about one arc-second (about 30 m) (e.g. Hirt et al. 2010, URL1). Reconciling the models in a rougher resolution will better reduce the influence of geolocation errors when determining the difference between models than determining differences in finer resolution.

Therefore, the models were converted from their initial definitions to a resolution of 30 arc-seconds. The Model GTOPO30 was originally given in the resolution of 30 arc-seconds and so was used in comparison. The models which were given in more detailed resolutions of 30 arc-seconds, ASTER DEM, SRTM DEM, ACE2 and GMTED2010, were averaged by the method of moving the average to a resolution of 30 arc-seconds. ETOPO1 was recalculated from the originally given resolution of 60 arc-seconds to a resolution of 30 arc-seconds, by simple Kriging interpolation.

After reconciling the models' resolution, the absolute values of the differences were calculated as the differences between heights at identical points in all combinations of models. The absolute value of the height differences between the models was observed, because the goal was to detect and extend disagreement, not a range. The statistical indicators used were minimum, maximum, median and mean absolute deviation from the median (MAD). According to (Höhle and Höhle 2009) for an evaluation and analysis of the accuracy of a digital elevation model, robust statistical indicators should be used, such as median and absolute deviation from the median, instead of mean and standard deviation. The reason for this is that mean and standard deviation are statistical indicators based on the assumption that errors in the sample are distributed according to Gaussian (normal, symmetrical) distribution, while in digital elevation models this is usually not the case. From previous analyses of the accuracy of global digital elevation models (e.g. Bašić and Buble 2007, Denker 2004, Hirt et al. 2010, Nikolakopoulos et al. 2006) it is known that in many models, systematic and major errors cause the asymmetric distribution of errors, and therefore affect the usefulness of statistical indicators of mean and standard deviation. Median defines the middle of a dataset; half the values in the dataset are above the median and half below. Mean absolute deviation from the median (MAD) is defined as the median absolute deviation of data from the median of the whole dataset. It is calculated according to the formula $MAD = median_i(|X_i - median_j(X_j)|)$, where firstly the absolute values of the residuals (differences) between data X_i) and median of the whole dataset $median_j(X_j)$ are calculated, and then the median between those absolute differences is determined.

4 Results and Discussion

The statistical indicators of the digital elevation models tested that were previously reconciled to a resolution of 30 arc-seconds are given in Table 2. The maximum height for all models except SRTM30+ and ETOPO1 is approximately 2,650 m. Median and median absolute deviation for all models are of similar values; the median is approximately 330 m, and the median absolute deviation approximately 360 m.

In addition to the statistical indicators of the differences between elevation models, intervals were defined in which the absolute values of the differences between the models were classified. The percentage of differences in a specific interval (less than 20 m, from 20 m to 100 m and more than 100 m) was calculated. The statistical indicators and distribution of differences between the digital elevation models are summarized in Table 3.

Generally, the greatest differences between the models were between the ETOPO1 or GTOPO30 models and all other models. For example, the largest median of 32 ±61 m was obtained from the difference between ASTER and GTOPO30. Up to 22% of height differences between the two models were greater than 100 m. The smallest median 3 ±4 m was obtained from the difference between the SRTM and ACE2 models, while 98% of height differences were less than 20 m. Figure 3 shows the differences between the ASTER and GTOPO30 models with the highest median, and differences between the SRTM and ACE2 models with the lowest median.

The causes of the emergence of differences of less than 20 metres between models are probably systematic in character and caused by the horizontal disagreement of models, surface type (with or without vegetation) and the definition of the vertical datum (geoid or mean sea level). The areas in which differences between models were more than 20 m are outliers, and were probably caused by errors in collecting and processing measured data.

Table 3 Differences between global digital elevation models. (sorted in descending order by median). Abbreviations: SRTM: CGIAR-CSI version 4.1, GMTED: version 2010, 7.5 arc-seconds.

Tablica 3. Neslaganje globalnih digitalnih modela reljefa. Sortirano silazno po medijanu. Kratice: SRTM: inačica CGIAR-CSI 4.1, GMTED: inačica 2010, 7,5 lučnih sekundi.

		Statistika apsolutnih vrijednosti razlika / Statistics of absolute value of differences $|\Delta H_{model\,A-model\,B}|$ [m]				Intervali aps. vrijednosti razlika [%] / Intervals of absolute values of differences [%]		
Model A	**Model B**	**Min.**	**Max.**	**Median**	**MAD**	**|ΔH|<20 m**	**20 m<|ΔH|<100 m**	**|ΔH|>100 m**
ASTER	GTOPO30	0	970	32	61	39	39	22
ACE2	GTOPO30	0	1266	31	59	41	38	21
SRTM	ETOPO1	0	901	31	59	41	38	21
GMTED	GTOPO30	0	861	30	57	41	38	21
SRTM30+	ETOPO1	0	928	29	54	42	39	19
GTOPO30	ETOPO1	0	928	29	53	42	39	19
ASTER	ETOPO1	0	762	13	21	63	34	3
ACE2	ETOPO1	0	885	11	21	64	33	3
SRTM30+	ACE2	0	830	11	21	64	33	3
ASTER	SRTM30+	0	557	10	17	71	28	1
SRTM30+	GMTED	0	886	8	15	73	26	1
GMTED	ETOPO1	0	684	8	14	72	26	2
SRTM	SRTM30+	0	625	8	14	73	26	1
ASTER	GMTED	0	291	6	11	88	12	0
ASTER	ACE2	0	1067	6	9	88	12	0
ASTER	SRTM	0	208	5	8	94	5	0
SRTM30+	GTOPO30	0	479	5	7	85	15	0
ACE2	GMTED	0	998	4	7	92	8	0
SRTM	GMTED	0	224	3	6	94	6	0
ETOPO1	SRTM30+	0	366	3	5	85	15	0
SRTM	ACE2	0	999	3	4	98	2	0

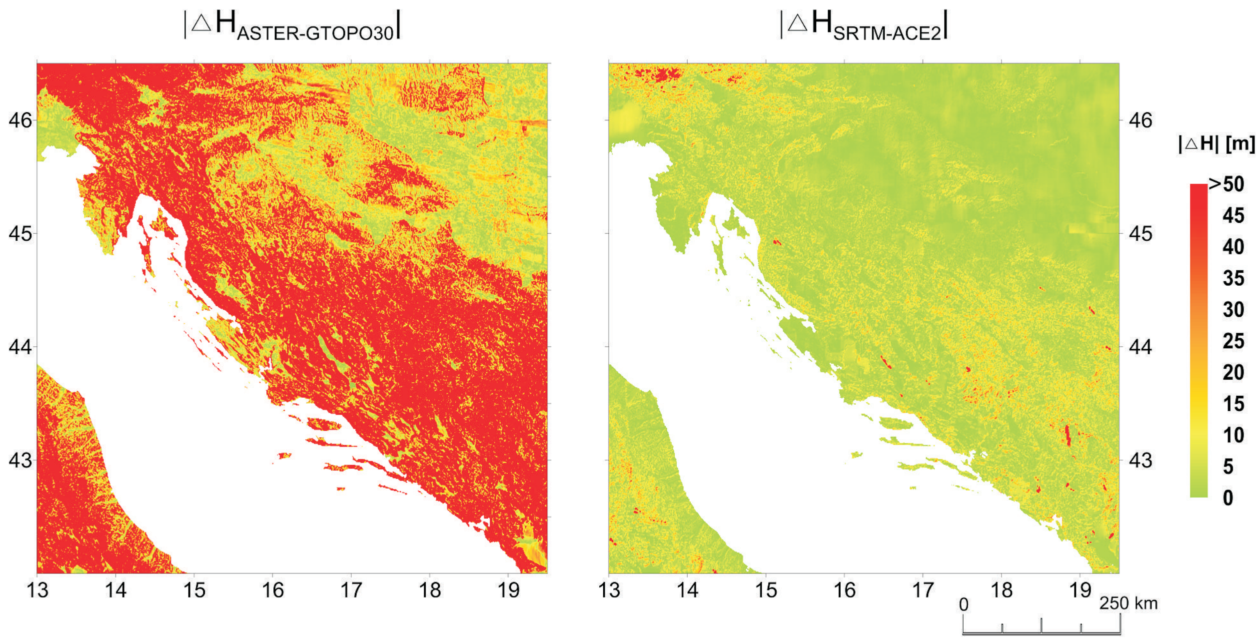

Figure 3 Models with the highest and lowest medians of absolute values of differences

Slika 3. Modeli s najvećim i najmanjim medijanom apsolutnih vrijednosti razlika

5 Conclusion

High-quality digital elevation models are needed in nearly all geoscientific applications. The causes of errors and differences between digital elevation models are numerous and include measuring techniques (laser or photogrammetric measuring of the Earth's surface), roughness of terrain (lowland and mountainous area), surface type (with or without vegetation and man-made structures), resolution, vertical datum (mean sea level or geoid model), horizontal disagreement between models, etc.

In the absolute sense, the height accuracy of global DEMs ranges from ±5 m in lowland areas, to ±15 m in mountainous areas. According to this study, the differences between the global DEMs tested are far from negligible. Large differences between elevation models (> 20 m, see Table 3) indicate the obvious and significant presence of outliers in all models. Compared to other digital elevation models tested, the GTOPO30 and ETOPO1 models show the highest percentage of disagreement and the presence of major errors, and with a coarse resolution, are not recommended for use. The best agreement is found between the ASTER, SRTM (CGIAR-CSI version 4.1), ACE2 and GMTED2010 models, where the smallest percentage of absolute values of differences is over 20 m, indicating the lower presence of major errors.

An important factor, particularly in professional and scientific application in all digital elevation models, is the presence of major, systematic errors, along with insufficiently accurate knowledge of their spatial distribution. Depending on the particular application and task, when using a global digital elevation model, from the user's point of view, this is is obviously restrictive, and in some areas, major uncertainties in global digital elevation models must be detected, documented and, if possible, modelled or eliminated, considering the importance of their potential impact on final results.

For a complete evaluation of the quality (accuracy and reliability) of DEMs on Croatian territory, a comparison and evaluation of heights from DEMs is required, including the heights of geodetic points such as benchmarks with known heights.

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od 20 m grubo su pogrešne i vjerojatno su posljedica pogrešaka prikupljanja i obrade mjernih podataka.

5. Zaključak

Kvalitetni digitalni modeli reljefa potrebni su u gotovo svim geoznanstvenim aplikacijama i primjenama. Uzroci nastajanja pogrešaka i razlika između digitalnih modela reljefa su mnogobrojni, a neki su od njih: mjerna tehnika (lasersko ili fotogrametrijsko snimanje površine Zemlje), razvedenost reljefa (nizinsko ili planinsko područje), tip površine (površina Zemlje s vegetacijom ili bez vegetacije i izgrađenih objekata), razlučivost modela, pogreške vertikalnog datuma (srednje razine mora ili modela geoida), horizontalno neslaganje modela i drugi.

U apsolutnom smislu, visinska točnost globalnih digitalnih modela reljefa kreće se od ± 5 m u nizinskim područjima, do ± 15 m u planinskim područjima. Prema ovom istraživanju, razlike između testiranih globalnih digitalnih modela reljefa nisu zanemarive. Razlike između modela reljefa velikih iznosa (>20 m, tablica 3) upućuju na evidentnu i značajnu prisutnost grubo pogrešnih visina u svim modelima. U odnosu na ostale digitalne modele reljefa, modeli GTOPO30 i ETOPO1 pokazuju najveće neslaganje i postotak prisutnosti grubih pogrešaka, te uz krupnu razlučivost, nisu preporučljivi za korištenje. Između modela ASTER, SRTM (inačica CGIAR-CSI 4.1), GMTED2010 i ACE2 postoji najbolje slaganje i najmanji postotak apsolutnih vrijednosti razlika većih od 20 m, što upućuje na manju prisutnost grubih pogrešaka.

Prisutnost i nepoznavanje dovoljno točne prostorne distribucije grubih i sustavnih pogrešaka u svim digitalnim modelima reljefa za pojedine stručne i znanstvene primjene značajan je faktor. Ovisno o konkretnoj primjeni i zadaći pri upotrebi globalnih digitalnih modela reljefa, evidentno ograničavajuća i na nekim područjima velika nepouzdanost globalnih digitalnih modela reljefa mora od strane korisnika biti detektirana, dokumentirana i ako je moguće modelirana ili eliminirana, s obzirom na možebitnu važnost utjecaja na konačne rezultate.

Za potpunu ocjenu kvalitete (točnosti i pouzdanosti) na ozemlju Republike Hrvatske predstoji i potrebna je usporedba visina iz digitalnih modela reljefa s visinama geodetskih točaka, primjerice reperima poznatom nadmorskom visinom.

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