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High-quality seamless DEM generation blending SRTM-1, ASTER GDEM v2 and ICESat/GLAS observations

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ABSTRACT

The absence of a high-quality seamless global digital elevation model (DEM) dataset has been a challenge for the Earth-related research fields. Recently, the 1-arc-second Shuttle Radar Topography Mission (SRTM-1) data have been released globally, covering over 80% of the Earth's land surface (60°N–56°S). However, voids and anomalies still exist in some tiles, which has prevented the SRTM-1 dataset from being directly used without further processing. In this paper, we propose a method to generate a seamless DEM dataset blending SRTM-1, ASTER GDEM v2, and ICESat laser altimetry data. The ASTER GDEM v2 data are used as the elevation source for the SRTM void filling. To get a reliable filling source, ICESat GLAS points are incorporated to enhance the accuracy of the ASTER data within the void regions, using an artificial neural network (ANN) model. After correction, the voids in the SRTM-1 data are filled with the corrected ASTER GDEM values. The triangular irregular network based delta surface fill (DSF) method is then employed to eliminate the vertical bias between them. Finally, an adaptive outlier filter is applied to all the data tiles. The final result is a seamless global DEM dataset. ICESat points collected from 2003 to 2009 were used to validate the effectiveness of the proposed method, and to assess the vertical accuracy of the global DEM products in China. Furthermore, channel networks in the Yangtze River Basin were also extracted for the data assessment.

1. Introduction

Digital elevation model (DEM) data have been widely applied in scientific fields such as ecology (Kellndorfer et al., 2004; Næsset et al., 2016), agriculture (Fu and Rich, 2002), and hydrological modeling (Wechsler, 2007; Zheng et al., 2015). With the development of remote sensing and photogrammetric techniques, DEMs now mainly refer to elevation data stored as regularly gridded elevation values, based on remote sensing observations (Robinson et al., 2014).

There are a number of DEM products available for global Earth observation and analysis. The Advanced Spaceborne Thermal Emission and Reflectance Radiometer Global Digital Elevation Model (ASTER GDEM) is a product generated from optical data collected by the ASTER instrument onboard NASA's Terra satellite (Hengl and Reuter, 2011). This dataset is the only DEM that covers ~99% of the entire land surface at a high resolution, but the accuracy of the ASTER GDEM has attracted controversy due to the anomalies and noises caused by the limitations of the optical imaging (Tachikawa et al., 2011a,b; Mukherjee et al., 2013). Comparatively, the Shuttle Radar Topography Mission (SRTM) DEM is the most commonly used data source due to its relatively stable accuracy (Yang et al., 2011). This near-global dataset was generated based on spaceborne radar measurements collected in 2000 (Jarvis et al., 2008). However, data voids are common in the mountainous regions with large slope angles due to the squint mode of the SAR imaging (Crosetto, 2002; Toutin, 2002; Baselice et al., 2009). After void filling, SRTM-3 v4.1 was publicly released with a 1-arc-second (~30 m) resolution in the U.S and a 3-arc-second (~90 m) resolution in the rest of the world. More recently, the 1-arc-second global SRTM-1 data product has been released; however, voids still exist in some tiles of complex terrain. Other commonly used global DEM products include the Global 30-Arc-Second Elevation Data Set (GTOPO30) (USGS, 1996), the Global Multi-resolution Terrain

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Elevation Data 2010 (GMTED2010) (USGS, 2010), NEXTMAP WORLD 30™ (Tighe and Chamberlain, 2009) and WorldDEM™ (2014). Among them, the 30-m NEXTMAP WORLD 30™ and the 12-m WorldDEM™ have not yet been freely available to the public. Furthermore, the Geoscience Laser Altimeter System (GLAS) onboard NASA's Ice, Cloud and Land Elevation Satellite (ICESat) provides global laser points with high-accuracy elevation information (Schutz et al., 2005).

There has been extensive research into the assessment of the main public global DEM products (Athmania and Achour 2014; Wang and Wang 2015). Due to the limited spatial resolution of GTOPO30 (~1 km) and GMTED2010 (30, 15, and 7.5 arc seconds), the two datasets cannot satisfy some application demands. Therefore, researchers have mainly focused on the accuracy comparison of the SRTM-3 data and the ASTER GDEM (Hirt et al., 2010; Li et al., 2013; Mukherjee et al., 2013; Satgé et al., 2015; Wang and Wang, 2015). The vertical accuracies of both these DEM datasets are closely related to slope and terrain roughness (Toutin, 2002). It is generally acknowledged that the SRTM-3 data are superior to ASTER GDEM in terms of vertical accuracy in the low-relief areas (Jacobsen, 2010; Zhao et al., 2011; Li et al., 2013), while the ASTER GDEM shows a better performance in some mountainous areas than the SRTM-3 data, which is probably due to the inaccurate void filling of the SRTM-3 data (Li et al., 2013; Yue et al., 2015). The vertical accuracy of ICESat GLAS data points can reach a sub-meter level; however, the sparsely distributed GLAS points are separated by intervals of nearly 170 m along-track and several kilometers across-track (Zhang et al., 2011).

With the growing demand for the monitoring of Earth surface changes, the absence of a high-quality seamless global DEM dataset has been a challenge for the Earth-related research fields (Robinson et al., 2014). On one hand, modern imaging technologies have been applied to Earth observation, and new DEM products are being generated and released (Fritz et al., 2012; Tadono et al., 2015). On the other hand, the analysis and improvement of the currently available datasets also make sense (Reuter et al., 2007; Arefi and Reinartz, 2011; Yue et al., 2012; Robinson et al., 2014). Reuter et al. (2007) presented a void-filling strategy in conjunction with other sources of elevation data using a range of interpolation algorithms. The SRTM-3 v4.1 data were processed following the method described by Reuter et al. (2007). However, the accuracy of the void-filled results are still unstable as validated in the related works (Li et al., 2013; Yue et al., 2015). Arefi and Reinartz (2011) tried to utilize ICESat data to improve the accuracy of ASTER GDEM data. Given the sparse distribution of the ICESat data, it is difficult to control the accuracy of the corrected ASTER tiles without sufficient reference points using an ordinary Moving Average interpolation method. Robinson et al. (2014) reconstructed a new 90-m DEM product by integrating multi-scale DEM products (1-arc ASTER GDEM v2, 3-arc SRTM-3 v4.1 and 3-arc GLSDEM). Nevertheless, they did not fully consider the unstable filling results in SRTM-3 v4.1, and the spatial resolution of the final product is limited (only 90 m). In addition, the method only used information from GLSDEM to fill the voids of ASTER GDEM at high latitudes, ignoring the low accuracy of the auxiliary data within the voids.

On the whole, there are two main limitations among these works presented. Firstly, most of the researchers focused on SRTM-3 and ASTER GDEM v2, which are the most popular global DEM datasets. However, the ASTER GDEM is severely affected with random noise and anomalies, while the previously released SRTM-3 v4.1 dataset is limited by the 3 arc second resolution and the inaccurate void-filling results. Secondly, there are few works incorporating the high-quality elevation data in addition to the raster DEM datasets into the process of multi-source data fusion.

Given these facts, the fusion of multi-source and multi-scale data to generate a high-quality seamless DEM product is still challenging. For the first issue, the release of the global 1-arc SRTM-1 dataset can be considered as progress. As voids and anomalies still exist in some tiles, the current SRTM-1 data cannot be directly used without further processing. Nevertheless, with the release of the high-resolution SRTM-1 data, there is now a chance to generate a DEM product with a high resolution, a global extent, and a reliable accuracy, by integrating multi-source elevation data. Given the comparative resolutions and the same project coordinate system, the ASTER GDEM v2 can be regarded as a good elevation source for SRTM-1 void filling. Moreover, ICESat laser points can be incorporated to correct the inaccurate elevation values in the ASTER data within the void regions considering the relatively low accuracy in the rugged terrain.

This paper intends to convey a processing method to generate a high-resolution, high-quality, and seamless global DEM product blending the recently released global SRTM-1 dataset, the optical-derived ASTER GDEM v2, and ICESat GLAS data points. To correct the ASTER elevations using the ICESat points, it turns out to be a point-surface fusion problem on account of the large spacing between the ICESat data. The common solution is to generate a correction layer using an interpolation method (Arefi and Reinartz, 2011; Verdin et al., 2015), while the ICESat points are used as ground control points (GCPs). Nevertheless, the distance between the scanning tracks of the ICESat data results in significant errors. In this paper, we employ an ANN model to simulate the relationship between the ICESat and ASTER GDEM data, followed by a void filling process. Furthermore, an adaptive outlier filter is applied to reduce the anomalies for the non-void areas in the SRTM-1 data.

The rest of the paper is organized as follows. Section 2 gives a detailed description of the data used. In Section 3, we provide the details of the processing flow. The results after void filling and correction are analyzed in Section 4. Finally, Section 5 provides the conclusion.

2. Datasets

In this paper, we integrate multi-source elevation data for the generation of a seamless global DEM dataset. The data sources include the 1-arc SRTM-1 DEM, the 1-arc ASTER GDEM v2, and the ICESat GLAS land elevation product. Meanwhile, the SRTM-3 DEM data are also included for the accuracy validation and comparison. The specific characteristics of the datasets are provided in the following.

2.1. SRTM data products

The SRTM was an international project conducted by NASA and the National Geospatial-Intelligence Agency (NGA) in February 2000 (Van Zyl, 2001). The 11-day mission acquired data via radar interferometry using an onboard/outboard antenna system and single-pass data acquisition, which were used to generate near-global land elevation data products. The SRTM was successful in collecting elevation data over 80% of the Earth's land surface (60°N–56°S) (Farr and Kobrick, 2000). There are two main global SRTM DEM datasets with different levels of processing.

The original SRTM elevation data were processed from C-band radar signals spaced at intervals of 1 arc seconds at NASA's Jet Propulsion Laboratory (JPL). However, the original data for regions outside the U.S were released at 3 arc seconds for open distribution, and are referred to as the SRTM-3 data. Since its original release, the SRTM-3 dataset has been updated several times for quality improvement. The most commonly used SRTM-3 v4.1 was released by the Consortium for Spatial Information of the Consultative Group of International Agricultural Research (CGIAR-CSI) after data improvement and void filling, and distributed as $5^\circ \times 5^\circ$