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Validation of surface height from shuttle radar topography mission using shuttle laser altimeter

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Abstract

Spaceborne Interferometric SAR (InSAR) technology used in the Shuttle Radar Topography Mission (SRTM) and spaceborne lidar such as Shuttle Laser Altimeter-02 (SLA-02) are two promising technologies for providing global scale digital elevation models (DEMs). Each type of these systems has limitations that affect the accuracy or extent of coverage. These systems are complementary in developing DEM data. In this study, surface height measured independently by SRTM and SLA-02 was cross-validated. SLA data was first verified by field observations, and examinations of individual lidar waveforms. The geolocation accuracy of the SLA height data sets was examined by checking the correlation between the SLA surface height with SRTM height at 90 m resolution, while shifting the SLA ground track within its specified horizontal errors. It was found that the heights from the two instruments were highly correlated along the SLA ground track, and shifting the positions did not improve the correlation significantly. Absolute surface heights from SRTM and SLA referenced to the same horizontal and vertical datum (World Geodetic System (WGS) 84 Ellipsoid) were compared. The effects of forest cover and surface slope on the height difference were also examined. After removing the forest effect on SRTM height, the mean height difference with SLA-02 was near zero. It can be further inferred from the standard deviation of the height differences that the absolute accuracy of SRTM height at low vegetation area is better than the SRTM mission specifications (16 m). The SRTM height bias caused by forest cover needs to be further examined using future spaceborne lidar (e.g. GLAS) data.

Keywords: Shuttle Radar Topography Mission (SRTM); Shuttle Laser Altimeter (SLA); Interferometric SAR; DEM; Lidar waveform; Tree height

1. Introduction

The capability to obtain quality DEM data over large areas is important for Earth science studies. The SRTM instrument was the first fixed baseline single-pass spaceborne dual frequency (C-band and X-band) interferometric SAR (http://www.jpl.nasa.gov/srtm). The dual antenna system of SRTM provides the best elevation data ever available at a global scale. Both airborne and space based lidar systems are emerging as high precision topographic mapping tools (Blair, Rabine, & Hofton, 1999; Hofton, Rocchio, Blair, & Dubayah, 2002) as well as effective systems for the estimation of surface geology and vegetation biomass (Drake et al., 2002; Hudak, Lefsky, Cohen, & Berterretche, 2002; Lefsky, Cohen, Acker, et al., 1999; Lefsky, Cohen, & Spies, 2001; McCombs, Roberts, & Evans, 2003; Slatton, Crawford, & Evans, 2001; Treuhaft, Asner, & Law, 2003). Large-footprint laser altimeters are able to provide elevation of bare Earth even in dense forest areas (Hofton et al., 2002). These systems are complementary in developing DEM data. For example, InSAR can provide DEM over large areas, but has inherent speckle noise and requires ground control points to establish height accuracy. Laser based systems currently provide discrete surface height samples instead of a continuous coverage of Earth's surface, but these samples can serve as ground control points in high accuracy required by InSAR. In this study data from the SRTM mission was evaluated.

Our studies of boreal forest disturbance and biomass in Siberia require high quality DEMs (Ranson, Sun, Kharuk, &

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Kovacs, 2001; Sun, Ranson, & Kharuk, 2002). The objective of this study is to use surface height from the second Shuttle Laser Altimeter mission (SLA-02) to validate the height from SRTM. The SLA data was first verified by field observations, and examination of individual lidar waveforms. The geolocation accuracy of the SLA height data sets was examined by checking the correlation between the SLA surface heights of an orbit with SRTM height while shifting the SLA orbit within its specified horizontal errors. The uncertainty of SLA surface height then was determined by the nominal error at flat area plus an additional error caused by local slope. The absolute surface height from SRTM and SLA referenced to the same horizontal and vertical datum (World Geodetic System (WGS) 84 Ellipsoid) were compared. The uncertainty or error of SRTM surface height was estimated from the variance of the height differences of the two instruments and the uncertainty of SLA surface height. The effects of forest cover and surface slope on the height difference were also examined.

2. Study area

Our study area is in central Siberia. In Fig. 1, the region within the trapezoid box is the International Geosphere–Biosphere Programme (IGBP) West Siberian transect. This area was selected for international collaboration by the IGBP Global Change and Terrestrial Ecosystems (GCTE) program and is located along the Yenisey River meridian (92°E) from the Arctic to the Mongolian desert. The portion of the area covered by SRTM is about 1000 km in width and 1000 km in length (50–60°N, 82–98°E) and in the southern part of the IGBP West Siberian transect. In the south–east portion of the study area the Sayani Mountains rise up to heights 3000 m or more. Siberian forests are composed of larch (*Larix sibirica*), Scotch pine (*Pinus silvestris*), Siberian pine (*Pinus sibirica*), Siberian fir (*Abies sibirica*), Siberian spruce (*Picea obovata*), birch (*Betula verrocosa*, *B. pubescence*) and aspen (*Populus tremula*). The SRTM data validated in this study covers a 3 × 3° area of 56–59°N and 92–95°E, which is the first dataset we received for our studies. This area is relatively flat compared to the Sayani Mountain in the south.

Fig. 1. Map showing IGBP Western Siberia Transect (trapezoid box) and SRTM covered area (between 50°N and 60°N). The orbit marks (dark) within the study area show the SLA-02 data points.

3. SRTM and SLA-02 data

The Shuttle Radar Topography Mission (SRTM) is an international project spearheaded by the National Imagery and Mapping Agency (NIMA) and NASA (van Zyl, 2001). The objective of the mission was to obtain the most complete high-resolution digital topographic database of the Earth. SRTM consisted of a specially modified radar system that flew onboard the Space Shuttle Endeavour during an 11-day mission in February of 2000. SRTM data provides the most complete global topographic map ever made, from 60° north to 56° south latitude. The digital topographic map products meet Interferometric Terrain Height Data (ITHD)-2 specifications: at 30 × 30 m spatial sampling, the absolute vertical height accuracy (90% linear error) is 16 m. The absolute horizontal accuracy (90% circular error) is 20 m (http://www.jpl.nasa.gov/srtm/datafinaldescriptions.html). Due to restrictions imposed by the sponsoring agency (NIMA) and processing capabilities only 90 m (three arc second) resolution data was available for our area. More information about the SRTM mission can be found at http://www.jpl.nasa.gov/srtm/.

There are two types of data from the SRTM mission. One was processed in a systematic fashion using SRTM Ground Data Processing system (GDPS) supercomputer at Jet Propulsion Laboratory and was formatted according to the Digital Terrain Elevation Data (DTED) specification for delivery to NIMA. The GDPS data includes only the DEM and is referenced to the WGS84 geoid. The other is the PI Processor data, which was processed using the algorithm and hardware being developed for GDPS. These data are for Principal Investigators selected by NASA under the Solid Earth and Natural Hazards program and other special purposes. These data were not formatted according to DTED specification, and the terrain height data is relative to the WGS84 ellipsoid. The PI data set also includes other data sets, such as the power radar images, incidence angle, polarization, and height error, in addition to the terrain height data. (SRTM documentation, ftp://edcsgs9.cr.usgs.gov/pub/data/srtm/PI_Processor/..SRTM_Topo.txt). PI data may contain residual offsets and tilts, without using coastlines for absolute height calibration, and the continental-scale block adjustment. The data used in this study is the PI data in central Siberia.

A number of tie points are required to reduce the height error when InSAR is used to generate digital elevation data

(Li & Goldstein, 1990; Zebker, Werner, Rosen, & Hensley, 1994; Sun, Ranson, Bufton, & Roth, 2000). SLA-02 was one of a series of lidar missions for the acquisition of geodetic quality surface elevation measurements, corrected for local slopes and vegetation heights to augment the SLA-based global database of ground control points (Bufton, Harding, & Garvin, 1999; SLA-02 Web site: http://denali.gsfc.nasa.gov/research/laser/sla02/). The SLA-02 flight experiment aboard the STS-85 mission (August 1997) was also intended as an incremental step in orbital echo-recovery or ''surface lidar'' (Garvin et al., 1998). The goal was to acquire a global database of laser echoes describing a wide range of land cover classes. The SLA-02 data can be used to characterize the vertical roughness of different land cover classes and landscapes on a global basis. For SLA mission, the shuttle flew at an altitude of about 300 km, and SLA-02 sent 10 laser pulses per second along track, sampling the Earth's surface about every 750 m. The footprint, i.e. the illuminated ground surface area by a laser shot is 100 m. There are seven orbits and about 10,000 SLA-02 shots without clouds in our study area (see Fig. 1). The returned laser signal (a waveform) from a pulse was digitized by a pulse digitizer, which has a sampling rate up to 500 megasamples per second. The vertical resolution of the waveform was decreased after observation period 4 due to system problems. In order to compensate for the large jitter found in the position of the stop pulse event, following observation 4 the waveform digitizer bin size was increased from 4 to 10 ns (http://denali.gsfc.nasa.gov:8001). Only the data from observation periods 1 and 3 were used in this study.

The elevation (surface height) given in the SLA-02 data sets is the height of the top canopy, i.e. the height of the starting point of the waveform. The canopy height is the distance from the top of canopy to the last peak of pulse return, which presumably is the return from the ground surface. The range accuracy of lidar is very high (in centimeters), but other factors, such as the surface roughness, and the uncertainty of footprint location, reduce the vertical accuracy of the lidar data. The RMS height and horizontal position errors are in the order of 1 and 100 m, respectively (http://denali.gsfc.nasa.gov/research/laser/sla/srowton/summary.html). The errors were further reduced using an enhanced geolocation algorithm (Luthcke, Carabajal, & Rowlands, 2002). The slope, surface roughness, and vegetation cover cause the ambiguities of the last return. While the surface slope severely reduces the vertical accuracy of the lidar, the SRTM data provides the slope information at the lidar footprints. It is also well known that in vegetated areas, the ''height'' measured by InSAR is the height of the scattering center within the canopy, which is wavelength-dependent (Treuhaft, Madsen, Moghaddam, & van Zyl, 1996). For the snow-covered Siberia landscape (SRTM flew in February 2000), the comparisons between the measurements from SRTM and lidar (flew on August 7–18, 1997) should reveal the height error caused by the vegetation and snow cover.

4. Methods

4.1. SLA-02 data verification

The SLA-02 data was first screened for removing the footprints with clouds. This was done by removing all shots with surface height greater than 3000 m, the highest elevation in the area. Then the surface height, tree height and waveforms of all SLA-02 shots in our study region from observation periods 1 and 3 were extracted, and located on Landsat images. The consistency between the land cover types shown on Landsat images and the tree height and waveform from SLA-02 was examined. There are abnormal waveforms, from which the tree and surface heights could not be estimated. These shots and the shots on water surfaces were excluded from this analysis, leaving a total of 322 shots used in the study.

SLA data was verified by field observations, and examinations of individual lidar waveforms. The geolocation of the SLA height data sets was examined by checking the correlation between the SLA surface height of an observation orbit with SRTM height while shifting the SLA ground track within its specified horizontal errors (~ 100 m). It was found that the heights from the two instruments were highly correlated along the SLA orbit, and shifting the orbits didn't improve the correlation, so the confidence on the geolocation of the SLA height data sets was established.

The waveform of SLA-02 is a measure of the height distribution of the vertical structure in the 100-m diameter footprint. The round-trip travel time duration of waveform digitizer bin for the SLA-02 orbits (1 and 3) used in this study is 4 ns, corresponding to a vertical distance of about 0.6 m. The height and horizontal position accuracies of the SLA-02 data used in this study are on the order of 1 m, and about 100 m, respectively (Carabajal et al., 1999; Luthcke et al., 2002). In order to verify (or have a high confidence on) SLA-02 data, footprints of some SLA-02 laser shots were visited in summer of 2002 as part of GSFC and Sukachev Forest Institute field work for a Siberia Land Cover Mapping project. SLA-02 footprints were marked on Landsat-7 ETM images, and then selected for field observations based on cover type, accessibility, and location of the footprint being well inside a homogeneous area of the cover type.

Fig. 2A shows a portion of the Landsat-7 ETM+ image and overlaid SLA-02 footprints at a test site within the study area. SLA-02 shots 29478 and 29479 were located within a forest stand (Fig. 2B) and a fallow agricultural field (Fig. 2C), respectively. Fig. 3 shows the SLA-02 lidar waveforms from these two lidar shots. From the lidar shots, the ground cover type (forest or non-forest), the height of the ground surface and the tree height can be estimated. For example, in Fig. 3A, the vertical line was added to the waveform to show the estimated noise level. The start point of the waveform, i.e. the first signal above the noise level, occurred near the bin 129. A ground return peak, i.e. the last peak in the waveform is located at bin 101. Since the width of each bin is 0.6 m and

Fig. 2. (A) SLA-02 lidar shots 29478–29480 were marked on a L-7 ETM+ image. The dark areas are forests. (B) A photo within the forest covered by shot 29478. (C) A photo of the open area for shot 29479.

there are 28 bins from top to the surface, the tree height for this footprint is about 16.8 m. In Fig. 3B, the single pronounced ground return is indicative of non-forested areas.

Test sites with identified SLA_02 footprints were visited during the summer of 2002. We located several footprints within forests using Landsat-7 images and a GPS unit. The size and height of the trees were sampled. Forest conditions were sampled based on a US Forest Service technique used in Alaskan forests (USFS, 2002). Each test site includes 4 circular plots (with 7.6 m radius): one in the center and three located 30 m from the center of center plot. These plots were placed in an equilateral triangle arrangement with one vertex orientation to true north. Within each site the overstory and undergrowth inventory characteristics were measured or described (species, diameter at breast height (dbh), height, age, crown shape, tree vigor). Soil and ground cover were also described. The central site was geo-referenced by GPS, with precision ± 15 m. The data are listed in Table 1 and will be described in Results.

If a laser pulse hits vertically on a horizontal smooth surface, the peak of the return will have the same width as the laser pulse (Sun & Ranson, 2000). In the SLA instrument specifications (http://denali.gsfc.nasa.gov:8001), the pulse width (full width at half maximum power) was 15 or 20 ns for pulse energy at 35 and 20 mJ, respectively. The real width estimated by checking the pulses with single peaked, high amplitude returns from flat surfaces was 7.5 m or 25 ns (Luthcke et al., 2002). Therefore, it should be noted that even for a smooth flat surface, the SLA data gives a 'tree height' of several meters. The surface height given in SLA-02 data (ellip_ht) is the top canopy height referenced to a WGS84 Ellipsoid. Therefore, the ground surface height should be the ellip_ht minus the tree height of the same laser shot.

4.2. SRTM and SLA height comparisons and SRTM height error estimation

The lidar elevation data was first overlaid on SRTM height data. The correlations between the surface heights from these two instruments were calculated. Assuming that the horizontal accuracy of SLA-02 shots location was not

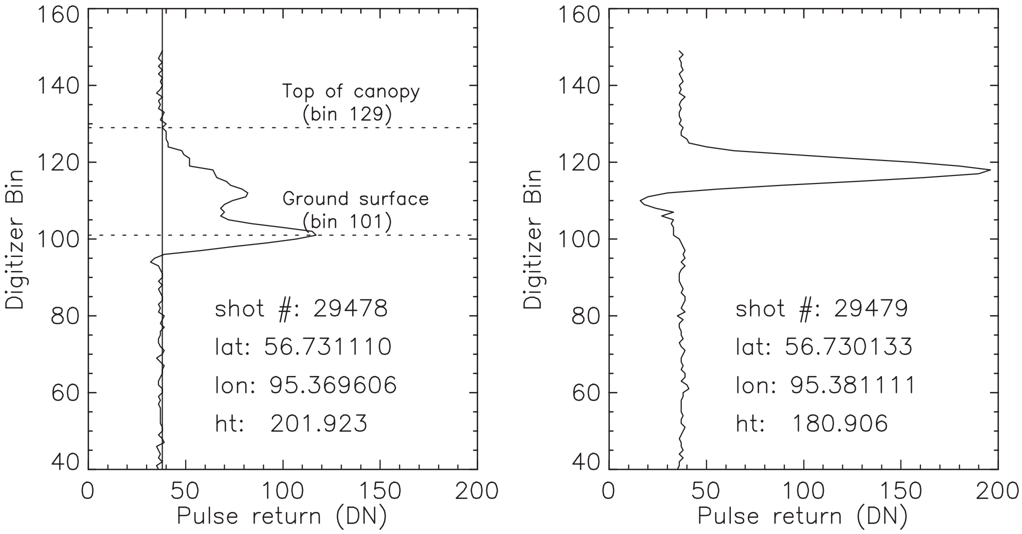

Fig. 3. SLA-02 lidar waveforms for shots 29478 and 29479. The tree height measured by lidar is the distance from the first return above the noise level (top of canopy) to the peak return from the ground.

Table 1
Tree heights from field measurements and SLA-02 data

Site	Shot no.	Species	Lat/Long	Trees	Max height	SLA height	% of h difference	Comments
KT14	29478	Pine/Birch	56.73/95.37	66	18.6	16.74	10.00	6 trees >15 m
KT16	29467	Birch	56.73/95.23	35	16.9	17.56	3.91	5 trees >15 m
KT17	29468	Pine/Birch	56.73/95.25	50	17.3	18.15	4.91	4 trees >15 m
KT18	34704	Pine	57.11/95.31	25	33.8	26.5	21.60	Most >20 m
KT19	34675	Pine	57.12/94.93	14	23.0 (one)	20.86	9.38	Rest 6–8 m
KT20	34676	Mix	57.12/94.94	31	26.8	30.75	14.74	10 trees >20 m
KT25	34528	Pine	57.13/93.17	6	26.0	24.44	6.00	All >20 m

perfect, the SLA-02 orbit was shifted 2 pixels (about 200 m) in south–north and east–west direction to find the ‘best’ match using the correlations. The absolute surface height from SRTM and SLA referenced to the same horizontal and vertical datum (WGS84 Ellipsoid) were compared. The effects of forest cover and surface slope on the height difference were examined by investigating the dependence of the SRTM-SLA height difference on tree height and local slope. The SlA-02 footprints were grouped into two categories: bare surface and forests. The regression lines between SRTM and SLA-02 height were produced for these two categories, and for total points. Exact correspondence between SRTM and SLA-02 measurements would result in a slope term equal to 1.0 and intercept (bias) of 0.0. A non-unity slope may suggest some systematic effect such as radar tilt angle or off-nadir beam angle of the lidar. A non-zero intercept may indicate an error or bias introduced by surface effects. Two-tailed *t*-tests (e.g. Neter & Wasserman, 1974) were constructed to examine these relationships.

With known uncertainty (or error) of SLA-02 height, and the variance of SLA-SRTM height difference, the uncertainty of SRTM height can be estimated. The error or uncertainty of DEM derived from SLA and SRTM may be assumed as independent. Although both instruments flew on the space shuttle, one was during August 7–18, 1997 on Discover, and the other was during February 11–22, 2000 on Endeavour. The system error from SRTM is weakly related to the shuttle position, and is caused by the uncertainty of the baseline (the length and orientation of mast), timing error, phase measurement error and thermal noise of the radar (http://www.jpl.nasa.gov/srtm/faq.html). The system error from SLA is mainly related to the uncertainty of position and attitude of the laser. The physical basis and data processing for measuring the surface height from these two instruments are totally different so the effects of separate system errors on derived DEM should not be correlated. The error of DEM due to the target characteristics (vegetation cover, slope, surface roughness, etc.) should not be correlated. In the following analysis, we will also assume that these errors are normally distributed. According to the theory of propagation of uncertainties (Bevington, 1969; Taylor, 1997), if a variable is the sum or difference of two other independent variables, its uncertainty is the sum of the uncertainties of the two original variables. Assuming that the surface height measured from an instrument is the sum of the true height (h) and a Gaussian distributed error (e), the height difference of SRTM-SLA then is a variable equal to the difference of these two errors:

$$h_{\mathrm{diff}} = e_{\mathrm{SRTM}} - e_{\mathrm{SLA}} \qquad (1)$$

Therefore, the variance of the height difference equals the sum of the variances of the two independent variables, i.e.

$$\sigma^2_{\mathrm{height-diff}} = \sigma^2_{\mathrm{SRTM\_ht}} + \sigma^2_{\mathrm{SLA\_ht}} \qquad (2)$$

from which the error of the SRTM surface height may be estimated.

The correlation between the height difference and tree height was used to reduce the canopy effect, i.e. to adjust the SRTM height to the ground surface height.

4.3. Comparisons of SRTM height with DTED-1 DEM

The Level-1 Digital Terrain Elevation Data (DTED1) from National Imagery and Mapping Agency (NIMA) were available for this study under a Memorandum of Understanding between NIMA and NASA. Because SRTM data and DTED1 use different height reference these heights could not be compared directly. The SRTM data was first converted to the same reference and then compared with DTED data, and the slope images derived from both DEM were compared.

5. Results

5.1. SLA-02 data quality

Several footprints with different forest types were sampled, and the results were presented in Table 1. For example, the footprint of SLA-02 shot #29478 was located using Landsat-7 image and a GPS unit. A total of 66 trees at this site were measured. Six of these trees have a height greater than 15 m, and the tallest tree was 18.6 m. The SLA-02 gives a canopy top height of 16.74 m. In the SLA-02 data processing, Gaussian fits were used to locate the waveform peaks, and distant from signal ‘start’ to centroid of the last maximum derived from the fits is given as the canopy height

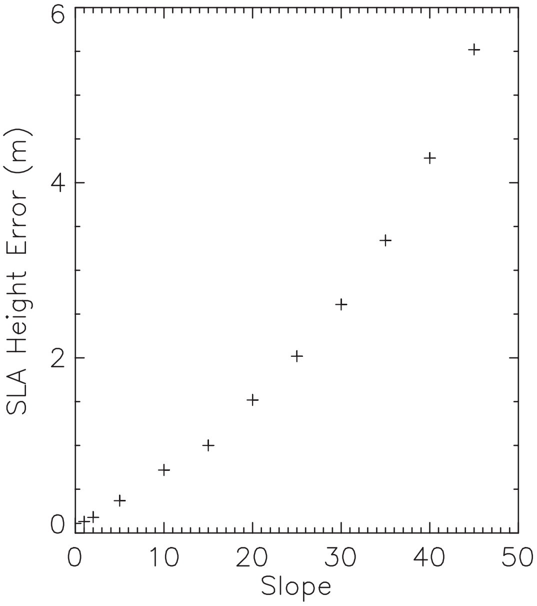

Fig. 4. Slope dependence of SLA-02 height errors.

of the footprint. The differences between maximum height measured on ground and the canopy top height from SLA-02 data are also listed in the Table 1. The results show that the tree heights measured by SLA-02 correspond to the field data quite well. The tree height changes between 1997 (SLA-02 flight), 2000 (SRTM Mission) and 2002 (field work) were not considered in this study. The lidar waveform and the tree height information retrieved from the lidar waveform are also affected by tree crown shape (Sun & Ranson, 2000). These will be topics of our future studies.

Based on the above examination and other validation studies by SLA-02 teams (Luthcke et al., 2002; Luthcke, Carabajal, Rowlands, & Pavlis, 2001), it is reasonable to believe that the location error of SLA footprints is within the size of a footprint (100 m), and that the error of the SLA surface height at a flat bare surface is on the order of less than 1 meter as shown by Luthcke et al. (2002). The slope dependence of SLA-02 height errors is shown in Fig. 4 and described by Sun et al. (2000). In the following analyses, we will use 1.72 m (0.72 m, the error at 10° slope in Fig. 5, plus the 1.0 m error at a flat surface) as the standard deviation of the SLA height measurements in this study area. Very dense canopy and very rough surface can also make it difficult to identify the ground return peak from the waveform, and introduce more error in SLA height. These cases were excluded from examination of Landsat images and lidar waveforms.

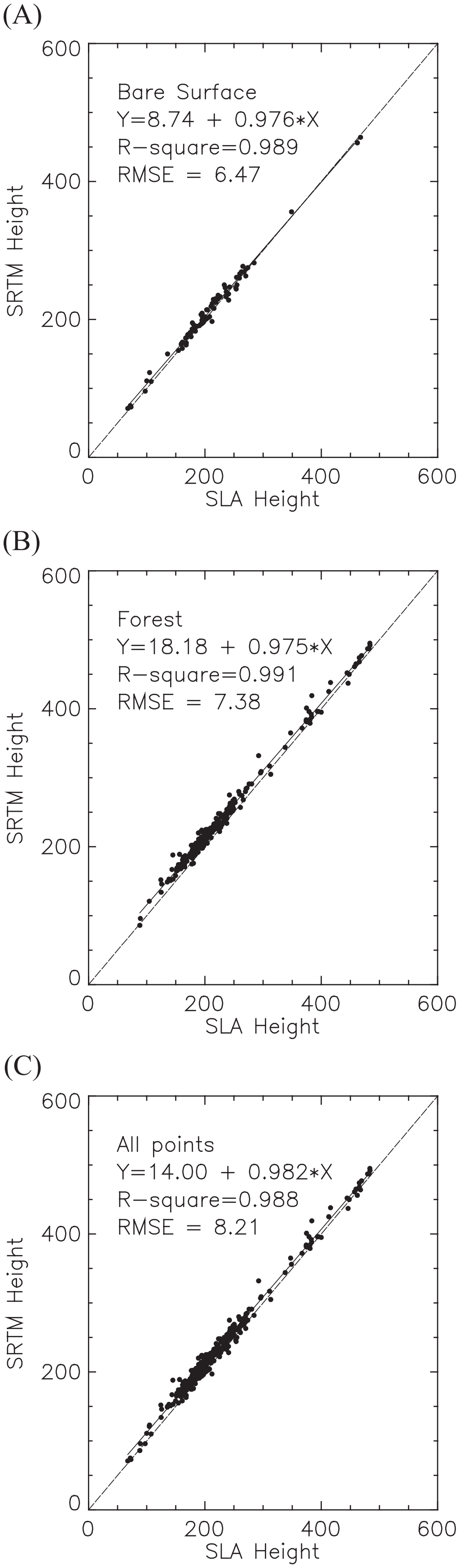

Fig. 5. Correlations between surface heights from SLA and SRTM are high for all cases: (A) bare surface, (B) forests and (C) all points. The height bias, i.e. the SRTM height is higher than SLA height (especially for the points with forest), may be due to the fact that the height measure by InSAR is the height of 'scattering center' within the canopy, not the ground surface.

Table 2
The correlations between the surface heights from SLA-02 and SRTM when the orbit of SLA was shifted (see text in Section 5.2)

Shift	−2/−2	−2/−1	−2/0	−2/1	−2/2	−1/−2	−1/−1	−1/0	−1/1
Ob1	0.9763	0.9818	**0.9873**	0.9870	0.9815	0.9735	0.9787	0.9821	0.9818
Ob3	0.9886	0.9924	0.9954	0.9967	0.9940	0.9894	0.9940	0.9969	0.9976
Shift	−1/2	0/−2	0/−1	0/0	0/1	0/2	1/−2	1/−1	1/0
Ob1	0.9775	0.9704	0.9750	***0.9772***	0.9766	0.9734	0.9669	0.9710	0.9732
Ob3	0.9947	0.9900	0.9946	***0.9977***	**0.9980**	0.9947	0.9900	0.9947	0.9978
Shift	1/1	1/2	2/−2	2/−1	2/0	2/1	2/2		
Ob1	0.9723	0.9695	0.9636	0.9659	0.9694	0.9684	0.9667		
Ob3	0.9977	0.9942	0.9896	0.9940	0.9972	0.9969	0.9934		

The highest correlation was bolded, and the correlation without shifting was in italic-bold.

5.2. SRTM and SLA location matching and height comparisons

The lidar elevation data was first overlaid on SRTM height data. Using the recorded SLA-02 and SRTM latitude and longitude information, the correlations between the surface heights from these two instruments were calculated. Assuming that the horizontal accuracy of SLA-02 shots location was not perfect, the SLA-02 orbit was shifted 2 pixels (about 200 m) in the north−south and the east−west directions to find the 'best' match using the correlations. We expected to find improved correlations if the SLA-02 location was offset in a particular direction, or the correlation should drop significantly if the current orbit position is perfect. The correlations between SLA and SRTM heights were listed in Table 2. The correlations are very high and the results showed that there was no significant improvement in correlation when the SLA orbit location was shifted. Therefore, the geolocations of lidar shots given by SLA-02 data were used to extract the surface height from the SRTM DEM. Since the ellipsoid height of SLA-02 data represents the elevation of the top canopy, the height of the canopy needs to be subtracted to get the ground surface height. The 'SLA height' used in the following analyses and on the figures was the ground surface height or elevation. The 'SRTM height' used was the ellipsoid height from the PI data.

The correlations between SLA-02 and SRTM surface heights are plotted in Fig. 5 for bare surfaces (Fig. 6A), and for forested areas (Fig. 6B). Bare surface points are lidar shots where computed tree height are less than 10 m and the waveforms show profound ground returns. This was also confirmed by checking the Landsat images of these points. For both cases, the r^2 and the slope of the regression lines are close to 1.0. The two-tailed *t*-tests described by Neter and Wasserman (1974) were used to test if the slope and intercept were significantly different from 1.0 and 0.0, respectively. The testing results are shown in Table 3. Even though the regression slopes seem very close to 1.0, but they are, in fact, significantly different from 1.0 at a confidence

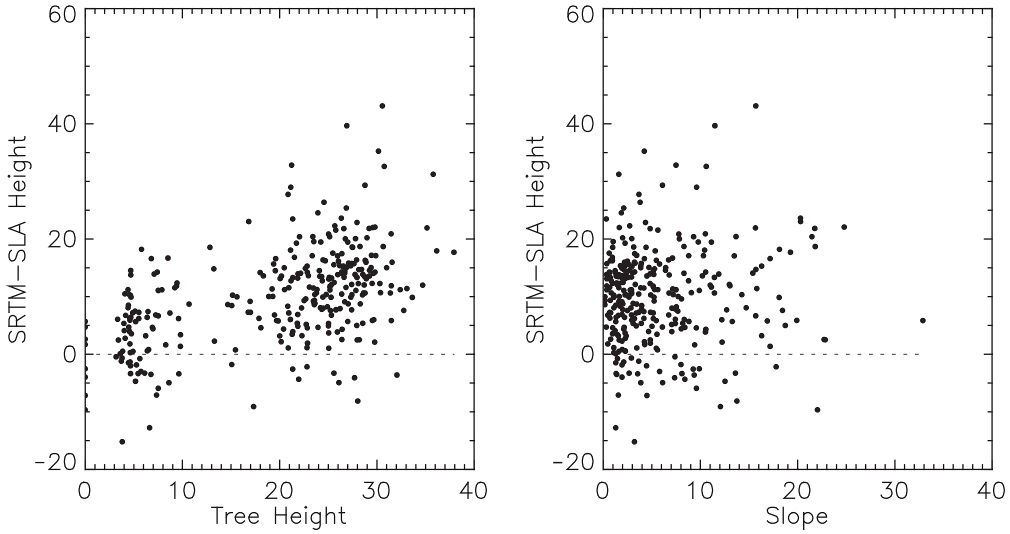

Fig. 6. The SRTM and SLA surface height differences versus tree height (left) and local slope (right). The mean and standard deviation of the height differences are 9.80 and 8.57 m, respectively.

Table 3
Test results for the range of slope and intercept of the regression lines in Fig. 5

	No of samples	Slope		Intercept	
		Low	High	Low	High
Bare surface	87	0.9493	0.9966	4.13	14.51
Forests	235	0.9643	0.9886	14.52	20.46
All samples	322	0.9708	0.9948	10.82	16.49

level of 95%. The reasons for this needs to be further investigated. There is definitely a positive intercept in these regression lines.

These plots reveal the effect of vegetation cover on the surface height measurements. The positive intercepts of regression lines in Fig. 5B indicate that SRTM height is higher than SLA height. The height differences between SLA and SRTM were calculated for all points in Fig. 5, and the mean and standard deviation of the differences are 9.80 m and 8.57 m, respectively. The height difference versus tree height and local slope (determined from SRTM DEM) are plotted in Fig. 6. The SRTM height is systematically higher than SLA height. While the height difference appears to be random when the 'canopy height' is less than 10 m, there is a trend when the tree height is taller than 10 m (Fig. 6A).

The mean and standard deviation of SRTM-SLA height difference for bare surfaces (tree height from SLA-02 < 10.0 m) were 3.11 and 5.45 m, respectively. For forest areas (tree height>10.0 m), the mean and standard deviation were 16.17 and 5.66 m, respectively. It is obvious that the recorded SRTM height within forest areas is not the surface height of the "Bald Earth". The reasons for the 3-m bias for bare surfaces could be in part due to snow cover during the SRTM mission, but probably mainly due to the residual offsets or tilts in the SRTM PI data we have used. This needs to be further investigated when more space lidar data is available through the GLAS mission.

From the Eq. (2), the error of SRTM surface height for bare surface will be

$$\sigma_{\mathrm{SRTM\_ht}} = \sqrt{\sigma^2_{\mathrm{height-diff}} - \sigma^2_{\mathrm{SLA\_ht}}} = \sqrt{5.45^2 - 1.72^2}$$
$$= 5.17m$$

Using the estimated SRTM height error at the 90% confidence level (1.6 standard deviation × 5.17 m = 8.27 m) plus the positive bias (3.11 m) for SRTM height at the bare surface, the total error is 11.38 m, which is less than the SRTM specification (16 m). For the forested areas, the bias alone (16.127 m) exceeds the error specification. Following the method for bare surfaces, the total error for SRTM forest pixels could reach (16.17 + 1.6*5.39) = 24.79 m.

The correlation between the height difference and tree height can be used to reduce the canopy effect, i.e. to adjust the SRTM height to the ground surface height. The points above the zero line in Fig. 6 were used to develop a linear regression relation between height difference and tree height. By applying the linear relationship, for each point a bias height was calculated from tree height, and then was removed from SRTM height. The results were plotted in Fig. 7. The mean of the height difference between SRTM and SLA is near zero, i.e. − 0.11 m, and the standard deviation is 7.24 m. The 90% linear error (1.6 standard deviation) for SRTM height is 11.25 m, which is less than the SRTM specification (16 m).

For this relatively flat area, the slope effect on the height measurements from two instruments was not very obvious. Slope will mainly reduce the height accuracy of SLA height, and the variance of the SRTM/SLA height difference should be larger when the slope increases. This trend is probably

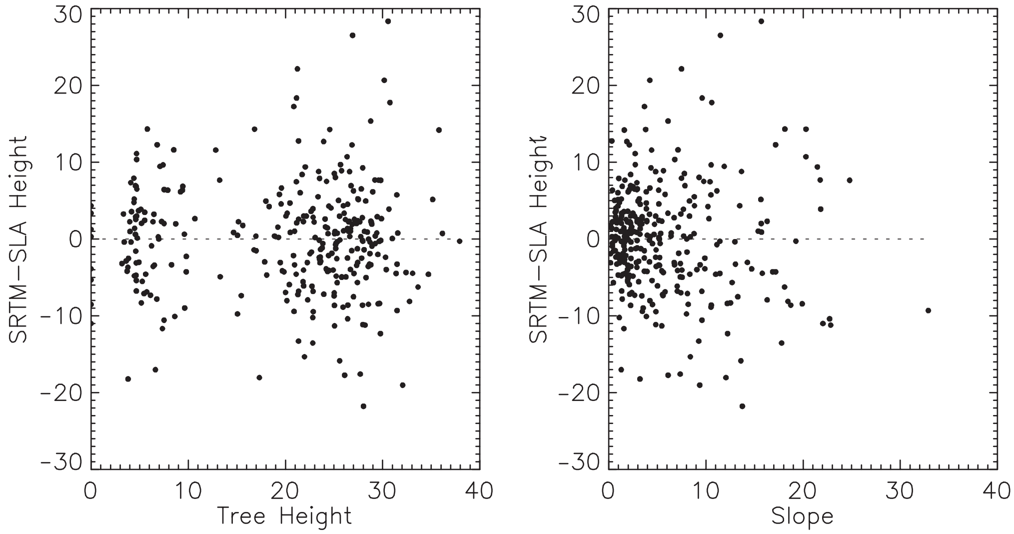

Fig. 7. The SRTM and SLA surface height differences after the tree effects on SRTM height were reduced. The mean and standard deviation of the height differences are − 0.11 and 7.24 m, respectively.

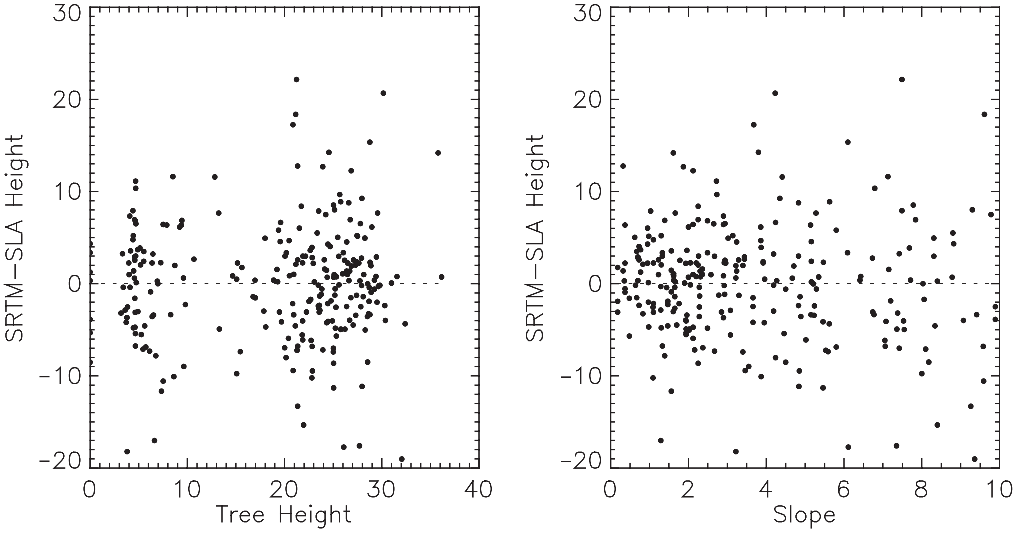

Fig. 8. Same data as in Fig. 7, but only those points with local slope less than 10° were plotted. The mean and standard deviation of the height differences are − 0.21 and 6.15 m, respectively.

included in Figs. 6B and 7B, but it is not obvious. Fig. 8 is a plot of the data points with local slope less than 10°. The standard deviation of height difference is smaller (6.15 m), indicating that the slope increases the uncertainty in height measurements.

5.3. Comparisons of SRTM height with DTED-1 DEM

The Level-1 Digital Terrain Elevation Data (DTED1) from National Imagery and Mapping Agency (NIMA) as available for this study under a Memorandum of Understanding between NIMA and NASA. The spatial resolution of both SRTM and DTED1 is three arc-seconds. As we have mentioned, the SRTM height reference used here is WGS84 ellipsoid, and DTED1 data is in WGS84 Mean sea Level. These heights cannot be compared directly. For the study region the height differences between WGS84 Ellipsoid and EGM96, the geoid developed by NIMA and GSFC (Lemoine et al., 1998) have a mean value of 37.31 m with minimum and maximum of 33.51 and 40.24 m. Using this

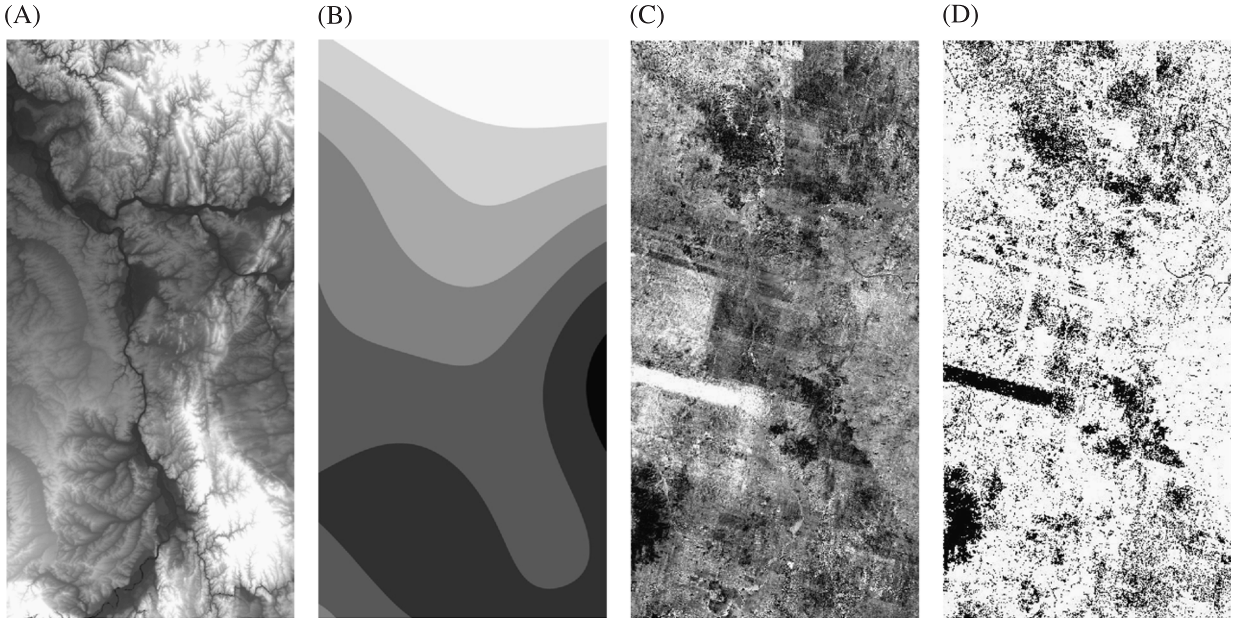

Fig. 9. (A) SRTM DEM—The SRTM data is in WGS84 Ellipsoid, and the DTED1 data is in WGS84 Mean Sea Level-geoid. (B) For the study region the height differences between WGS84 Ellipsoid and EGM96 have a mean value of − 37.31 m with maximum and minimum of − 33.51 and − 40.24 m, respectively. (C) Height differences of SRTM DEM in EGM96 geoid minus DTED1 DEM. (D) Height differences of SRTM DEM in EGM96 geoid minus DTED1 DEM—white areas are within 16 m, and dark area exceed 16 m.

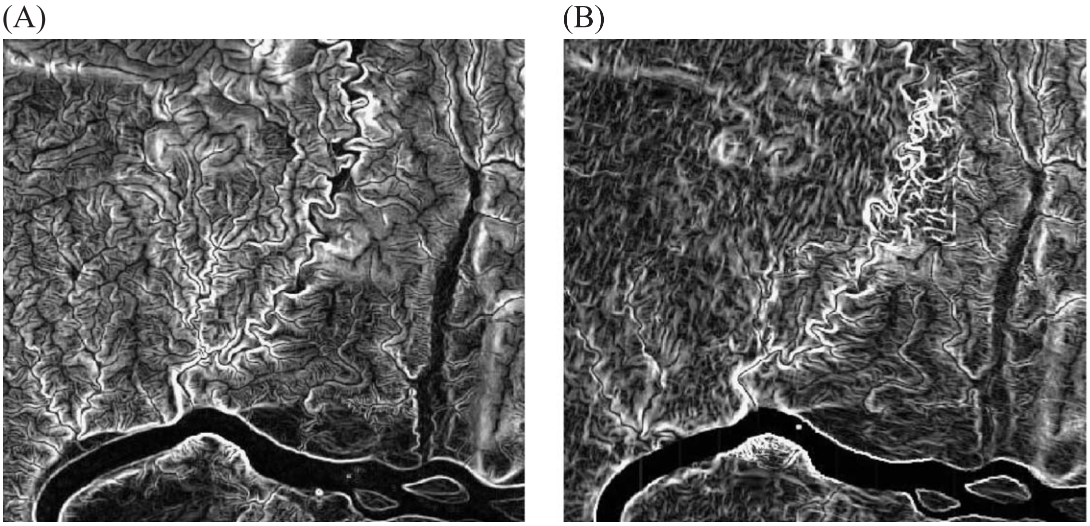

Fig. 10. Surface slope calculated from (A) SRTM DEM and (B) from DTED1. Note the greater detail in drainage pattern from SRTM and the noisy stripes from DTED1 data, especially in the mid-left portion of the image.

offset, SRTM ellipsoid height was converted to EGM96 geoid reference surface, which will be closer to the reference surface used by DTED data. The exact MSL geoid used by DTED data in our study area cannot be determined because the geoid used by DTED data is not consistent (personal communications with NIMA engineers).

Fig. 9 shows the SRTM DEM (A), the height offsets from WGS84 ellipsoid to EGM96 geoid (B), and the differences between SRTM (after conversion to EGM96) and DTED1 DEMs (C). In yellow and pink areas the height differences were within 16 m. The absolute values of the differences may be in doubt, but the strip patterns, which show in the difference image (Fig. 9C), but not in SRTM DEM image, indicate that these patterns are from the DTED1 data. Fig. 10 compares the surface slope calculated from SRTM and DTED1 data in an area. It shows clearly the higher quality of SRTM data. For example, in the area on left of the image, the SRTM data gives clear drainage patterns, but DTED data exhibits less detail of the drainage pattern and artifacts.

6. Conclusions

In this study, the quality of SLA-02 data was first verified by field observations, and examinations of individual waveforms. After confidence in SLA data was established, the SRTM height was compared with the surface height from SLA. The SRTM DEM was also compared with DTED Level-1 DEM. The following conclusions were drawn from this study:

(1) In our study area, which is relatively flat, the accuracies of both the geolocation and vertical height measurements of the SLA-02 data taken on orbits 1 and 3 were suitable for validating SRTM height measurements.

(2) The vegetation effect on SRTM height was obvious. The absolute accuracy of SRTM height in open areas exceeds the mission specification. But for forest-covered areas SRTM C-band interferometric SAR measures a height within the tree canopy. This positive bias may be estimated if the vegetation structure information is available.

(3) Compared with DTED data, the SRTM DEM proves to be the best-known DEM ever generated at the global scale with its consistency and overall accuracy.

With the successful launch of satellites with lidar (GLAS on ICESat) (Zwally et al., 2002) and radar (such as ENVISAT ASAR, and ALOS POLSAR), combined use of lidar and radar data for DEM generation and studies of regional and global forests becomes feasible. The results also indicate that combining lidar's vertical profiling and horizontal sampling and radar's mapping capabilities, the capability of producing high-resolution DEM and extracting forest carbon information using remote sensing technology will be significantly improved.

Our future work will incorporate existing SLA-02 and new GLAS lidar measurements and SRTM to develop accurate DEM for our mountainous Southern Siberia study sites. The 60° north latitude limit of SRTM is a problem for much of Northern Eurasia and North America. Hopefully future mission will provide more extensive coverage.

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