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Abstract: One of the most fundamental geophysical measurements of the Earth is that which describes the shape of its land surface. Topographical data are required by virtually all Earth science disciplines engaged in studies at or near the land surface. Topography is also civilization's most heavily used non-atmospheric geophysical measurement. NASA's Shuttle Radar Topography Mission (SRTM) and ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) projects have each completed independent near-global digital elevation measurements at comparable resolutions that approach 30 m spatially and 10 m vertically. Exploration of these datasets provides a new perspective of our planet. Fusion of these datasets will produce a more complete global elevation database, and differentiation of these datasets can be used to quantify select geomorphic processes.

The shape of the Earth's surface is a dominant controlling factor in virtually every natural process that occurs there. It also significantly controls processes within the overlying atmosphere and indicates processes within the underlying lithosphere. Consequently, topographical information is important across the full spectrum of Earth sciences, including climatology, ecology, hydrology, glaciology and geology.

Precipitation, runoff, soil moisture, incident sunlight and temperature all vary with topography. Consequently, topography dominantly controls the local and regional distribution and character of vegetation. Erosion and sedimentation, and consequently soil formation and nutrient transport, are also strongly controlled by topography, and are important factors in ecological studies.

Topography strongly influences the location and magnitude of surface and subsurface water flux. The modelling of water supply and flood potential requires knowledge of the area's drainage extent, its slopes and the pattern of the drainage network. In many areas snowmelt is the major contributor to water supply, and the modelling of melt rates depends on knowledge of the radiation balance that is largely controlled by elevation, topographical shadowing and reflectance from neighbouring terrain.

Particularly in rugged terrain, topography is commonly the dominant variable in remote sensing imagery. Topographical shading affects the radiance measured at every wavelength and is consequently the statistical first principal component of many remotely sensed datasets. Meanwhile, atmospheric optical thickness varies inversely (and non-linearly) with topographical height, so that topography is an important factor in the atmospheric correction of remotely sensed data. Topography also distorts (with view angle) the geographic pattern recorded. In short, high-resolution and high-quality elevation data are essential in fully distinguishing terrain reflectance from terrain illumination and atmospheric optics, as well as in mapping the reflectance pattern with high spatial fidelity.

While topography controls many natural processes at and near the Earth's surface, many natural processes conversely control the topography. Consequently, to various degrees, topography records and reveals evidence of current and past natural processes. An obvious example is the development and occurrence of erosional and depositional fluvial landforms. However, tectonic, volcanic, glacial and gravitational processes also produce characteristic landforms that reveal past, ongoing and even potential change. The present is the key to the past (and future), and the past is the key to the present (and future). For example, topographical analysis is one of the primary means of determining the *current* global fault pattern, created by *past* and current processes, for assessing *future* seismic threats. Tectonic landforms, including surficial faults (commonly obvious as disruptions in the fluvial pattern), can indicate zones of earthquake hazards. Satellite imagery has greatly facilitated the mapping of the global tectonic pattern, revealed primarily in topographical shading, but topographical data facilitate more versatile and powerful means of landform analysis, not convolved with obscuring land cover patterns and not limited to analysis of shade patterns on a given day and time.

Topographical data also facilitate Earth surface visualization, a powerful tool that uniquely

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addresses the strength of the human perceptual system. Satellite technology has produced vast amounts of remote sensing data that are often understood first, and commonly understood best, by visual interpretation. Over the past four decades, most of these data have been spatially two-dimensional. But the Earth's surface is three-dimensional (3D). Detailed topographical data provide the means to visualize and analyse current, future and archival remote sensing data, within their natural 3D structure, facilitating greater understanding of the features and processes that these data record.

Given all of its uses, demand for elevation data is very high. Consequently, NASA, working with interagency and international partners, has produced (and is continuing to develop) two major contributions to global elevation measurement at 1 arcsecond (or a few arcseconds) spatial resolution (30–100 m). These are the Shuttle Radar Topography Mission (SRTM) and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) mission.

SRTM and ASTER

One of the most practical and valuable returns from the United States space programme is the SRTM digital elevation model (DEM). Until the production of the SRTM DEM, good-quality measurements of the Earth's surface at practical levels of detail did not exist or were not generally available for much of the planet. SRTM was developed at NASA's Jet Propulsion Laboratory (JPL) as a joint venture of NASA, the United States National Geospatial-Intelligence Agency (NGA), and the German and Italian Space Agencies (Farr *et al.* 2007). The mission collected 12 terabytes (10^{12} bytes) of data over nearly all of Earth's landmass between 60°N and 56°S in just 11 days in February 2000. Elevation measurements were derived from interferometric analysis of the C-band radar signal and were processed at JPL. The resultant DEM has 1 arcsecond (*c.* 30 m) postings, with an absolute vertical resolution significantly better than the mission specification of 16 m (Rodriguez *et al.* 2005). The SRTM DEM is now freely available (at a somewhat reduced effective resolution for non-US areas). However, the DEM is not spatially comprehensive. It did not cover areas within 30° latitude of the poles and, more troublesome for most users, it has substantial gaps ('voids') where the radar interferometric system failed to provide a signal adequate for DEM generation.

Meanwhile, generally coincident with the SRTM Project, but continuing to 2010 and beyond, ASTER has been acquiring imagery across all areas of the planet up to within 8° latitude of the poles. ASTER is one of the sensors operating on Terra, a satellite launched in December 1999 as part of NASA's Earth Observing System (EOS) (Abrams 2000). The ASTER Project is a co-operative effort between NASA, Japan's Ministry of Economy, Trade and Industry, and Japan's Earth Remote Sensing Data Analysis Center. ASTER covers a wide spectral region with 14 bands from the visible to the thermal infrared, with high spatial, spectral and radiometric resolution. The spatial resolution varies with wavelength: 15 m in the visible and near infrared (VNIR 0.55–0.80 μm); 30 m in the short wave infrared (SWIR 1.65–2.4 μm); and 90 m in the thermal infrared (TIR 8.3–11.32 μm). An additional band is the key to producing digital elevation models. This band (named 3B) is the same as nadir band 3 (NIR), except that it observes at a backward angle of *c.* 28°, producing a stereo pair for each daytime ASTER image (Welch *et al.* 1998; Hirano *et al.* 2003). Each ASTER scene covers an area of 60 × 60 km, and the sensor has up to 8.55° of pointing capabilities. Standard DEMs produced by the United States Geological Survey Eros Data Center (USGS-EDC) have 30 m postings, similar to SRTM's 1 arcsecond postings. However, users can also produce their own DEMs from the band 3 stereo pair using any chosen software. ASTER DEMs are comparable in resolution to those from SRTM. However, potential improvements are still possible since the DEMs do not capture all of the topographic detail that is visually apparent in the stereo imagery.

Topographical exploration

We are in the golden age for the exploration of Earth's surface via satellite data visualization. After a quarter century of high-quality satellite image acquisitions, the production of near-global elevation measurements, and access to these datasets via advanced computers, software and networks, Earth exploration is available to most people with tools as simple as Google Earth™. SRTM provided much of the Google Earth DEM and it complements the resolution of Landsat, the primary satellite imagery. Such merged image–DEM perspectives (Fig. 1) and fly-through visualizations work well even when the imagery is somewhat more detailed than the DEM because the image detail often extends topographical visual cues to higher spatial frequencies, primarily via topographical shading.

Sometimes, however, exploring Earth's surface with pure geomorphic (DEM only) data and user-selected enhancements is especially effective (Figs 2 & 3). Satellite images problematically convolve and obscure topographical shading with land

Fig. 1. Mount Ararat and Little Ararat in easternmost Turkey. Landsat image on SRTM elevation model, near-horizontal southerly view, 1.25× vertical exaggeration. Seismic, volcanic and mass-wasting hazards are all evident in these datasets, and all contributed to a major natural disaster here in 1840 (PIA03399 at http://photojournal.jpl.nasa.gov).

cover reflectance such that these two largely independent variables are not readily distinct. DEMs, of course, measure only the shape and not the radiance of the surface, and so avoid this problem. SRTM provides the best single source of near-global elevation data for pure geomorphic observation.

Stereoscopic satellite views also avoid the problem, but do so instead by perceptual deconvolution (rather than quantitative extraction) of the topographical information from reflectance information. ASTER provides one of the most readily available near-global sources of high-resolution stereoscopic imagery. Significantly, these stereo images reveal topographical detail much finer and more accurate than the DEMs derived from them. This is because individual pixels can be perceived stereoscopically, but each DEM measurement is generated from an areal correlation and is thus somewhat spatially averaged. The standard ASTER DEM uses a 9 × 9 pixel (135 × 135 m) kernel, which degrades the DEM spatial resolution to some value much greater than the 15 m pixel size and 30 m posting but somewhat less than the kernel size (*c*. 120 m).

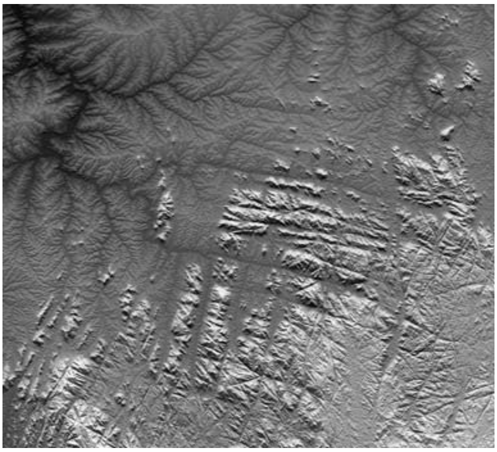

Fig. 2. Lithology and landscape evolution, Gotel Mountains, Nigeria and Cameroon. SRTM DEM mix of shading and height as brightness. Rectangular and other linear drainage patterns in the highlands contrast greatly with the dendritic drainage patterns in the lowlands. These differing geomorphic patterns strongly indicate substantial differences in rock type (PIA04954 at http://photojournal.jpl.nasa.gov).

Synthetic stereo is a simple yet effective method for viewing elevation models, whether incorporating image overlays or just using shading of the DEM itself. Imagery, of course, must first be spatially registered to the DEM. Alternatively, DEM shade images have inherently perfect registration. The synthetic stereo algorithm simply shifts image pixels left for the right-eye image and right for the left-eye image as a linear function of elevation. Shade and other grey image results can be displayed as a red (left eye) and blue–green (right eye) anaglyph, with the use of red–cyan anaglyph glasses, and can be interactively enlarged and roamed on a computer display. Static displays, including full colour displays, can be viewed instead with stereoscopes or without glasses using wall-eyed (parallel) or cross-eyed viewing. Cross-eyed viewing is generally easier than wall-eyed viewing because eyes naturally focus close when they cross. Figure 4 provides an example of a DEM viewed in its full three dimensions, without special glasses, when observed with cross-eyed stereo.

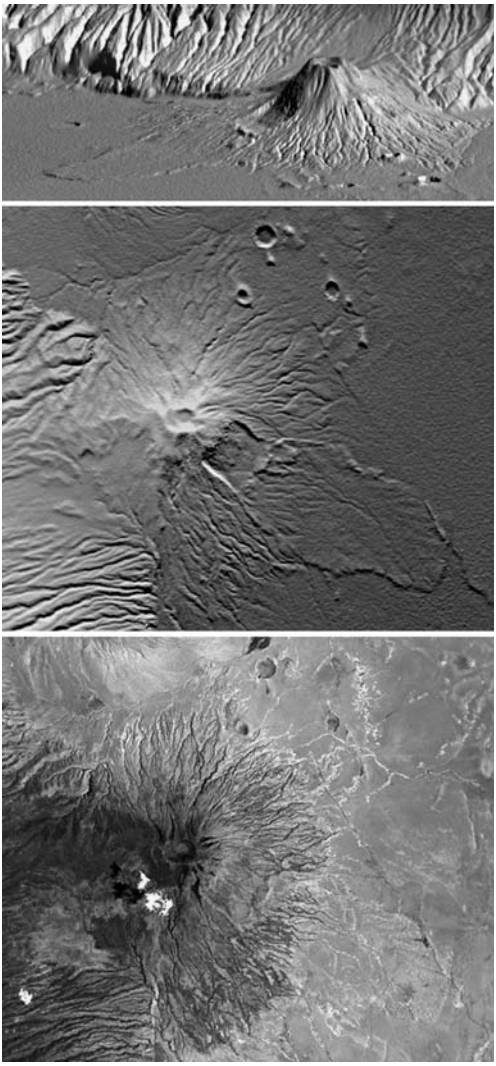

Fig. 3. Crater Highlands, East African Rift, Tanzania. Top: Perspective view of shaded SRTM DEM (PIA06669 at http://photojournal.jpl.nasa.gov). Middle: Nadir view of shaded SRTM DEM, north at top. Bottom: Corresponding Landsat nadir view. Note that the collapse of the SE flank of the volcano and the 10 km-long (and up to 45 m-thick) debris field are clear in the DEM but not recognizable in the Landsat image.

Topographical exploration of Earth has numerous specific uses. A particularly interesting use is the search for interplanetary analogues, especially for Mars (Fig. 5). Mars has no apparent fluid or biotic land cover. All surfaces are petrological (including ice), and globally deposited dust creates a relatively uniform spectral reflectance (except for ice). This near uniformity of reflectance on Mars (at least compared to Earth) makes Mars satellite imagery appear more like Earth shaded elevation models than like Earth satellite imagery. Consequently, in some aspects, Earth exploration for Mars geomorphic analogues may be more readily achieved with SRTM (and ASTER and other) elevation models than with satellite images.

DEM fusion: improving the global DEM

Most users of elevation information view it as a temporally static spatial variable, but certainly an important one that greatly impacts surface and near-surface natural processes. As such, many researchers require elevation data, but without regard to its date of measurement. Typically, they would prefer to simply acquire the best available topographical data rather than generate it or refine it themselves, site by site. Consequently, global fusion of the SRTM and ASTER DEMs into an enhanced and readily accessible standard product is a goal of ongoing work at JPL.

Fundamental differences in the methods of acquisition for SRTM (radar interferometry) and ASTER (photogrammetry) mean that the limitations of each are not highly correlated spatially. In other words, the strengths of each combine synergistically. Clouds are a problem for ASTER but were not for SRTM. Terrain that is either very steep or very smooth has posed challenges for each sensor but in different ways and, therefore, in somewhat different locations.

SRTM elevation data are of reliably high quality but very commonly have voids (areas of missing data). Generally, voids are most common in very steep terrain where the side-looking radar-imaging geometry was problematic, and also in very smooth areas where little of the radar signal was reflected back towards the sensor. Consequently, the locations most impacted by data gaps in the SRTM elevation model are rugged mountains and desert plains and sand sheets. Void filling by interpolation is generally unsatisfactory except for the smallest voids, and the voids can be a hindrance to nearly every use of these data. Filling the SRTM DEM voids with ASTER elevation measurements is an obvious possible solution.

A very simple, yet very effective, method of filling an SRTM DEM void with DEM data from an alternative source was developed by Grohman *et al.* (2006) and was applied in Figure 6 using an ASTER DEM. In simple terms, the method calculates the difference between the surfaces (simple subtraction, but retaining voids), interpolates this ‘difference image’ across the SRTM void and then adds the result to the alternative (e.g. ASTER)

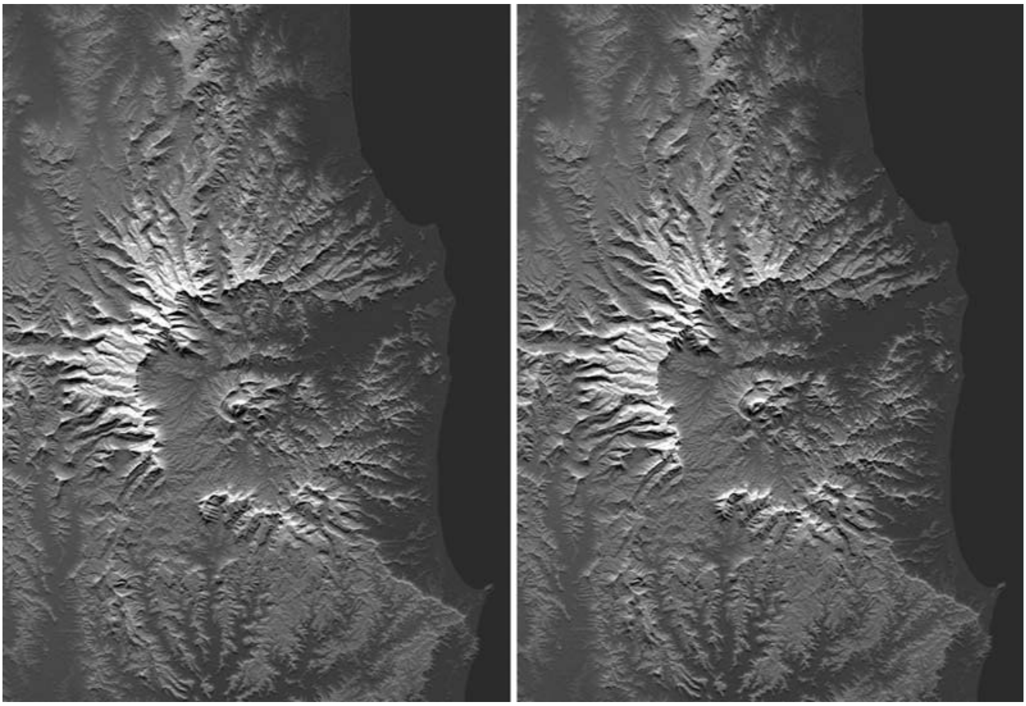

Fig. 4. Tweed Volcano (extinct), Gold Coast, Australia, cross-eyed stereo pair, SRTM shading combined with height as brightness. Area shown is 74 × 102 km (PIA06664 at http://photojournal.jpl.nasa.gov).

DEM. In the resultant merged DEM, SRTM non-void values remain unchanged and the DEM patch is smoothly rubber-sheeted across the void while retaining its relative shape.

ASTER has acquired more than one million scenes. Approximately 45 000 scenes are required to cover Earth's land surface with minimal overlap, but repeat coverage is needed for temporal studies and cloud avoidance. Global daytime coverage is nearly complete and repetitive for most areas, although persistent clouds remain problematic at some locations. (Night-time thermal global coverage is expected too, but early acquisitions were concentrated in southern Asia, and other high relief locations, and along the Antarctic coast.) Since 2006 new software has produced a much improved standard ASTER DEM product but some difficult areas still result in gross errors. Errors occur most commonly on north-facing slopes, due to the viewing geometry of the stereo pair, and over radiometrically smooth terrains and land covers (and large shadows) where photogrammetric pattern matching is difficult.

Recently, an ASTER Global DEM (GDEM) has been produced from the entire ASTER image archive. This project was designed, proposed, and implemented by Sensor Information Laboratory Corporation (SILC), a Japanese company that also produced the software for the new ASTER DEM standard product. GDEM benefits from both cloud masking and multi-DEM averaging, and greatly eases the comparison and merger of ASTER elevation information with that of SRTM. An enhanced version of GDEM is now in production, using additional (recently acquired) scenes, better error corrections, and a smaller (5 × 5) correlation kernel for potentially finer resolution.

The SRTM DEM, even the 3 arcsecond version, is generally of higher quality than individual-scene ASTER DEMs (Fig. 7), and preliminary evaluations of ASTER Global DEM test sites show that the (non-void) SRTM DEM is still generally superior, but not greatly so. The general plan is, therefore, to use SRTM DEM values wherever available, and to use ASTER DEM values to fill voids and other areas not covered by SRTM.

Problem areas will remain even after fusion of the SRTM and ASTER global DEMs, and development of a definitive global elevation model will be an ongoing process using additional and forthcoming data sources and innovative techniques. The global ASTER image archive may contribute

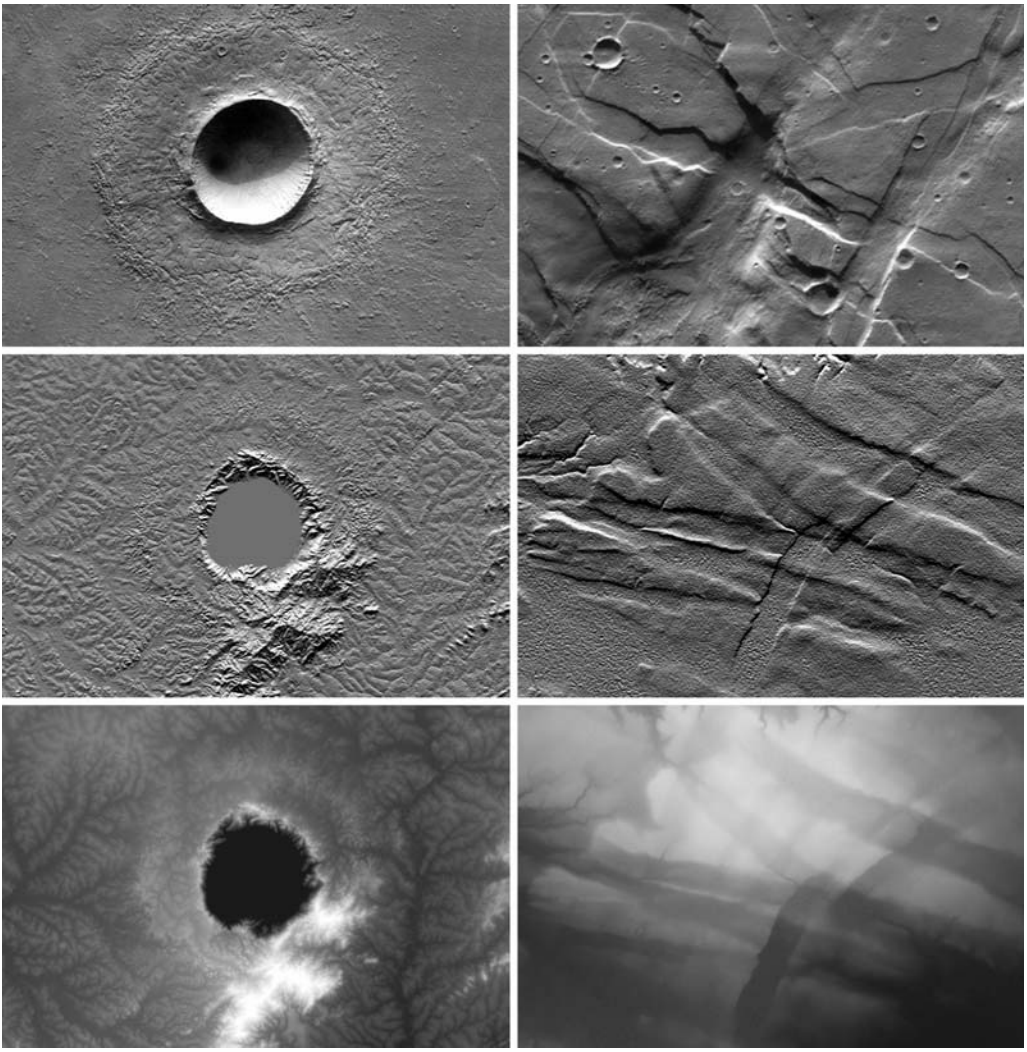

Fig. 5. Analogues of Mars landforms using the SRTM elevation model. Top left: Mars Global Surveyor image of impact crater on Elysium Planitia (PIA02084 at http://photojournal.jpl.nasa.gov). Middle left: Shaded SRTM view of Bosumtwi Crater, Ghana. Bottom left: Bosumtwi Crater, SRTM height as brightness; note especially the ejecta blanket, which is *c.* 35 m thick. Top right: Mars Odyssey image of crossing grabens on Tempe Terra (PIA04471 at http://photojournal.jpl.nasa.gov). Middle right: Shaded SRTM view of crossing grabens in Afar Triangle, Ethiopia. Bottom right: Afar Triangle grabens, SRTM height as brightness.

to that effort beyond NIR (band 3) photogrammetry. Crippen *et al.* (2007) demonstrated the derivation of elevation values from night-time thermal ASTER images for high-relief terrain in certain environments via the environmental lapse rate. Kirk *et al.* (2005) developed a method of extracting quantitative topographical information from combinations of visible and thermal imagery that may be applicable to ASTER data in some locations. Carlotto (2000) described a method of enhancing the spatial resolution of a relatively low-resolution elevation model using a relatively high-resolution multispectral image via multidimensional empirical relationships between spectral responses and terrain slopes and azimuths. In addition, Levin *et al.* (2004) determined the topography of sand dunes using shade information from two Landsat non-stereoscopic images with differing sun zenith and

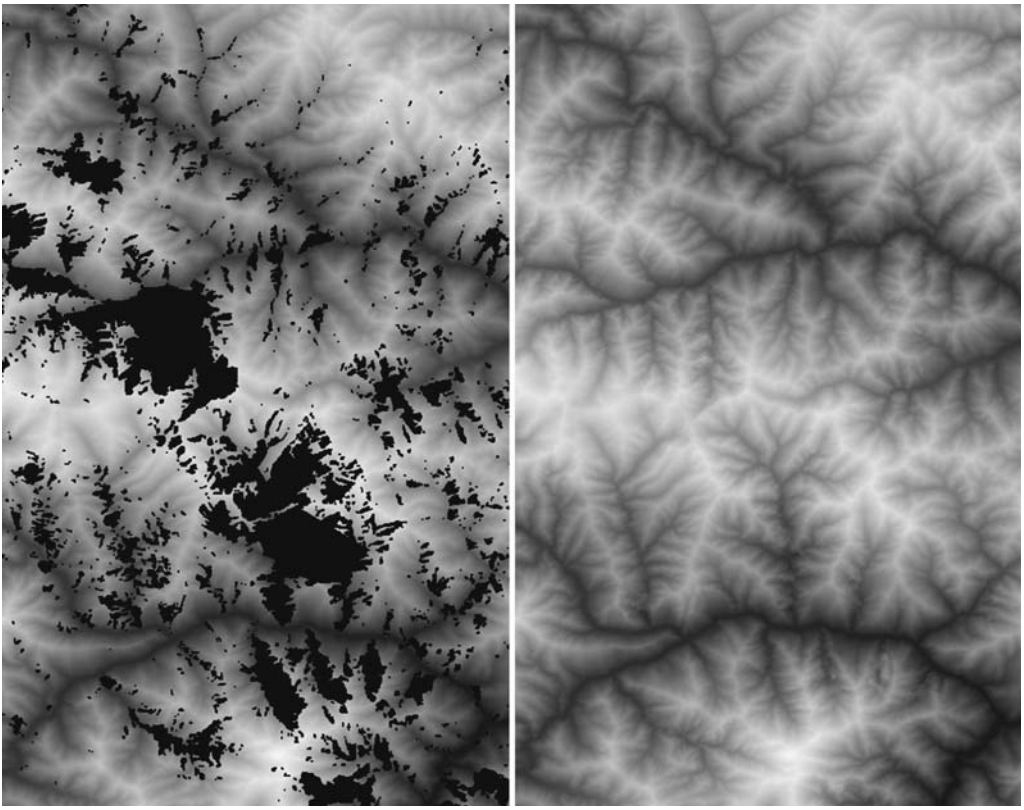

Fig. 6. SRTM voids filled with ASTER DEM, Sichuan Province, China. Height as brightness. Area shown is 41 × 78 km.

azimuth angles (and image resolutions similar to ASTER). This method is called 'photometric stereo'. Notably, they concluded that their result was better than a DEM produced from an ASTER stereo pair.

Indeed, ASTER imagery contains topographical information at resolutions up to the 15 m resolution of the VNIR bands (e.g. band 3, Fig. 7). This level of detail can be seen radiometrically (as natural shading) and stereoscopically but is not now extracted photogrammetrically. Innovative extraction methods might tap this unrealized potential.

DEM differentiation: measuring topographical change

Although topography is essentially static at most temporal and spatial scales of interest at most locations, and for most users' purposes, dynamic topography and its hazards are important in geological studies and land-use planning. Earthquakes, volcanoes, landslides, and extreme erosion and deposition events all produce significant, problematic and even dangerous topographical change. Likewise, glaciers, as part of the solid Earth, exhibit topographical changes that may collectively indicate ominous global climate change.

Elevation differencing is fundamentally a simple subtraction, but spatial registration is critical (Van Niel *et al.* 2008), and systematic differences of the DEMs must not be confused with temporal differences of the surface they were meant to measure. It is generally intended that DEMs measure the interface of rock, soil, ice, lakes and rivers (below the interface) with the atmosphere and above-ground vegetation and buildings (above the interface). Although classic methods of field surveying and aerial photogrammetry have generally excluded above-ground vegetation and buildings while manually mapping the surface, automated satellite methods generally cannot do so. Instead, both SRTM and ASTER map a 'reflectance' surface that includes the vegetation and buildings. Consequently, temporal elevation changes will include vertical land cover changes. These may be interesting signals for ecologists and other researchers

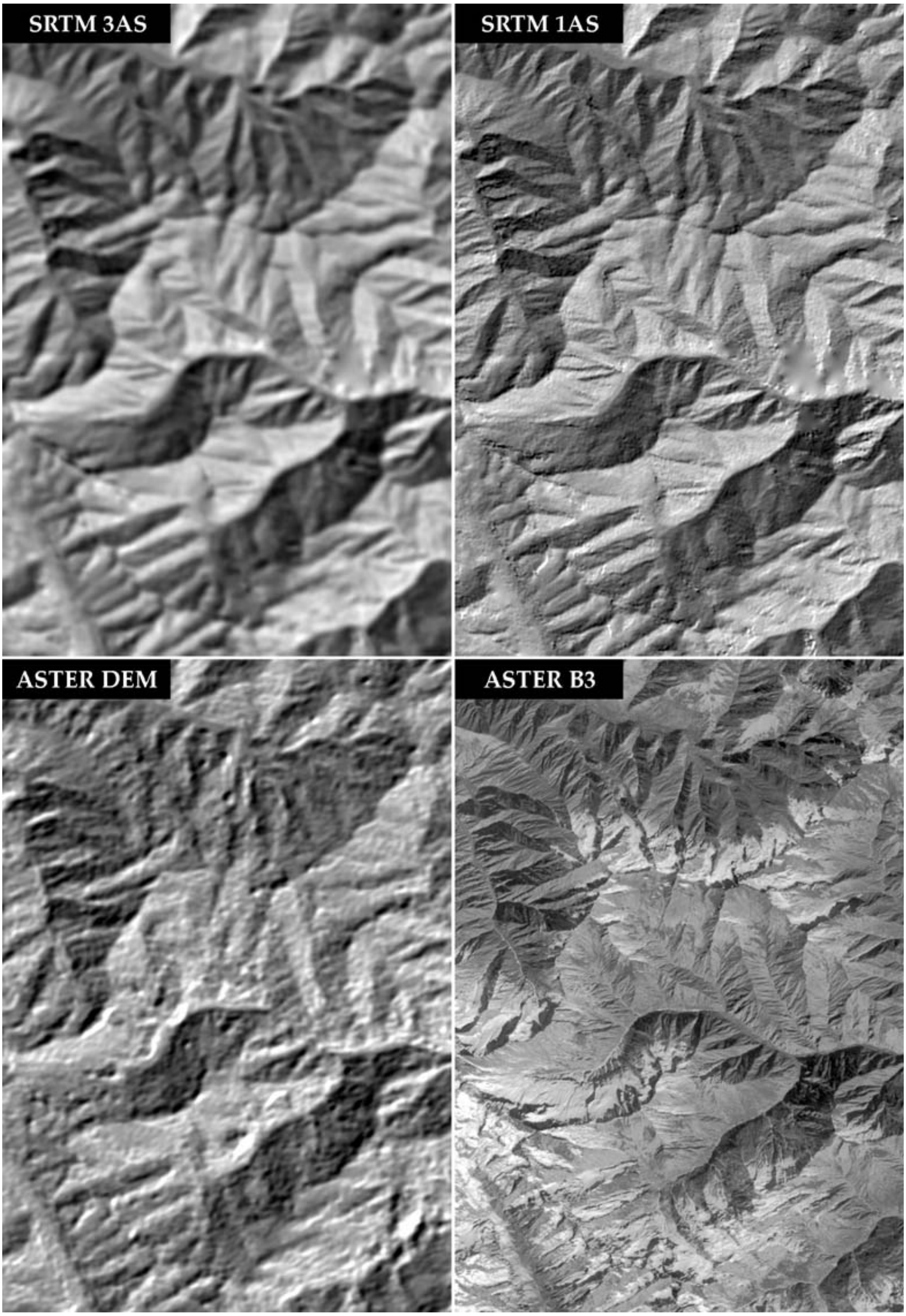

Fig. 7. Resolution and quality comparison of SRTM elevation models and the ASTER image and elevation model, Sichuan Province, China, north at top, 12 × 21 km area. SRTM 1 arcsecond (1 AS), 3 arcsecond (3 AS) and ASTER DEM shown with simulated illumination from the SE. ASTER band 3 (B3) has 15 m resolution and natural illumination from the SE.

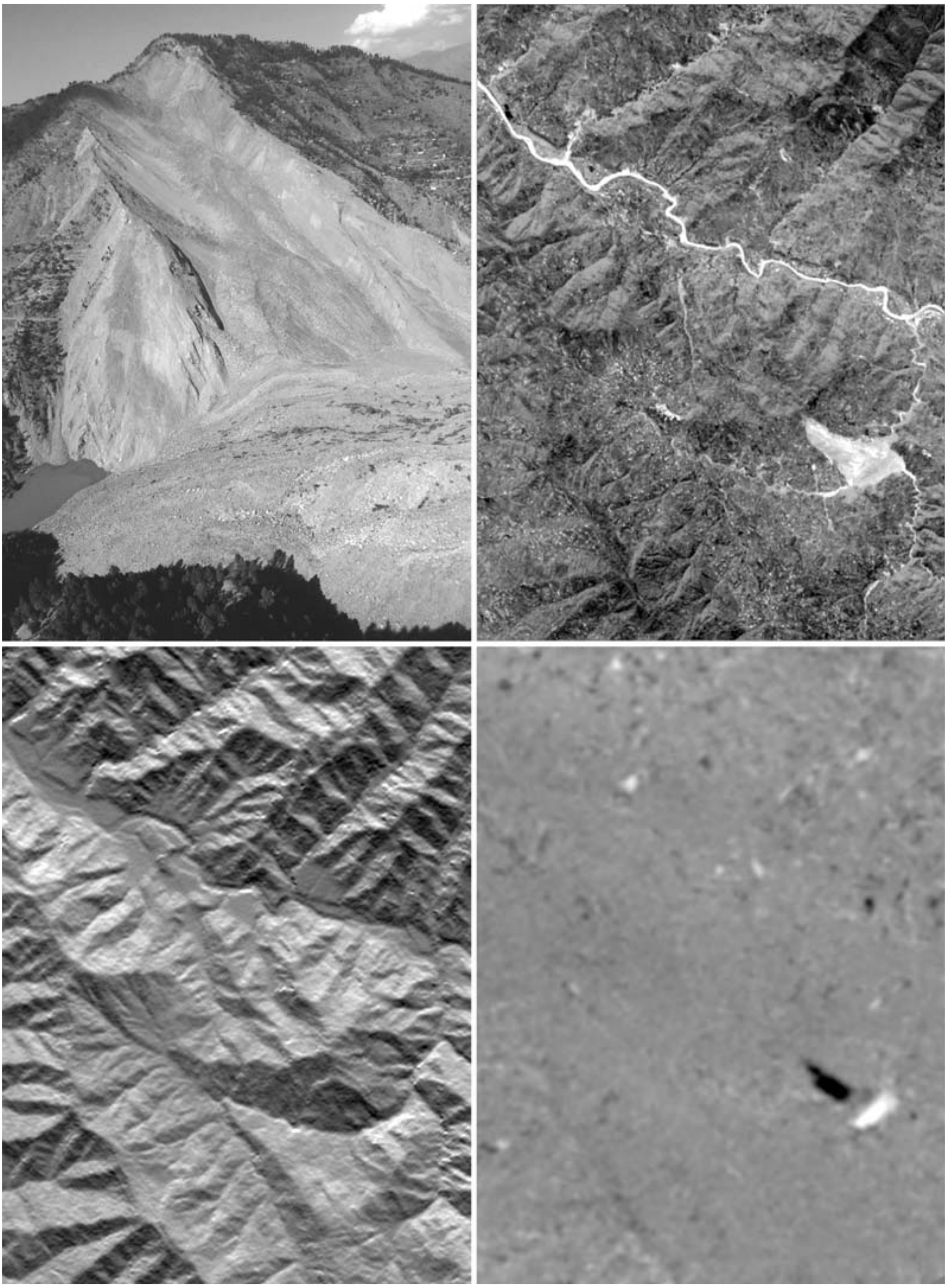

Fig. 8. Hattian landslide in Kashmir triggered by the major earthquake of 8 October 2005. Top left: Photograph (from helicopter) looking NW. Top right: ASTER image difference of bands 1 and 3 (green band minus near-infrared band) showing the landslide scar as bright, indicating a lack of vegetation. The area shown is 11 × 16 km. Bottom left: Corresponding shaded SRTM DEM (pre-quake). Bottom right: Corresponding difference of ASTER pre- and post-quake DEMs shown as bright (up) and dark (down).

(Kellndorfer *et al.* 2004) but they are noise for geologists. Furthermore, radar (SRTM) and near-infrared (stereoscopic ASTER) radiation may reflect from somewhat different levels of a vegetation canopy resulting in a 'systematic noise' in differencing the surfaces they detect. Such issues are important where the signal to noise ratio of topographical change is relatively small.

Elevation change detection for measurement of glacial thinning adds the critical third dimension to satellite surveys when estimating changes in glacial mass that may relate to climate change and sea-level rise (Rignot *et al.* 2003; Rivera *et al.* 2005). The value of such fine measurements critically depends on their accuracy, about which there is currently considerable debate and controversy. Berthier *et al.* (2006) claimed a well-documented bias in SRTM measurements for their study site at Mont Blanc in the French Alps, with elevation underestimated by as much as 10 m at high altitudes. Kääb (2005) found SRTM data to be 7 m too high for a glacial site in the Swiss Alps. Meanwhile, Carabajal & Harding (2006) found variable biases and standard deviations for sites in the western USA and Central Asia when comparing SRTM data with measurements from ICESat LiDAR (Light Detection And Ranging) profiles. Clearly, a better general understanding of SRTM (and ASTER) accuracies and precisions is needed in order to calibrate important findings of small but measurable topographical changes.

Larger topographical changes are less sensitive to the foregoing issues as the change signal is large while the noise remains small. For example, ASTER DEMs and the SRTM DEM of Kashmir were used for volumetric measurements of a major landslide, named the Hattian landslide, and the 248 m-tall natural dam that it created in the major earthquake of 8 October 2005 (Fig. 8). The hazard potential of this site regarding lake growth, possible failure of the landslide dam, and possible generation of an extraordinarily large and catastrophic debris flow was monitored with a series of ASTER images and DEMs. One test used two ASTER DEMs that differed by about 5 years in total but differed in season by only 18 days. The landslide scar (elevation down) and landslide dam (elevation up) are clear relative to the nearby DEM-difference noise of only about 8 m vertically, as viewed in a DEM difference image (Fig. 8, lower right). The 'down' and 'up' volumes are similar, at about 75×10^6 m^3. A difference measurement using the SRTM DEM as the pre-quake DEM provided similar results. Note, however, that the actual landslide volume exceeds the difference measurements because some slide debris remains in the source area.

It is noteworthy that the 'static' topography in areas surrounding the Hattian landslide provides evidence of previous landslides, primarily as hillside scars and dissected terraces of valley-fill deposits that must have accumulated behind other natural dams that are now eroded away. This site provides an excellent example of elevation data exploration revealing past natural processes while also quantifying similar current natural processes.

Conclusion

At 30×30 m resolution, DEM coverage of Earth's landmass involves about 165×10^9 spatially distinct elevation measurements. NASA's SRTM and ASTER missions have contributed to measuring a large majority of the landmass at resolutions approaching 30 m, but much work remains. Merging these two elevation datasets will be highly beneficial for many users. In addition, some void filling, resolution improvement and error correction may be possible using additional information from the ASTER multispectral imagery. These latter efforts might take great advantage of empirical relationships between the images and the DEMs within local areas.

For several years now, the SRTM and ASTER DEMs have provided new views and measurements of our environment that bear upon our understandings across numerous scientific disciplines. In many areas they have provided the first good look at the true 3D nature of Earth's surface. Meanwhile, multitemporal ASTER DEMs, ASTER DEMs with SRTM data, and either of these datasets with historic topographical data have provided some direct measures of geomorphic change. Importantly, they also provided a near-global, near-synoptic baseline for measuring future topographical change.

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