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DEM Generation with ASTER Stereo Data

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ASTER

ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) is an imaging instrument that is flying on Terra, a satellite launched in December 1999 as part of NASA's Earth Observing System (EOS). ASTER is the only high spatial resolution instrument on the Terra platform. It will be used with MODIS, MOPITT, MISR and CERES, which monitor the Earth at moderate to coarse spatial resolutions. A Joint US/Japan Science Team was responsible for instrument design, calibration, and validation. Details may be found at http://asterweb.jpl.nasa.gov. The primary objective for the ASTER mission is to obtain high spatial resolution (local, regional, and global) images of the Earth in fourteen spectral bands. ASTER consists of three different subsystems: the Visible and Near Infrared (VNIR 15m), the Shortwave Infrared (SWIR 30m), and the Thermal Infrared (TIR 90m).

The VNIR subsystem consists of two independent telescope assemblies that minimize image distortion in the backward and nadir looking telescopes. The focal plane of the nadir telescope contains three silicon charge coupled detector line arrays (Bands 1, 2, 3N) while the focal plane of the backward telescope has only one (3B). The nadir and backward looking telescope pair are thus used for same-orbit stereo imaging (along-track stereo). The two near-infrared spectral bands, 3N and 3B, generate along-track stereo image pair with a base-to-height (B/H) ratio of about 0.6 and an intersection angle of about 27.7 degrees. The two telescopes can be rotated +/- 24 degrees to provide extensive cross-track pointing capability and 5-day revisit capability. Across-track stereo imaging with better B/H ratio (close from 1) is theoretically possible. However, due to the high data rate of the three ASTER imaging subsystems, only eight minutes of data are acquired per orbit and the along-track stereo imaging is then favored.

The release of ASTER data has two significant impacts. First, the data can be downloaded free of charge from the web (http://asterweb.jpl.nasa.gov). Second, it provides a new alternative for mapping at medium-to-large scales and for generating digital elevation model (DEM) from the along-track stereo data.

DIGITAL ELEVATION MODEL

Producing Digital elevation models (DEMs) from satellite data has been a vibrant research and development topic for the last thirty years ever since the launch of the first civilian remote sensing satellite. Stereo-viewing of images has been the most common method used by the mapping, photogrammetry, and remote sensing communities for elevation modeling. To obtain stereoscopy with images from satellite scanners, two solutions are possible:

- the along-track stereoscopy from the same orbit using fore and aft images; and
- the across-track stereoscopy from two different orbits.

The latter solution has been applied more often since 1980 - first with Landsat from two adjacent orbits, then with SPOT using across-track steering capabilities, and finally with IRS-1C/D by "rolling" the satellite. In the last few years, the first solution has gained renewed popularity due to the JERS-1's Optical Sensor (OPS), the German Modular Opto-Electronic Multi-Spectral Stereo Scanner (MOMS), and now ASTER.

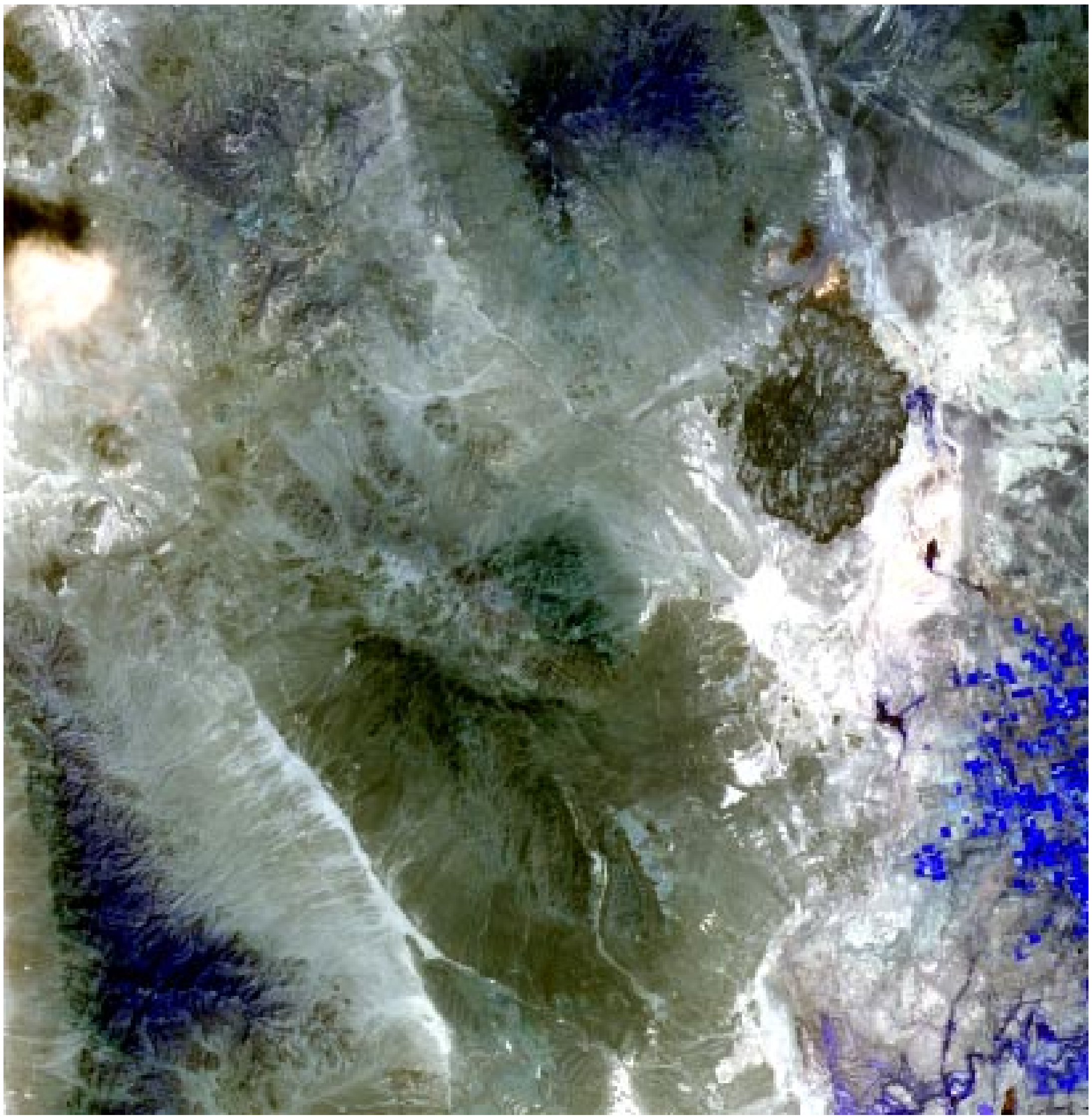

Figure 1: Composite ASTER image of band 1, 2 and 3N of Drum Mountains, Utah, U.S.A.

The simultaneous along-track stereo-data acquisition gives a strong advantage in terms of radiometric variations versus the multi-date stereo-data acquisition with across-track stereo, which can then compensate for the weaker stereo geometry. Since an error of within ±1 pixel for the parallax measurements in the automated matching process has been achieved with different stereoscopic data sets (along-track and across-track), the potential accuracy for the along-track stereo derived DEM from ASTER with a B/H ratio of 0.6 could be in the order of 25m.

The main objective of this article is to evaluate automatic DEM generation and accuracy using a stereo pair of ASTER data. The results were then compared with the USGS 7.5-Minute DEM with 30m grid spacing.

STUDY SITE AND DATA SET

The study site is Drum Mountains, located in west central Utah, U.S.A. The area is semi-arid with few cultural features and little vegetation. The study site is approximately 40% steep-and-rugged and 60% relatively flat. The elevation ranges from roughly 1300 to 2600 meters. The ASTER level 1A raw data, acquired on July 31, 2000, with the VNIR subsystem from a descending orbit, were directly downloaded from the NASA web site. The data (61.5 km by 63 km) is reconstructed, unprocessed instrument digital counts with a ground resolution of 15m. It also contains depacketized, demultiplexed, and realigned instrument image data with geometric correction coefficients and radiometric calibration coefficients appended (but not applied). The spacecraft ancillary and instrument engineering data are also included. The radiometric calibration coefficients, consisting of offset and sensitivity information, are generated from a database for all detectors. The geometric correction is the coordinate transformation for band-to-band co-registration. Only the near-infrared backward and nadir images (3B and 3N) are used in the DEM generation. The radiometric calibration coefficients were applied to both images afterwards to remove banding and striping effects.

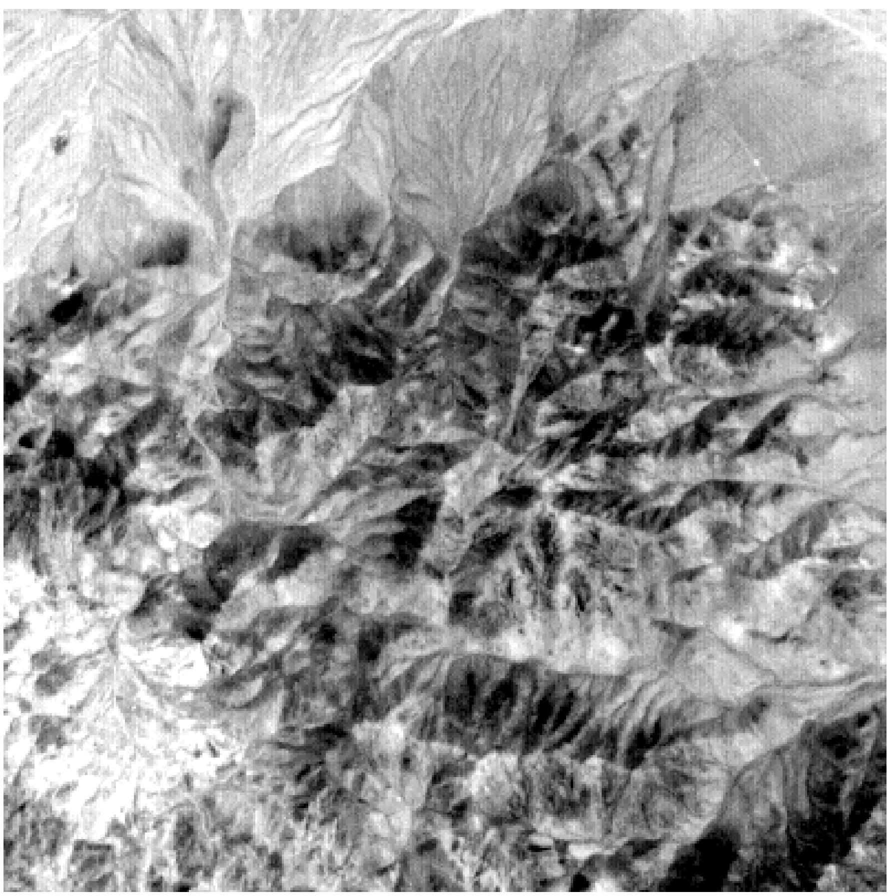

Figure 2: Full resolution image of ASTER band 3N of Drum Mountains, Utah, U.S.A.

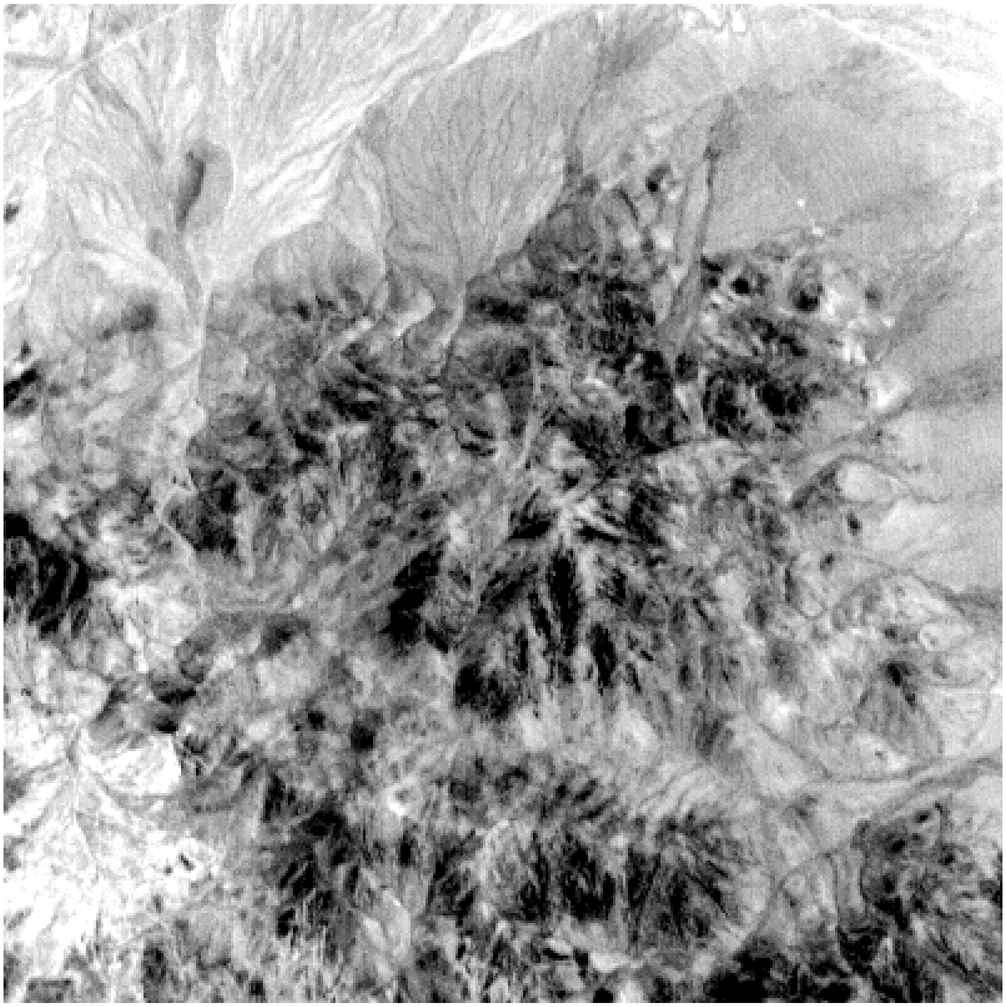

Figure 3: Full resolution image of ASTER band 3B of Drum Mountains, Utah, U.S.A.

SATELLITE GEOMETRIC MODEL AND SOFTWARE

PCI OrthoEngine software was used for the testing. This software supports reading of the data, ground control point (GCP) collection, geometric modeling, DEM generation and editing, ortho-rectification, and either manual or automatic mosaicking. The geometric model used inside the software is a rigorous (parametric) model developed by the first author at the Canada Centre for Remote Sensing (CCRS), Natural Resources Canada. This model is based on principles related to orbitography, photogrammetry, geodesy, and cartography. It reflects the physical reality of the complete viewing geometry and corrects distortions that occur in the imaging process due to the platform, sensor, Earth, and cartographic projection. It has been successfully applied with few GCPs (3-6) to VIR data (Landsat, SPOT, IRS, MOS, KOMPSAT, and IKONOS), and also to SAR data (ERS, JERS, SIR-C, and RADARSAT). Based on good quality GCPs, the accuracy of this model was proven to be within one-third of a pixel for VIR images and one resolution cell for SAR images.

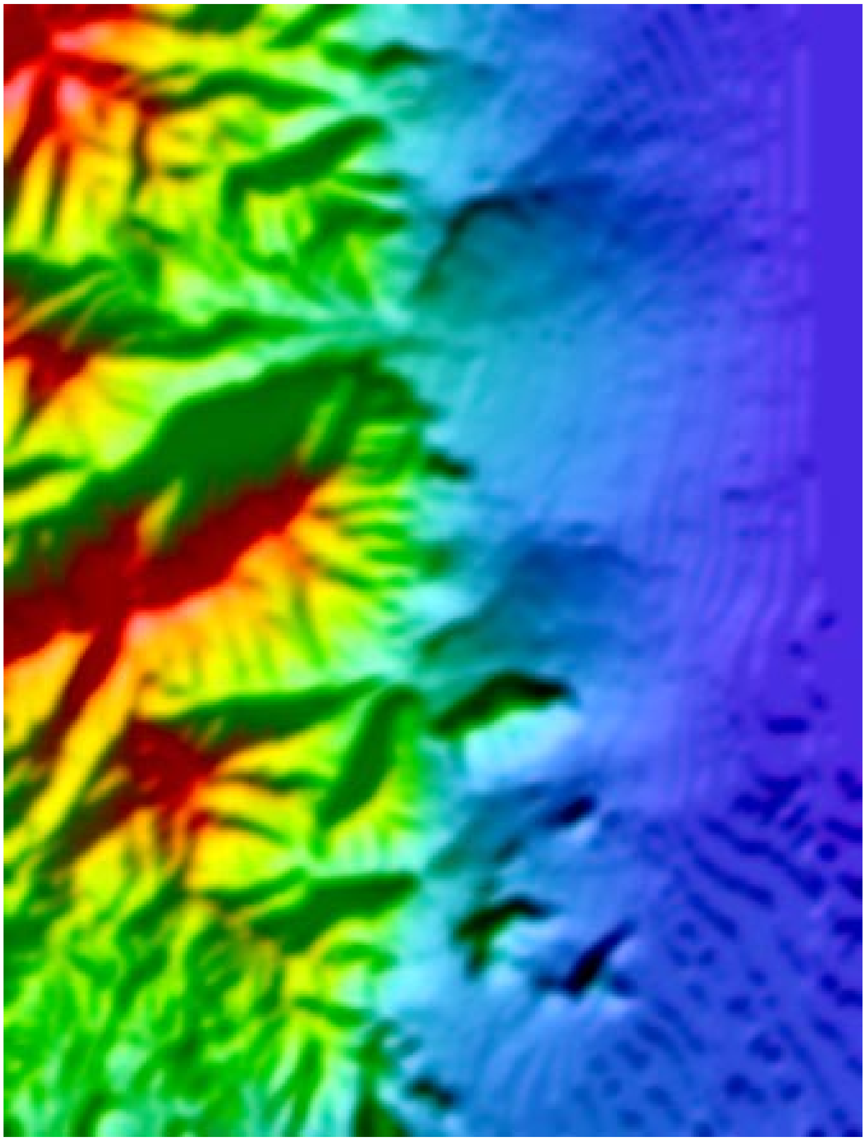

Figure 4: USGS DEM of Drum Mountains, Utah, U.S.A (Blue:1400-1540m, Green :1541-1 800m, Yellow: 1801-1950m, Orange: 1951-2000m, Red : 2001-2200m)

The automatic DEM generation software was developed by the second author at PCI. It can be used to generate DEMs from aerial photos and satellite stereoscopic sensors such as IKONOS, IRS, SPOT, and RADARSAT. After the rigorous models (colinearity and coplanarity equations) are computed for the 3B and 3N images using a minimum of six ground control points (GCPs), a pair of quasi-epipolar images are generated from the images in order to retain elevation parallax in only one direction. An automated image matching procedure is then used to produce the DEM through a comparison of the respective grey values of these images. This procedure utilizes a hierarchical sub-pixel normalized cross-correlation matching method to find the corresponding pixels in the left and right quasi-epipolar images. The difference in location between the images gives the disparity or parallax arising from the terrain relief, which is converted to absolute elevation values above the local mean sea level datum using a 3D space intersection solution.

DEM RESULTS AND ANALYSIS

Eight stereo GCPs and six independent check points (ICPs) were collected from the stereo pairs. GCPs were collected in the border of the images and at the high and low elevation to avoid planimetric and elevation extrapolations. ICPs were then collected inside the areas bounded by the GCPs and were not used in the computation of the geometric model. The GCP cartographic coordinates were collected using DGPS with ±1m accuracy. Table 1 gives the full statistical results over GCPs/ICPs (root mean square (RMS) and maximum residuals/errors) of the stereo-model computed only with the GCPs.

Table 1: Statistical results over GCPs/ICPs with the root mean square (RMS) and maximum residuals/errors of the stereo-model computed with the eight GCPs and six ICPs.

Residuals/ Errors	RMS (m)			Maximum (m)		
	X	Y	Z	X	Y	Z
GCP Residuals	10.7	5.6	8.5	15.9	9.2	14.4
ICP Errors	15.8	10.5	7.9	22.7	15.7	13.8

The errors are a little larger than the residuals but in the order of GCP plotting accuracy (a little better than 1 pixel) and the maximum errors are less than two times the RMS errors. Consequently, the mathematical model properly describes the stereo-viewing geometry, and is stable and robust for the full stereo-model without generating local or systematic errors. GCP residuals can thus be used as *a priori* stereo-mapping error in operational environments.

The DEM generation including quasi-epipolar image generation, image matching and filtering, and geocoding took approximately 1.5 hours on a Pentium III 933 MHz computer. The generated DEM was then compared with an USGS 7.5-Minute DEM (30m grid spacing) obtained from the USGS web site (http://edcftp.usgs.gov). Only one USGS DEM for the test site was available from the web site. USGS 7.5-Minute DEM is derived either by digitizing USGS 1:24,000 scale quad maps (which gives less accurate results) or by scanning aerial photographs. The old 7.5-Minute DEM has a RMS error of 15m and a maximum error of 50m. Most of the 7.5-Minute DEMs (and all new ones) have a 7.5m RMS error.

Because only one USGS DEM was available, 150,000 of the 4 million stereo-extracted elevation points were used to compute the statistics between the ASTER extracted DEM and the USGS DEM. 60% of the elevation points are within 5m difference, 83% are within 10m difference, 90% within 17m difference, and 99% are within 50m difference. In summary, the elevation difference has a minimum value of –109m, a maximum value of 155m, a mean value of 1.9m, a median value of –1m, and a standard deviation (STD) of 11.8m with an 85% level of confidence. The largest differences occur in the mountain areas. Part of these errors includes the error of the USGS DEM. When compared to the previous estimation of the elevation accuracy (25m) based on a normal 1-pixel image matching accuracy, these elevation results (STD of 11.8m) correspond to better than half-pixel matching accuracy. These better results can be attributed to the good quality of these data, the radiometric calibration of the detectors, but mainly to this study site (semi-arid with few cultural features, little vegetation and without forest cover). According to these results, contour lines with an interval of 30-35m could be derived from the DEM.

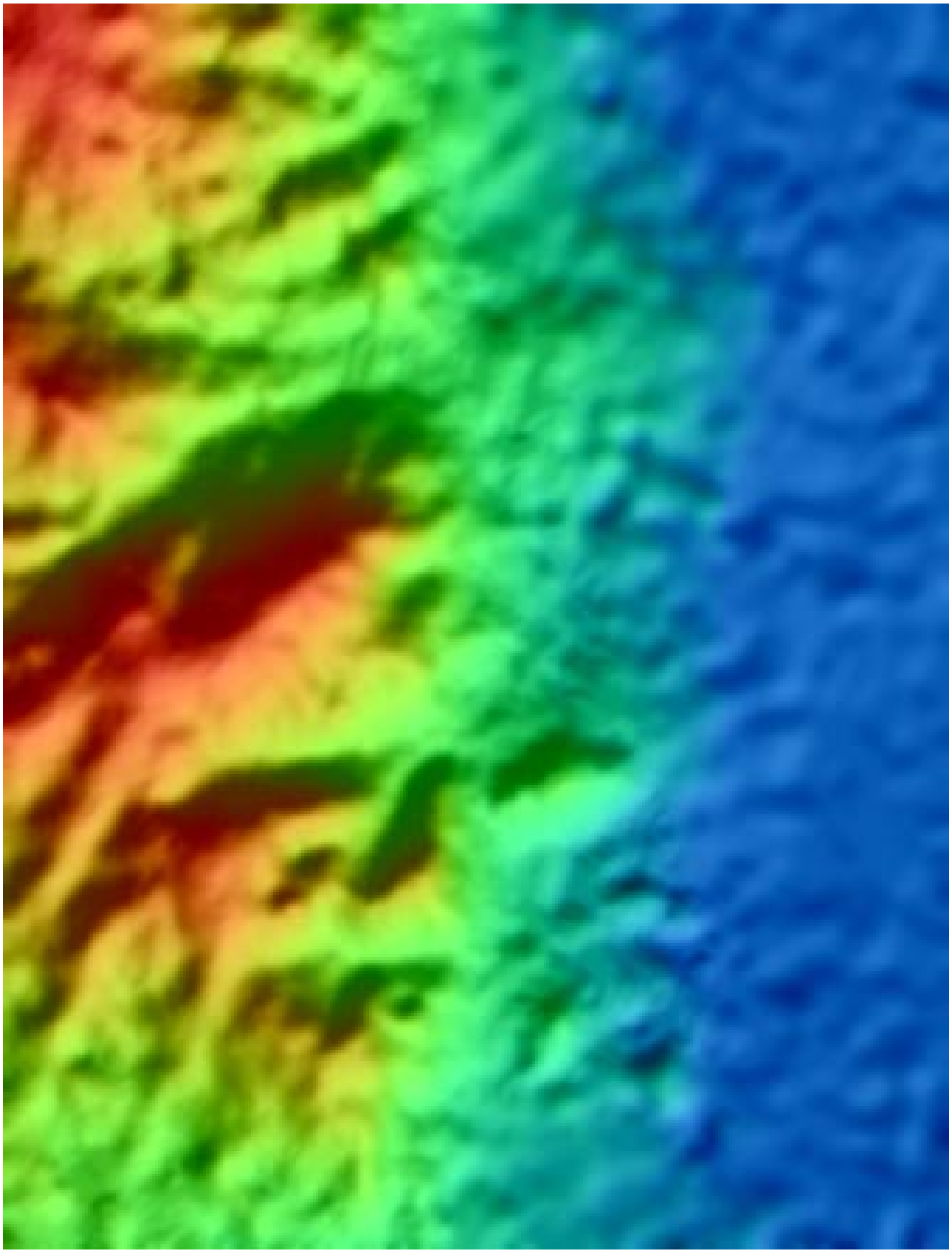

Figure 5: DEM extracted using ASTER stereo data (Blue:1400-1540m, Green :1541-1 800m, Yellow: 1801-1950m,Orange: 1951-2000m, Red : 2001-2200m)

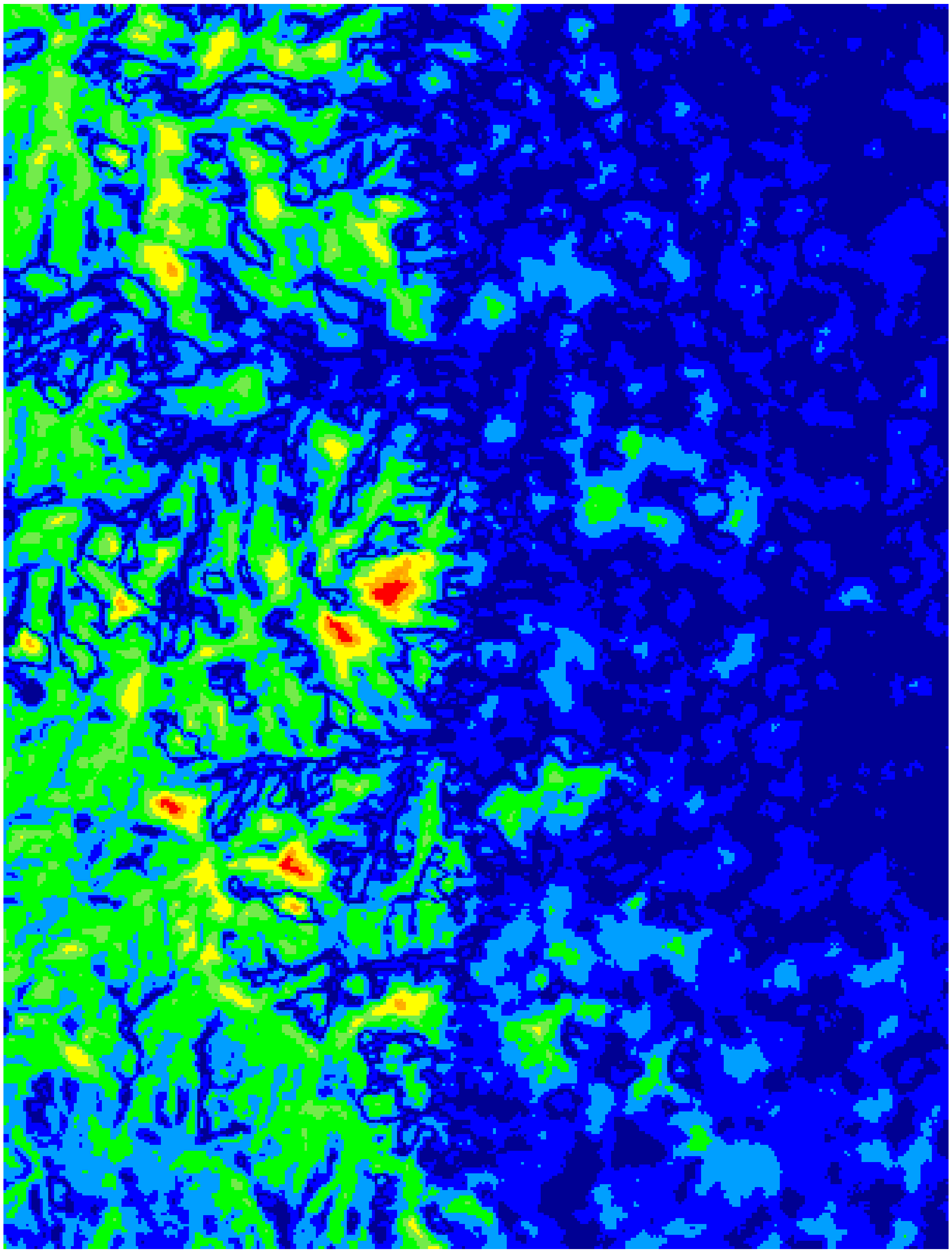

Figure 6: DEM differences between the USGS DEM and the ASTER extracted DEM.
(Blue: 4-9m, Cyan: 10-19m, Green: 20-49m, Yellow: 50-80m, Orange: 81-100m, Red: 100-130m)

CONCLUSIONS

The success of ASTER sensor provides an economical opportunity for mapping at medium scales (1:100,000 and 1:50,000) and for extracting elevation information from nadir and aft images. The simultaneous along-track stereo data eliminates the radiometric variations caused by the multi-date stereo data acquisition while improving the image matching performance. Given accurate GCPs, it is possible to generate stereo-DEMs with good accuracy (better than 25m). When the images and study site are optimal, such as this semi-arid study site in Utah, USA, accuracy as high as 10m and 17m with 83% and 90% level of confidence, respectively, can be achieved. Consequently, 30m contour lines can be derived from the extracted DEM. This method and the PCI OrthoEngine software are currently used by the NASA EOS Land Processes Distributed Active Archive Center (DAAC), located at the USGS EROS Data Center, to produce EOS Standard Data Product DEMs from stereo ASTER data.

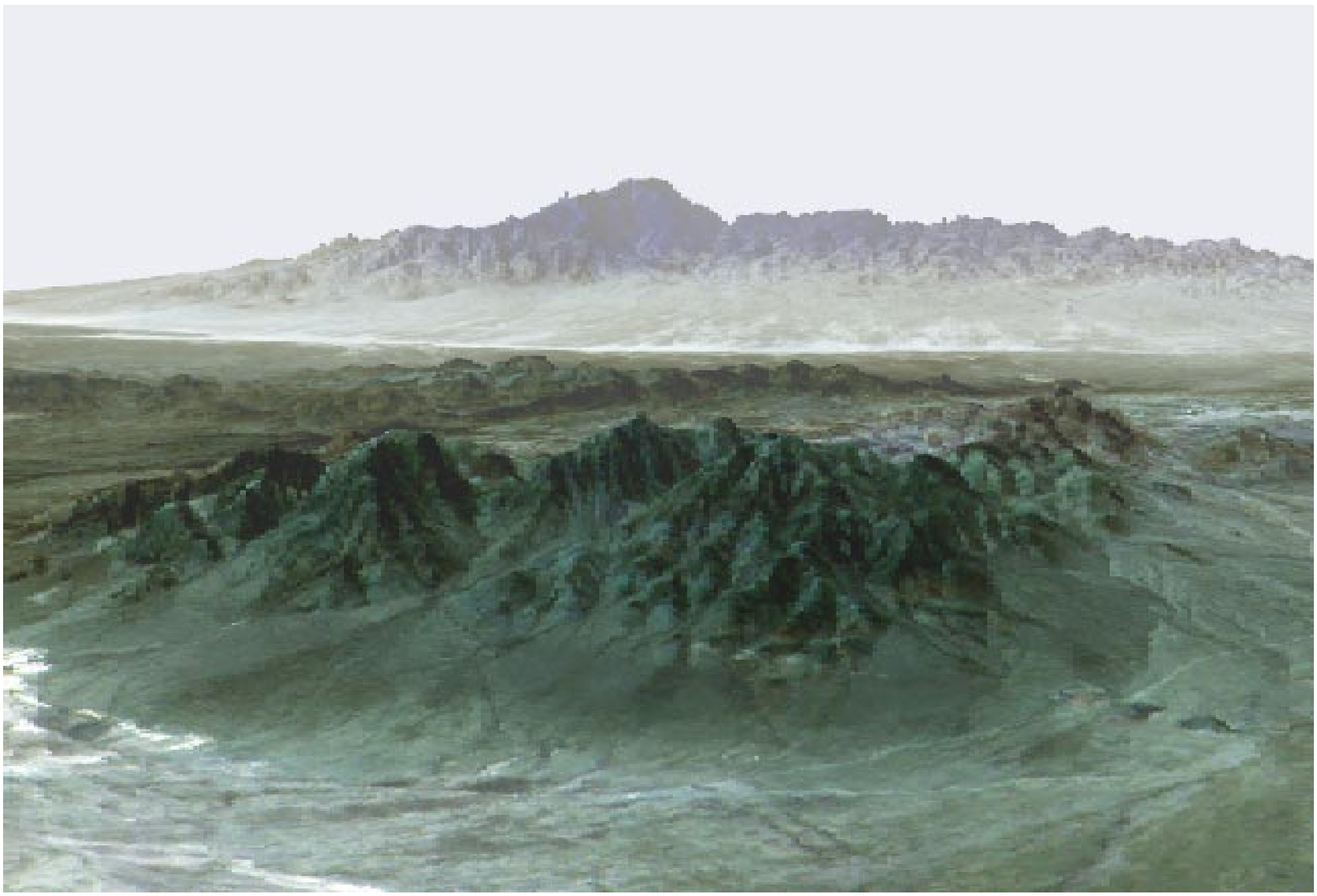

Figure 7: South composite perspective view of ASTER band 1, 2, and 3N of Drum Mountains

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