

Reply to reviewer#1

In their TCD manuscript “Glacier topography and elevation changes from Pléiades very high resolution stereo images” Berthier et al. generated high resolution DEMs of five glacierized study areas from recent Pléiades acquisitions. The accuracy and precision of the derived DEMs were tested by comparing the DEMs with recently collected GNSS data. Further, they determined the applicability of the new Pléiades DEMs to derive seasonal, annual and multi-annual glacier elevation changes by comparing the DEMs with GNSS data, a multi-temporal Pléiades DEM and an older SPOT DEM respectively.

Overall I find the manuscript is well written and interesting to read. I also think the data processing is clean and the derived DEMs are of high quality. Therefore I suggest publication in the Cryosphere after some revisions although the manuscript would also fit in a more technical remote sensing journal. However, I have some general remarks and a few specific comments as listed below.

General remarks:

1/ In the manuscript little is said about the behavior of Pléiades data in the accumulation area of glaciers or in the relative featureless and white terrain of Antarctica which is the main drawback of optical stereo photogrammetry of glaciers and which is probably interesting for researchers working in Greenland and Antarctica. On Page 4854 line 4 you mentioned that the wide radiometric range of Pléiades improves the image contrast significantly, but looking at Figure 2 (Astrolabe) I wonder how well is Pléiades really working in the upper part of the glacier, which seems to be mostly white and featureless and where no reference data is available (the spatial limitations of the reference data need to be mentioned in the discussion). I am not asking to compare the DEM with CryoSat-2 tracks as this is probably behind the scope of the manuscript, but a quantitative approach could be a visual interpretation of a zoomed shaded DEM in comparison with the original satellite images, as the interesting thing of Pléiades is its great detail. Another idea would be to compare zoomed parts of a Pléiades hillshade with a hillshade of the upper parts of the Astrolabe SPIRIT DEM published in Le Meur et al. (2014) in order to show the superiority of Pléiades against SPOT in featureless terrain.

Some of the GNSS measurements used to evaluate the DEMs were acquired in the accumulation areas. We failed to highlight this in the submitted MS. This is now more clearly discussed in the revised MS, in particular for the Mont-Blanc area where we acquired some measurements at altitude >4000 m a.s.l., well above the equilibrium line altitude of about 3000-3100 m a.s.l. in the French Alps (Rabatel et al., 2013).

We also included two additional figures in the revised paper (Fig. R4 & R5, shown at the end of our response to reviewer#1). The first one shows SPOT5 and Pléiades ortho-images, DEMs and shaded relief images for the accumulation basin of the Mer de Glace, also known as Glacier du Géant, in the Mont-Blanc area. Elevation contour lines are overlaid on the DEMs. During both glaciological years 2002-03 and 2011-12, the mass balances were strongly negative and surface conditions in August 2003 and 2012, at the time of acquisition of the SPOT5-HRG and Pléiades images, were similar. The figure shows that the Pléiades DEM is much smoother and has far fewer artefacts than the SPOT5 DEM.

A similar figure has been added for Astrolabe Glacier (Antarctica) with three panels. A Pléiades image (for the geographic context) and two shaded relief images derived from the Pléiades and SPOT5-HRS DEMs on top of which the 100 m elevation contour lines are overlaid. The panels illustrate visually the reduced noise level in the Pléiades DEM. Addition of this figure R5 (and not only Fig. R4 for the Mont Blanc) is justified by the curiosity of all reviewers regarding the quality of the Pléiades DEMs in Antarctica.

Finally, we have modified Figure R2 to include, in a sixth panel, an enlargement of the Pléiades image covering the upper part of Astrolabe Glacier (elevation of 700-750 m above the WGS-84 ellipsoid). The panel shows the presence of numerous surface features in the Pléiades images. Thus, we suggest in the revised paper that not only the 12-bit encoding of the radiometry but also the higher resolution of the sensor is important to obtain precise and nearly complete DEMs. Indeed, a fine resolution allows capturing some fine scale surface features that facilitate the matching between the images.

A sentence has been also added in the abstract regarding accumulation areas.

Specific comments:

Title: I think "Glacier topography and elevation changes derived from high resolution Pléiades stereo images" would be more correct?

New title adopted but high resolution replaced by sub-meter.

Abstract page 4851 line 5: I think it is important to work out the actuality of the study. You could mention that Pléiades is a very recent satellite mission (not sure if this is clear to all TC readers) and that little work has been done so far to derive glacier topography from Pléiades data. This would clearly increase the importance of the manuscript and justify publication in TC.

"recently launched" added to the abstract and a sentence added in the "Data" section of the MS.

Page 4852 line 3: here you could state that geodetic mass balances are also included in the new IPCC report (Vaughan et al., 2013). I think for the first time, double check. This would also underline the importance of the study.

True. In Chap4, section 4.3.3.3, Vaughan et al. (2013) states: "Since AR4, geodetically derived ice volume changes have been assimilated (Cogley, 2009b), providing more consistent regional coverage and better representation of the proportion of calving glaciers." A sentence was thus added in the introduction of our paper.

Page 4853 line 1: maybe you could mention the launch dates of the Pléiades satellites already here?

Years of launch added.

Page 4853 line 8: I am not so happy about the structure of this chapter. Would it not be clearer to make one chapter for "Datasets" and one for "DEM generation"? Subsection "Study areas" could also be included in the introduction.

Page 4854 line 21: extra subsection for the GNSS data could be included in the Data section. The same applies for the Lidar DEM and the SPOT DEMs (which also should be described shortly).

The structure of the MS has been modified by separating the description of the datasets and the method of DEM generation. The previous sub-section “study area” is now included in the “Pléiades stereo images” sub-section (so not in the introduction). Description of other datasets than Pléiades are now included in dedicated sections. See revised MS.

Page 4854 line 12-15: why not include a schematic figure of the triplet mode? I find it a bit confusing to go to such a long URL in the continuous text.

We agree that the long URL was not very convenient, it was thus removed. Given that the vast majority of readers will be familiar with the concept of stereo pairs, we think that tri-stereo will be easy to understand for most of them (quite intuitive). We did not include an additional figure.

Page 4855 line 28-29: “Some tests were also performed with a pixel size of 2 m that did not improve results and are therefore not reported here.” This sentence could probably be deleted.

Deleted.

Page 4858 line 5: typo: “prominent”, such as?

Typo corrected.

Page 4858 line 10: here you state that no GCPs were available for Astrolabe (Antarctica) and Mera (Nepal). However, in Table 4 you say that 22 GCPs were available for Himalaya – Mera from SPOT. Somehow inconsistent.

We have now clarified that no GNSS-measured GCPs were available for Mera Glacier.

Page 4866 line 15: “...can reduce the percentage of data voids and slightly improve precision.” Is not this an added value?

Correct. We have now clarified our wording. There is indeed an added value of tri-stereo but it is moderate and may not justify the additional cost for smooth glacier surfaces. We also modified the corresponding text (paragraph 4.4.4)

Page 4867 line 1-2: What about problems in featureless accumulation areas? How is the improvement compared to other optical sensors such as SPOT or ASTER?

See response to the general comment and new figures R4 and R5.

Page 4871 line 12: typo: “Kropacek”

Thanks, this was a typo introduced during type-setting. It was OK in the submitted (and now revised) MS.

Figure 2: I think this Figure can be deleted, as it is not really meaningful.

We believe it is important to show the distribution of the reference data used to evaluate the DEM. The figure has been retained but improved by adding a sixth panel with an enlargement of the Pléiades image of Astrolabe Glacier.

Figure 3 and 4: please insert geographic coordinates. Where are the glacier outlines from? Digitized from the Pléiades images? Please describe, maybe in the Methods section. Also

the GCPs could be shown. Figure 3 and Figure 4 might be combined into one a b subplot. Why not show a hillshade of the Pléiades DEM in the background (at least in Figure 4?) this would give much more information about the DEM quality on the glacier.

We decided to keep two separate figures (R3 and R6) to ensure they will be published at full width and not as two small panels side by side. Section 3.3 now describes how glacier outlines were obtained. Geographic coordinates added. GCPs are shown on former Fig. 4 (now Fig. R6) where the shaded relief DEM has been added as background.

Figure 5 and 6: maybe these Figures could also be combined into one a b subplot. Also geographic coordinates and GCPs should be included. Where are the glacier outlines from? Digitized from SPOT?

We prefer to keep them as two separate figures (R7 and R8). Geographic coordinates added. Source of the outlines provided in the new 'Methods' section (yes, digitized from SPOT5). Pléiades GCPs added in Figure 5 (now Figure R7).

Figure 6: looking at this figure, I am assuming a linear ramp across the entire scene reaching from -5 m in the upper left corner to +5 m in the lower right corner (hard to tell at this color scale). This possible ramp need to be checked and if present also removed as it might have a significant impact on the results. It possibly originates from the SPOT DEM as it is not so obvious in Figure 5?

Figure 6 (now Fig. R8) is deeply revised. We computed an additional August 2012 Pléiades DEM for the southern part of the Mont Blanc area in order to compute the geodetic mass balance for the whole Mont-Blanc area. This southern DEM was computed using only two GCPs shared with the northern DEM. The mean elevation difference between the southern and the northern DEM on the ice free terrain was 0.27 m and the horizontal shift was only 0.2 m. After 3D co-registration, the mean elevation difference between those two synchronous DEMs on glacier is 0.06 m. This additional analysis demonstrates further the quality of the DEMs, even with two GCPs. We also fitted a first order polynomial fit (i.e., a plane) to the 2003-2012 elevation differences off glacier. The standard deviation of the elevation difference is reduced marginally from 7.35 m (removal of a simple offset, 0 order fit) to 7.21 m (removal of a plane, 1st order fit). The geodetic mass balance for the whole Mont-Blanc area is nearly unchanged following this correction: from $-1.02 \pm 0.23 \text{ m a}^{-1} \text{ w.e.}$ (0 order fit) to $-1.04 \pm 0.23 \text{ m a}^{-1} \text{ w.e.}$ The changes are also negligible if a 2nd order polynomial is fitted to the elevation differences off glaciers (new mass balance $-1.02 \pm 0.23 \text{ m a}^{-1} \text{ w.e.}$)

Also a hillshade of the Aqua Negra study site, the Mera study site and Astrolabe glacier (see general comments) would be interesting, including the GNSS data points, the GCPs (if available), glacier outlines and geographic coordinates. For Astrolabe a comparison with the SPIRIT DEM could be interesting.

See shaded relief images of the Mont-Blanc area, Astrolabe Glacier and Icelandic study sites in the revised figures (R4 and R5, reproduced below).

Figure R4: Comparison of the 21 August 2003 SPOT5 and 19 August 2012 Pléiades DEMs of the accumulation basin of the Mer de Glace (known as the Géant Glacier). The upper panels show the SPOT5 data and the lower panels the Pléiades data. From left to right, the panels show successively the satellite images, the DEMs with the 50-m elevation contour lines and the shaded relief images derived from the DEMs. Note the higher percentage of data voids and artefacts in the SPOT5 DEM.

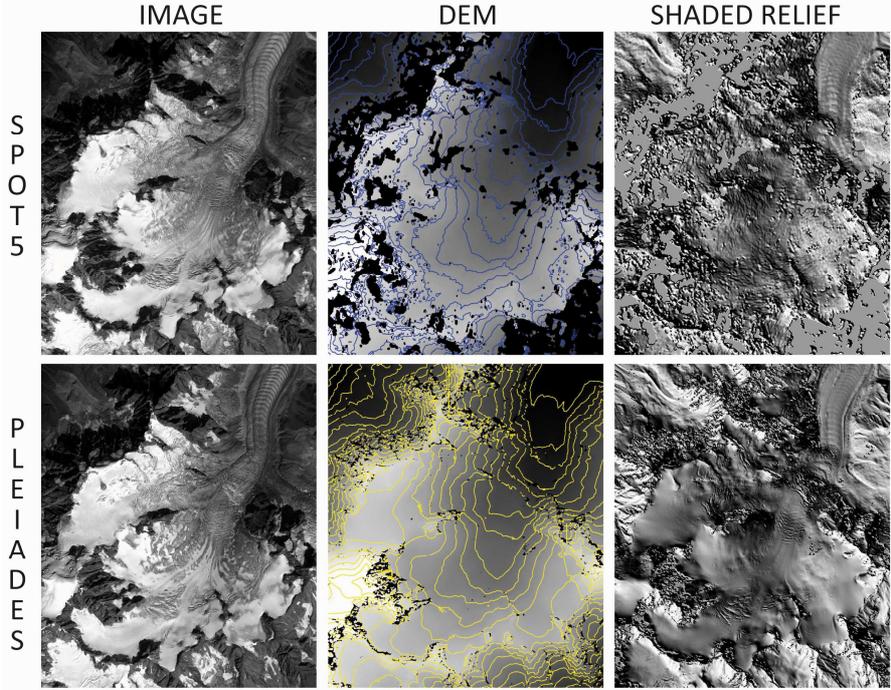


Figure R5: Comparison of the 14 December 2007 SPOT5 and 6 February 2013 Pléiades DEMs of Astrolabe Glacier. The left panel (a) shows the Pléiades image. The two right panels show shaded relief images derived from the Pléiades DEM (b) and the SPOT5-HRS DEM (c) with the 100-m elevation contour lines overlaid.

