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Deriving large-scale glacier velocities from a complete satellite archive : Application to the Pamir-Karakoram-Himalaya

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Abstract

Mountain glaciers are pertinent indicators of climate change and their dynamic, in particular surface velocity change, is an essential climate variable. In order to retrieve the climatic signature from surface velocity, large-scale study of temporal trends spanning multiple decades is required. Satellite image feature-tracking has been successfully used to derive mountain glacier surface velocities, but most studies rely on manually selected pairs of images, which is not adequate for large datasets. In this paper, we propose a processing strategy to exploit complete satellite archives in a semi-automated way in order to derive robust and spatially complete glacier velocities and their uncertainties on a large spatial scale. In this approach, all available pairs within a defined time span are analyzed, preprocessed to improve image quality and features are tracked to produce a velocity stack; the final velocity is obtained by selecting measures from the stack with the statistically higher level of confidence. This approach allows to compute statistical uncertainty level associated with each measured image pixel.

This strategy is applied to 1536 pairs of Landat 5 and 7 images covering the 3000km long Pamir-Karakoram-Himalaya range for the period 1999-2001 to produce glacier annual velocity fields. We obtain a velocity estimate for 76000km²

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or 92% of the glacierized areas of this region. We then discuss the impact of coregistration errors and variability of glacier flow on the final velocity. The median 95% confidence interval ranges from 2.0m/yr on average in stable areas and 4.4m/yr on average over glaciers with variability related to data density, surface conditions and strain rate. These performances highlight the benefits of processing of a complete satellite archive to produce glacier velocity fields and to analyse glacier dynamic at regional scales.

Keywords: Remote sensing, Feature-tracking, Surface velocity, Mountain glaciers, Landsat, Himalaya, Karakoram

1. Introduction

Mountain glaciers have a high societal impact; first on a local scale as they influence the water resources (Immerzeel et al., 2010) and economical activity (Barros et al., 2014) of a region, but also at a global scale by contributing to changes in the global sea level (Gardner et al., 2013). Moreover, mountain glaciers are sensitive to climate forcing and are thus relevant indicators of past and present climate changes (IPCC, 2013). Satellite imagery, with its global coverage and repeated acquisition, represents a unique opportunity to quantify the spatial and temporal changes affecting mountain glaciers. In particular, feature-tracking using repeated images allows us to construct velocity fields which are valuable information to understand dynamical processes such as the response to climate changes, glacier surges or development of glacial lakes and associated hazards (Paul et al., 2013).

Many studies have proven the capabilities of feature-tracking applied to repeated satellite images to measure glacier velocities. Scambos et al. (1992) applied normalized cross-correlation of Landsat TM images to measure the velocity of ice streams in Antarctica. Kääb (2002) and Berthier et al. (2005) show that it is possible to apply this method to mountain glaciers, using respectively ASTER and SPOT images. High resolution images as well as an improved algorithm, that determines the position of the correlation maximum from 1/2th to

21 1/20th of a pixel (Strozzi et al., 2002), allow the tracking of much smaller surface
22 features with a precision in yearly velocity of a few cm/yr, equivalent to the pre-
23 cision obtained by synthetic aperture radar interferometry (InSAR) (Goldstein
24 et al., 1993) and multiple aperture InSAR (MAI) (Gourmelen et al., 2011). Par-
25 ticular attention has been given to improving the techniques of feature-tracking.
26 Preprocessing steps to enhance and improve the performances of the tracking
27 include Principal Component Analysis, high-pass filters (Scambos et al., 1992;
28 Berthier et al., 2005) or edge-detection (Ahn and Howat, 2011). Several stud-
29 ies focused on the choice of the feature-tracking algorithm (Strozzi et al., 2002;
30 Heid and Kääb, 2012a), reduction of the orthorectification errors (Scherler et al.,
31 2008) or on optimizing the parameters for the feature-tracking (Debella-Gilo and
32 Kääb, 2012). However, automatation of the processing in order to reduce user
33 interaction remains a challenge (Ahn and Howat, 2011; Debella-Gilo and Kääb,
34 2012; Heid and Kääb, 2012a).

35 The large amount of currently available and future remote sensing data has
36 led to a large variety of applications. Copland et al. (2009) produced velocity
37 fields on a regional scale, for all glaciers within the central Karakoram region
38 for the period 2006-2007, thereby giving an instantaneous picture of the glacier
39 velocity in this region. This technique has also been applied to SAR images, to
40 study specific areas such as the Mont-Blanc glaciers (Fallourd et al., 2011), the
41 Everest region (Luckman et al., 2007) and the Baltoro glacier (Quincey et al.,
42 2009a). Heid and Kääb (2012b) exploit the long time span of Landsat images
43 to investigate the link between variations in mass balance and velocity over
44 the period 1985-2011 for 6 selected regions across the globe. However, they also
45 outline the problem of the representativeness of the selected regions and the need
46 to increase the efforts at a regional scale. Several studies have processed larger
47 number of images to produce velocity fields at a regional scale. Willis et al.
48 (2012) processed 124 manually selected ASTER images to produce a velocity
49 field for the $3593km^2$ Northern Patagonian Icefield and the period 2000-2011.
50 They obtain a composite velocity by averaging the stack of velocities weighted by
51 the uncertainty of each velocity. Burgess et al. (2013) apply feature-tracking to

52 344 pairs of ALOS images acquired between 2007 and 2010 but only 60 pairs are
53 manually retained to produce a final mosaic velocity of the Alaska range glaciers.
54 Scherler et al. (2011b) produce center flow line velocities for several parts of the
55 himalayan range by computing the mean of a stack of velocities obtained from
56 feature-tracking of 657 ASTER and SPOT images for the period 2000-2008.
57 Nevertheless, all of these studies always rely on manually selected images and
58 the repetitivity of the satellite imagery archive has not been exploited yet.

59 In this paper, we present a processing strategy to derive a robust and spa-
60 tially dense velocity field over an extended region from a complete satellite
61 archive. First, we give a broad outline of the method, we then apply this strat-
62 egy to the Landsat 5 and 7 archive to produce glacier annual velocity fields over
63 the Pamir-Karakoram-Hiamalaya (PKH) over a three-year period. This allows
64 us to assess the performance and uncertainties of the strategy.

65 **2. Data and methods**

66 In this section, we describe the processing strategy including the selection of
67 image pairs, the preprocessing steps to reduce the dimensionality of the prob-
68 lem and enhance the useful information, the feature-tracking algorithm and the
69 fusion of the multi-temporal results (Figure 1). The method can be applied to
70 any satellite imagery archive with sufficient repetition in the acquisition as for
71 example ASTER, SPOT or the upcoming Sentinel 1 and 2 missions of the Eu-
72 ropean Space Agency that will provide repeated images of the Earth surface. In
73 this paper we focus on the Landsat serie that represents the longest continuous
74 satellite archive, with acquisitions of the Earth surface from 1972 to nowadays
75 and a repeat-cycle of 16 to 18 days at medium-resolution (15 to 60m) and a
76 quasi-global coverage.

77 *2.1. Selection of image pairs*

78 The main idea of the method is to process all available data without man-
79 ual selection for several reasons. First, selecting the images beforehand with

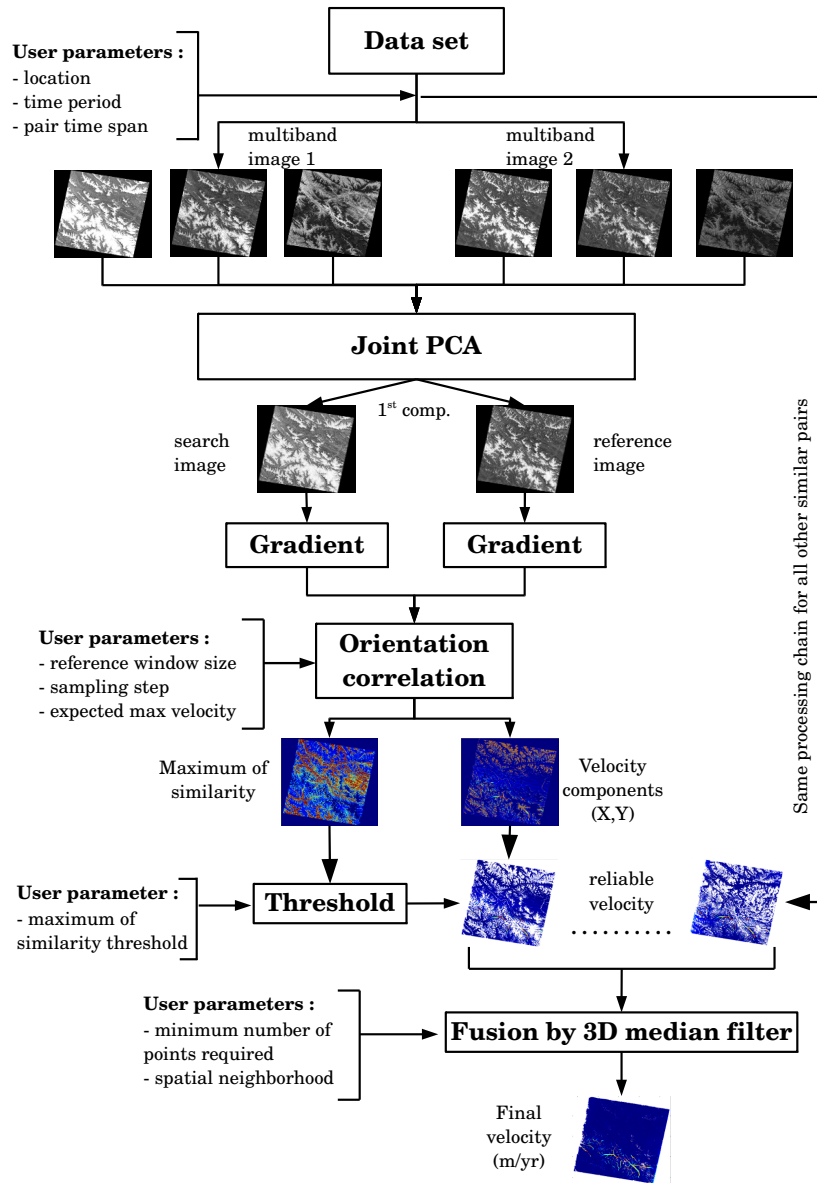


Figure 1: Processing strategy to derive glacier velocities from a complete multispectral satellite archive

80 consideration of the quality of the scene is very time consuming and subjective
81 and could lead to a loss of valuable information. Here we propose to process
82 all data and to filter the results based on the quality of the feature-tracking.
83 Secondly, a single pair rarely gives an spatially complete result due to shadows,
84 clouds or sensor saturation that induce outliers or gaps in the resulting data.
85 But several pairs might be complementary, allowing a more spatially complete
86 estimate of the velocity field. Thirdly, we can exploit data redundancy to reduce
87 the uncertainty in the results.

88 Thus images are selected solely based on the date and time of acquisition
89 and location. Pairs are then formed with a specific time span. In order to
90 produce, for example, annual velocity fields, we select pairs separated by one
91 year, or multiples of a year, to minimize the effects of the seasonal variability.
92 It also increases the chances that the two images have a similar surface
93 condition (linked to snow cover) which will improve the performance of the
94 feature-tracking. Finally, the time span has to be large enough so that the
95 displacement is significant with reference to the pixel size. Here, we obtain an
96 annual velocity for year T by selecting all pairs of the form $(T-1; T)$ and $(T;$
97 $T+1)$, as well as $(T-1; T+1)$, so that all velocity measured are centered around
98 year T . For example, the Landsat 5/7 repeat cycle is 16 days, and 23 cycles
99 represent 368 days, so not exactly one year, so we process pairs that have tem-
100 poral baselines of 368-16, 368 and 368+16 days for one year and 736-16, 736 and
101 736+16 days for 2 years. Thus each image is paired with up to 6 other images.
102 This allows us to compensate for some missing or poor quality images.

103 *2.2. Preprocessing*

104 *2.2.1. Image coregistration*

105 We assume that the images are corrected for topographic distortion, i.e.
106 that the displacement observed between two images is actual horizontal mo-
107 tion and not influenced by topography. But as some images are not exactly
108 georeferenced, they are first coregistered to a reference image. We chose to
109 use the Global Land Survey as a reference data set that have a positional

110 accuracy better than 50m (Tucker et al., 2004). Coregistration consists in :
111 computing the offsets on a regular grid (typically 100x100 estimates), fitting
112 a degree 2 polynomial and resampling to the reference image grid using Sinc
113 interpolation. The resampling is done only if more than 10% of the pixels
114 have offsets higher than 0.5 pixels in order to preserve the actual radiometry
115 of images that are already well coregistered. Higher order offsets may still ap-
116 pear, mainly due to instrumental uncertainties that cannot be corrected due to
117 the whiskbroom Landsat acquisition system (Scherler et al., 2008), but as long
118 as they are not coherent between images, they will be efficiently filtered out
119 by the proposed strategy. All images of the same frame are then cropped to
120 a common region to ensure that the correlation windows are the same from
121 pair to pair and the measurement always corresponds to the same region. We
122 use the coordinates of the frame corners provided by the USGS in shapefile
123 format (https://landsat.usgs.gov/tools_wrs-2_shapefile.php) to consis-
124 tently crop the images.

125 *2.2.2. Principal Component Analysis*

126 Images are then enhanced in order to improve the quality of the feature-
127 tracking algorithm. Different steps have been proposed : Principal Component
128 Analysis (PCA) to reduce the dimensionality of multi-spectral images, edge
129 filters to enhance crevasse contours and high-pass filters for removing larger
130 scale variations. (Scambos et al., 1992; Berthier et al., 2003; Ahn and Howat,
131 2011).

132 The PCA is the procedure of projecting a set of different observations of the
133 same variable, possibly correlated, into a new set of uncorrelated observations. It
134 is constructed so that the first component maximizes the variance of the variable,
135 then the second component maximizes the variance while being orthogonal to
136 the first etc... It is interesting as it enhances the signal into a single value but
137 the choice of the bands to be merged is a difficult task as it depends on the
138 gain of the acquisition, the surface conditions of the glacier (e.g clean or debris-
139 covered) and the sensor. Heid and Kääb (2012a) use the Landsat panchromatic

140 band because of its higher resolution whereas Scambos et al. (1992) and Berthier
141 et al. (2003) apply a Principal Component Analysis (PCA) on near-infrared and
142 visible bands (1-5 for TM and ETM+) and use the first component, but this
143 method does not explore the choice of the bands. Necsoiu et al. (2009) produce
144 a combination of ASTER bands 1 and 2 to improve the performance of the
145 correlation with SPOT panchromatic images. Redpath et al. (2013) determine
146 the best band or band combination by comparing the result of the feature-
147 tracking of ASTER images with ground truths.

148 As we are seeking a method that can be exploited globally, we decide not
149 to rely on ground truth for this step but rather on the performance of the
150 feature-tracking itself. First, a few representative scenes of the studied region
151 are selected. For each of these scenes, the feature-tracking is run for each band
152 individually and the performance assessed using the success rate as defined
153 in section 2.5. Once the best band or bands according to this criteria are
154 determined, several band combinations can be considered. Every combination
155 is then compared to the others using the same criteria and eventually an optimal
156 band or band combination can be chosen. The results of this method for our
157 study case is detailed in section 3.

158 Finally, we noticed that the result of the PCA can vary much from image
159 to image, mostly due to changes in snow cover. In order to avoid correlat-
160 ing different band combinations, we perform the PCA on a concatenation of
161 the 2 images of the pair instead of performing it for each image individually.
162 This choice ensures that the same physical signal (same combination of spectral
163 bands) is introduced in the correlation step. The PCA has thus to be applied
164 for each pair specifically.

165 *2.2.3. Intensity gradient*

166 Two Sobel kernels of size 3x3 are applied to compute the intensity gradient
167 in the x and y directions, which enhances surface features such as crevasses and
168 serac or debris cover. The gradients are normalized in order to produce an ori-
169 entation image, which is the input for the feature-tracking algorithm described

170 below. The different enhancement steps are illustrated in Figure 2.

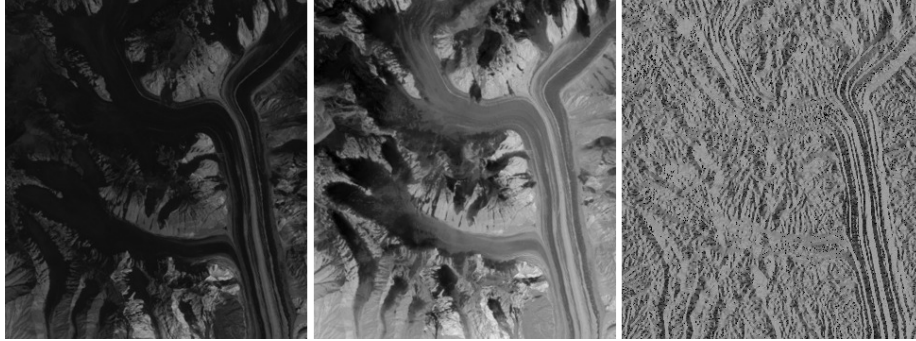


Figure 2: Example of enhancement procedure for Landsat images over northern tributaries of the Baltoro glacier (Karakoram) : Landsat mid-infrared band 5 (left) has the best performance in the Karakoram (see section 3.2.2), selecting the first component of a PCA of bands 4 & 5 results in brightening of the accumulation zones (middle), the gradient orientation displays enhanced glacier features (right).

171 2.3. Feature-tracking

172 Feature-tracking is a method that allows the estimation of a displacement
173 between a first image called reference image and a second image or search image.
174 First, a window Ω_r is chosen in the reference image centered around pixel (i,j).
175 Then a window of same size is extracted from the search image but translated
176 by (p,q) pixels within a specified search window Ω_s and compared to Ω_r using a
177 function of similarity. This operation is repeated for different values of (p,q) and
178 the position of the maximum of similarity, interpolated to a fraction of pixel, is
179 a measure of the displacement.

180 2.3.1. Algorithm

181 After a comparison between 6 different methods, Heid and Kääb (2012a)
182 showed that the method called "orientation correlation" proposed in Fitch et al.
183 (2002) has the best performance over mountain glaciers. Thus we focus only
184 on this algorithm that is fast, illumination invariant and not sensitive to uni-
185 form areas such as in the saturated accumulation zones or the null-stripes that

186 appear in the Landsat 7 ETM+ images after May 2003. In this algorithm, a
 187 synthetic complex image, called orientation image, is formed by setting the real
 188 and imaginary parts to the gradients in the x and y directions of the image
 189 intensity (I), respectively, and normalizing the quantity in order to take only
 190 the orientation into account (Fitch et al., 2002) :

$$f = \begin{cases} \frac{g_x + ig_y}{\sqrt{g_x^2 + g_y^2}} \\ 0, \end{cases} \quad \text{if } g_x = g_y = 0 \quad (1)$$

191

$$\text{where } g_x = \frac{\partial I}{\partial x}, \quad g_y = \frac{\partial I}{\partial y}, \quad (2)$$

192 Because the input images are complex, we perform a complex cross-correlation
 193 between the two orientation images. The similarity function is given for each
 194 pixel (p, q) by :

$$CO(p, q) = \frac{1}{n} \left| \sum_{(i,j) \in \Omega_r} f_r(i, j) f_s^*(i + p, j + q) \right| \quad (3)$$

195 where n is the number of points in the reference window Ω_r , f_r (f_s) the ori-
 196 entation image of the reference (search) image and f_s^* is the complex conjugate
 197 of f_s (this formula is simplified by the fact that the images being correlated
 198 are already normalized). Concretely, we match the orientation of the intensity
 199 gradient that is contained in the phase of the orientation image (see Figure 2
 200 right). We use the coherence tracking function proposed by Strozzi et al. (2002)
 201 that allows to track the gradient orientation which is contained in the phase of
 202 the orientation image. The coherence is computed in the Fourier domain and
 203 the maximum interpolated to a fraction of a pixel. The program also returns
 204 the Signal-to-Noise Ratio (SNR) i.e. the ratio between the correlation maximum
 205 and the average value in the search window which is a commonly used proxy
 206 for the confidence of the matching (Strozzi et al., 2002; Quincey et al., 2009a).

207 2.3.2. Parameters setting

208 The optimum parameters for the feature-tracking, i.e. the reference and
 209 search window sizes must then be chosen. The choice of the reference window

210 size is complex since it must be large enough to avoid correlating only noise but
211 small enough to avoid deformation of the matched objects inside the window.
212 We perform the offset-tracking for a few selected pairs and different reference
213 window sizes γ_r and choose the lowest value that minimizes the errors in stable
214 areas. It ensures that the window is large enough with respect to the image
215 resolution while retaining the highest possible spatial resolution. This choice
216 might not be optimal for all glaciers because it depends on the texture and
217 size of the glaciers, but more sophisticated methods such as locally adaptive
218 reference window sizes (Debella-Gilo and Kääb, 2012) are computationally too
219 expensive for processing a large number of images.

220 The search window is chosen to be larger than the expected maximum dis-
221 placement but small enough not to increase unnecessarily the computation time.
222 For an expected maximum velocity V_{max} and a time span Δt between two im-
223 ages of pixel size R , the search window size is set to $\gamma_s = 2V_{max}\Delta t/R + \gamma_r$.

224 *2.4. Postprocessing*

225 After processing all the selected pairs, it is important to filter the displace-
226 ment vectors and to merge all results into a single value. In the following
227 sections, we propose a method to exploit the redundancy in the series of pairs
228 in order to efficiently remove outliers and produce a more robust velocity field
229 with very little user interaction.

230 *2.4.1. Outliers removal*

231 Mismatches or outliers are identified and removed using a threshold value of
232 SNR. The choice of the threshold is a compromise between removing most of the
233 mismatches while retaining the interesting information. The threshold can be
234 easily determined by looking at the residuals in stable areas (see MAD in section
235 2.5). We show in section 3.2.3 that the residuals are high for low thresholds and
236 drop dramatically to reach an asymptot in the range of the coregistration errors.
237 Thus, we recommend to compute the MAD in stable areas for different SNR
238 thresholds and select the lowest threshold that approaches the asymptot.

239 *2.4.2. Fusion into a single velocity*

240 At this stage, we have a set of displacement fields that may contain gaps
241 but also redundant values. The idea is to exploit the redundancy of information
242 and physical properties of the glaciers to merge this set into a single, more
243 robust velocity. We propose to compute a median of all neighbouring values
244 both in a spatial and temporal neighbourhood, for each x and y component
245 of the velocity. To ensure that the median is statistically significant and in
246 order to remove spatially isolated pixels, we do not retain the value of the
247 velocity if the number of points used to compute the median is less than a
248 certain value N_{min} . This method relies on two assumptions. First, because
249 pairs were selected with similar time spans within a specified period, we assume
250 that the measured velocity does not vary much from pair to pair. Secondly, we
251 assume that the shear of the ice is low and that adjacent pixels on a glacier do
252 not have large velocity differences. This is arguable at the edge of the glaciers
253 where the moving ice is adjacent to the stable moraine and there might be a
254 strong gradient. Nevertheless, a median filter preserves edges and thus glacier
255 contours. The size of the spatial window for the median filtering depends on
256 the image resolution and the number of pairs available (the more points we
257 have, the smaller the window can be) and the size of the glaciers. For mountain
258 glaciers, this spatial window should not exceed a few hundred meters.

259 This method offers several advantages. First, the median is not sensitive
260 to isolated outliers and thus is able to filter out aberrant values that were not
261 removed in the first stage. The use of a median filter to discard aberrant values
262 is common in glaciology (Copland et al., 2009; Ahn and Howat, 2011; Heid and
263 Kääb, 2012a), but this method still requires supervision by an expert to select
264 the threshold and is region-dependent (Heid and Kääb, 2012a). By adding
265 more information with a set of displacement fields, we can minimize the expert
266 interaction. Secondly, several factors (orthorectification errors, shadows, clouds)
267 can induce matches with high confidence, because the features actually match
268 between the two images, but are not related to actual terrain motion. This

269 is often the main source of errors when applying feature-tracking to satellite
270 images. But because these errors are not coherent from pair to pair, the median
271 is not affected and the result of the fusion is still robust.

272 At last, in order to merge together velocity fields over a large region, with
273 possible overlap and different projections (for example, different Landsat frames
274 are projected on different UTM zones), we recommend to set a global grid and
275 to merge the velocity fields by taking the median value of neighbor estimates,
276 both spatially and in the stack of pairs, at each node of the grid.

277

278 *2.5. Performance assessment indices*

279 In this section, we define the indices that are used throughout the study to
280 evaluate the velocity fields. As noted by Burgess et al. (2013), the presence
281 of mismatches in the velocity fields tend to stretch the tails of the velocity
282 distribution. It is thus important to use robust statistical estimators (Rousseeuw
283 and Hubert, 2011). It is the reason why we suggest to use the median and
284 Median Absolute Deviation (MAD) instead of the mean and standard deviation.

285 In the following, velocity estimates are considered as valid after applying the
286 SNR threshold. Glaciers are delimited using version 3.2 of the Randolph Glaciers
287 Inventory outlines (Pfeffer et al., 2014) except for some parts of the Karakoram
288 where we used manually edited outlines due to a misalignment between the
289 outlines and the actual glaciers location. The performance assesement indices
290 we retained are :

- 291 • The success rate SR , which is the percentage of valid velocity estimates
292 on glaciers.
- 293 • The normalized Median Absolute Deviation (MAD) of the velocity :

$$MAD = 1.483 \times med(|V - med(V)|) \quad (4)$$

294 which is a robust equivalent of the standard deviation. When not men-
295 tionned, it is computed for the velocity magnitude V , or for each com-
296 ponent of the velocity when a different behavior is expected for the two

297 components. In particular, in stable areas, i.e off glaciers, where the ve-
 298 locity V is supposed to be null, the MAD is :

$$MAD_{off} = 1.483 \times med_{(i,j) \in \Omega_{off}}(|V(i,j)|) \quad (5)$$

299 where Ω_{off} is the ensemble of points off glaciers. This is a proxy for the
 300 uncertainty of the measurement.

- 301 • The dispersion : during the fusion step, the MAD can be calculated at
 302 each velocity location.

$$\sigma(i,j) = 1.483 \times med_{t \in T}(|V(i,j,t) - \bar{V}(i,j)|) \quad (6)$$

303 where T is the set of N velocity estimates $V(i,j,t)$ merged to obtain the
 304 median velocity $\bar{V}(i,j)$ at pixel (i,j) . This is indicative of the variability
 305 between the different velocity estimates.

- 306 • The coherence of the velocity vectors that contributed to the median,
 307 i.e. if they point in the same direction. We define the Velocity Vector
 308 Coherence (VVC) as :

$$VVC(i,j) = \frac{\|\sum_{t \in T} \vec{V}(i,j,t)\|}{\sum_{t \in T} \|\vec{V}(i,j,t)\|} \quad (7)$$

309 According to the triangle inequality, VCC is in the interval $[0,1]$, equal to 1 if
 310 all vectors are perfectly aligned and tend to 0 if they point in random directions.

311

312 2.6. Uncertainty

313 Uncertainties of the single-pair velocity fields are dominated by the preci-
 314 sion of the feature-tracking algorithm, the image to image registration and the
 315 temporal variability of glaciers flow. But the uncertainty of the final, i.e the
 316 median velocity over the considered period, is known to decrease with the num-
 317 ber of estimates. Suppose a sample of size N drawn from a normally distributed

318 population with variance σ_n , the sample median converges asymptotically to a
 319 normal distribution with standard deviation $\sigma_m = \sqrt{\frac{\pi}{2}} \frac{\sigma_n}{\sqrt{N}}$ (Chu, 1955). Here,
 320 we cannot make the hypothesis of a normal distributed velocity because of the
 321 possible presence of outliers, but because the different measurements are in-
 322 dependant and symmetrically distributed, we assume that the 95% confidence
 323 interval of each component of the final velocity follows a similar law :

$$t_{95} = k \frac{\sigma}{N^\alpha} \quad (8)$$

324 where σ is the MAD of the N velocities used to compute the median velocity,
 325 t_{95} the 95% confidence interval, i.e the difference between the 97.5th quantile
 326 and the 2.5th quantile of the final velocity distribution, and k and α parameters
 327 to be determined. Applying a logarithm to this equation, we obtain a linear
 328 relationship :

$$\log\left(\frac{t_{95}}{\sigma}\right) = p_0 + p_1 \log(N) \quad (9)$$

329 We propose to compute the 95% confidence interval in the stable areas,
 330 where the true velocity is know to be null, for each value of N . The relationship
 331 between t_{95} , σ and N is then fitted to equation 9 using a Least-square regression.
 332 This relationship is extrapolated to glacier areas to compute the 95% confidence
 333 interval of each component of the final velocity.

334 **3. Results**

335 *3.1. Data set*

336 We assess the ability of the processing strategy to produce glacier annual
 337 velocity fields over a large region. We thus process all Landsat pairs available
 338 between 1999 and 2001 over the Pamir-Karakoram-Himalaya (PKH) extend-
 339 ing over 3000km. As mentionned earlier, we process all pairs of images with
 340 a time span in the list 368-16, 368, 368+16, 736-16, 736 and 736+16 days. It
 341 represents 1382 images, 1536 pairs, covering 68 Landsat frames. The location
 342 of the studied region and the processed frames is shown in Figure 5. We use

Table 1: Selected test pairs for the choice of the preprocessing and feature-tracking parameters

Area	Path/Row	Sensor	First date	Second date	image 1	Image 2
Karakoram	148/35	LE7	25/02/2000	27/02/2001	LE71480352000056SGS01	LE71480352001058SGS00
Everest	140/41	LE7	30/10/2000	17/10/2001	LE71400412000304SGS00	LE71400412001290SGS00
Kunlun Shan	145/35	LT5	10/08/2007	15/08/2009	LT51450352007222IKR00	LT51450352009227KHC00

343 the Level 1T images, which are already terrain corrected using ground con-
344 trol points (GCPs) and Digital Elevation Models (DEMs) and available at no
345 cost on the USGS website in GeoTIFF format in UTM projection. We down-
346 loaded the images using the Bulk Download Application available on the USGS
347 website (<https://lta.cr.usgs.gov/BulkDownloadApplication>) that allows
348 downloading a large set of images at once. Each image is roughly 8000x7000
349 pixels (or 16000x14000 for the panchromatic) and each scene is over 600MB in
350 size. The processing of a pair takes approximately 15 minutes on an 8 cores
351 desktop computer and the entire processing took 16 days.

352 3.2. Parameters setting

353 Because it would be time-consuming to define specific parameters for each
354 of the available pairs, a few representative test pairs with a low cloud cover
355 and good contrast have been selected to set the parameters that will be applied
356 to all scenes. We selected three test pairs that are representative of different
357 glaciers types in the PKH (Table 1). A first frame covering a large part of the
358 Karakoram, north-west of the Himalaya is selected because it hosts some of
359 the largest mountain glaciers. The second frame covers the Everest region that
360 features smaller glaciers with an important debris cover which is an interesting
361 property for feature tracking. The last frame over the Kunlun Shan features
362 mostly clean-ice glaciers. Two different sensors, LE7 and LT5 have also been
363 selected to account for possible differences.

364 3.2.1. Feature-tracking parameters

365 The most critical parameter for the feature-tracking is the size of the ref-
366 erence window γ_r . Figure 3 shows the MAD in stable areas as a function of

367 the reference window size for the three test pairs and a SNR threshold of 5.
 368 It clearly shows that for values of γ_r below 12, the measured offsets are noisy,
 369 which is likely due to the small window size. Choosing higher values of γ_r would
 370 reduce the noise even more, but it would also decrease the resolution of the re-
 371 sults and increase the risk of deformation within the reference window, which is
 372 not desirable.

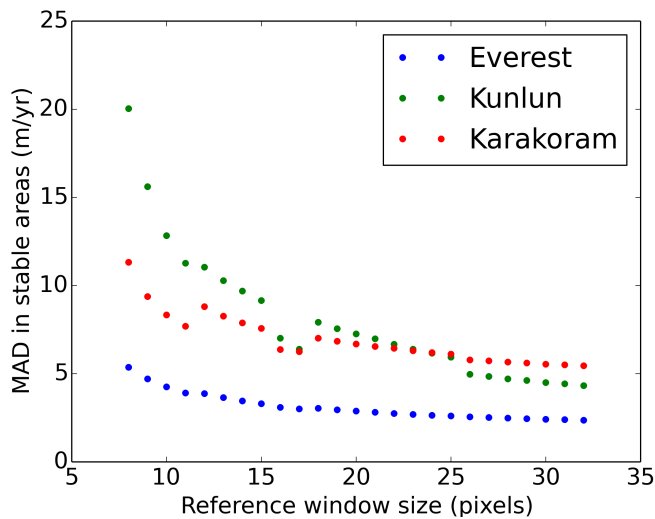


Figure 3: MAD of the velocity in stable areas as a function of the reference window size γ_r for the three test pairs and a SNR threshold of 5

373 We thus set the reference window to 16x16 pixels (480mx480m) that ap-
 374 proches a minimum in MAD while not being excessively large. Although not
 375 necessary, using a power of 2 optimizes the computation of the feature-tracking
 376 algorithm in Fourier domain. The search window is set to allow tracking dis-
 377 placements that are below 300m/year, which is the case for most of the studied
 378 glaciers with the exception of the surging glaciers (Quincey et al., 2011). So
 379 it varies from 30 to 48 pixels depending on the pair time span. Images time
 380 span and search window are tuned to maximize precision and long-term trend,
 381 for study aimed at the study of glaciers with rapidly changing dynamics (e.g.

382 surging glaciers,) these parameters can be adapted; e.g. the inclusion of pairs
383 with shorter time span or larger search windows. We set the spacing between 2
384 correlation patches to half the reference window, so 8 pixels.

385 *3.2.2. Band selection*

386 We select the best band or band combination following the method described
387 in Section 2.2, for the three test pairs. The success rate for each pair and band
388 1 to 5 (and panchromatic when available) are shown in Table 2, upper part,
389 for a SNR threshold of 5. We observe that the visible bands 1 to 3 have low
390 performance, this is due to saturation on snow and clean-ice. Then, band 5
391 gives the best results for the Everest and Karakoram region whereas band 4
392 is more interesting for the Kunlun region. The panchromatic band has better
393 performances than the bands 1 to 3 but is still very saturated and doesn't give
394 the best results on snow and ice. This ranking is not affected by the choice
395 of the SNR threshold. This difference comes from differences in glaciers types.
396 The Kunlun scene contains essentially clean-ice glaciers, which have a very low
397 and almost uniform signal in band 5 (mid-infrared) and explain the poor per-
398 formance for this band. On the contrary, the Everest and Karakoram regions
399 contain many debris-covered glaciers which have a more homogenous response
400 between all bands, but band 5 has a higher contrast in accumulation zones. In
401 summary, band 5 has overall best performance in the accumulation areas where
402 all others are saturated, except in shadows and over clean-ice where band 5 cap-
403 tures a very low signal (Figure 2). In those areas, band 4 has a higher contrast,
404 thus band 4 and 5 seem to be complementary.

405

406 We then perform the same tests for the first component of different PCA
407 combinations : the 1-5 combination that is used by Scambos et al. (1992) or
408 Berthier et al. (2003), a combination that excludes band 5 and a combination
409 of only bands 4-5. Results are shown in table 2 lower part.

410

411 They show that the combination of bands 4-5 has the best performance in

Table 2: Success rate of the feature-tracking over glaciers for each individual Landsat band (upper part) or different PCA combinations and component (lower part). The best value for each column is highlighted in bold. For the 15m band 8, the reference window has been set to 16x16 and 32x32 pixels to keep an identical window size in pixels and meters respectively.

	Everest	Karakoram	Kunlun
Band 1	8	7	4
Band 2	10	13	10
Band 3	9	8	8
Band 4	24	9	15
Band 5	42	40	9
Band 8 (r16)	19	14	
Band 8 (r32)	25	17	
1,2,3,4,5	37	48	15
1,2,3,4	24	14	15
4,5	44	48	15

412 all regions and it consistently performs better than any of the single bands. It
413 seems to profit from the complementarity of bands 4 and 5. This is not the case
414 for the PCA(1,2,3,4,5) that has sometimes worse performances than the best
415 band, as for example the Everest pair. So this band combination is not the best
416 choice for studying mountain glaciers of different cover types. The results for
417 PCA(1,2,3,4) confirm that band 5 brings valuable information and shouldn't be
418 excluded. In fact, it is the only band that differs significantly from all others
419 on snow and ice and allows to increase the variance of the PCA. Again, these
420 are robust conclusions for different choices of the SNR threshold (we tested 3,
421 5 and 7).

422 In conclusion, the first component of PCA(4,5) is the band combination that
423 has the most robust performance over mountain glaciers.

424 3.2.3. SNR threshold

425 Once the feature-tracking parameters and the preprocessing steps are chosen,
426 we can run the feature-tracking for each available pair to compute velocity
427 fields and an associated SNR. These intermediate results allow us to set the
428 SNR threshold used to remove residuals. Figure 4 shows the MAD in stable
429 areas for each component of the velocity and the success rate for different SNR
430 thresholds for all processed pairs. Low values of SNR mean that the reference
431 and matching window don't match and the associated offsets are very noisy. But
432 it is interesting to note that the MAD drops suddenly for SNR threshold higher
433 than 3 and reaches an asymptot. The value of the asymptot represents the
434 mean residuals for single pairs velocities, here it is in the range of $1 - 2m/year$
435 and is slightly different for the x and y component. They are due to remaining
436 orthorectification errors but thanks to the coregistration step they are reduced
437 compared to estimated uncertainty in Landsat image to image registration (Lee
438 et al., 2004; Storey and Choate, 2004). The success rate drops in the same way
439 but continues to decrease for higher SNR threshold. Thus, we choose an SNR
440 threshold of 4 that allows to substantially filter outliers while not removing too
441 many interesting points.

442 3.2.4. Fusion

443 The individual velocity fields are then merged together using a median filter.
444 The median velocity of each component is computed within all velocity fields
445 and a spatial neighborhood. Because the Landsat frames over this large region
446 are projected on different UTM zones, the median velocity is computed on a
447 240m Lambert conformal conic grid. Each velocity estimate within a radius
448 of $\sqrt{2} \times 240 = 340m$ is then included in the median, which means up to the
449 nine closest neighbors are retained. Finally, if the number of data points used
450 to compute the median is lower than $N_{min} = 5$, we discard the measurement
451 because the median is not robust enough.

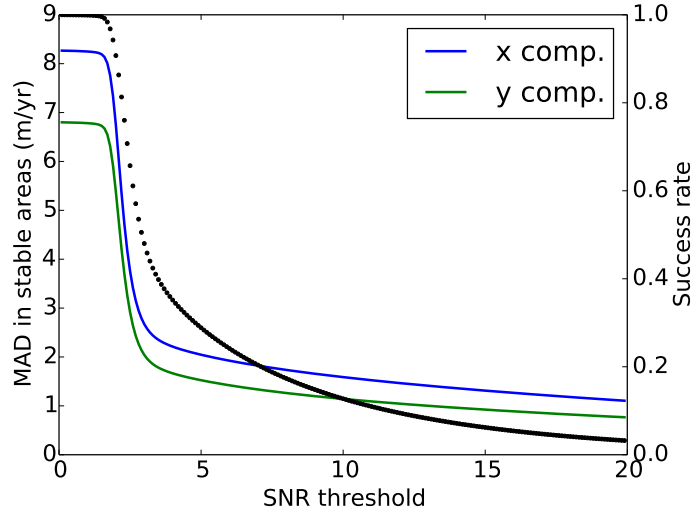


Figure 4: MAD of each component of the velocity in stable areas (plain lines) and success rate (black dots) for different SNR thresholds

452 3.3. Final velocity fields

453 The final velocity estimated for the PKH and year 2000 (period 1999-2001)
 454 is presented in Figure 5 for several subregions. A velocity has been estimated
 455 for $76000km^2$ or 92% of the total glacierized areas within this region. Main
 456 gaps (red patches) correspond to the accumulation zones with low texture and
 457 specific glaciers flowing faster than $300m/year$, especially in the Karakoram.
 458 The pattern of the velocity fields are in good agreement with previous works,
 459 in particular Copland et al. (2009), Heid and Käab (2012a) and Rankl et al.
 460 (2014) in the Karakoram (insert b), Quincey et al. (2009b) and Scherler et al.
 461 (2011b) in the Everest region (insert d), Käab (2005) in Bhutan (insert e).

462 4. Discussion

463 4.1. Contribution of the fusion versus single pairs

464 In this section, we assess the performance of the processing of the complete
 465 archive compared to the results of single pairs for the frame 148/35 (East

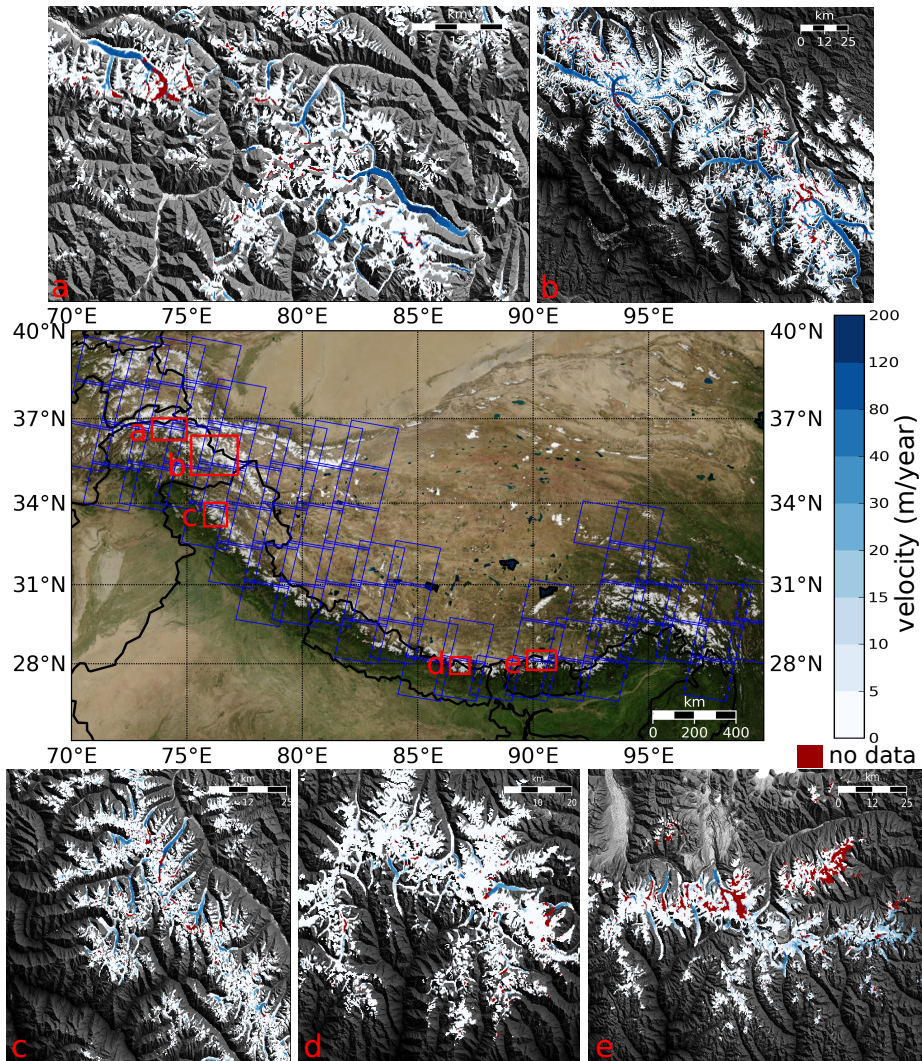


Figure 5: Map of the studied region : blue polygons show processed landsat frames, red squares highlight the position of the inserts a to e (a: Hindu-Kush, b : Karakoram, c : Jammu-Kashmir, d : Everest, e : Bhutan). Inserts show annual glacier velocity fields for year 2000 within the RGI masks (blue colorscale). Red points are region without velocity estimate.

466 Karakoram) and year 2000 (pairs within the period 1999-2001). The data set
 467 is 26 images and 29 pairs. Figure 6 represents the effect of each step of the

468 postprocessing for a velocity profile along the Baltoro glacier. The raw velocity
 469 fields (in grey) contain many aberrant values due to clouds and shadows in the
 470 images that need to be filtered out. Applying an SNR threshold of 4 removes
 471 most of them, but some outliers still remain and it does not ensure that the
 472 displacements are physically acceptable. By including more information, the
 473 spatio-temporal filtering method has several advantages : it efficiently removes
 474 outliers, it fills most gaps that may appear and gives a robust single value for
 475 each location.

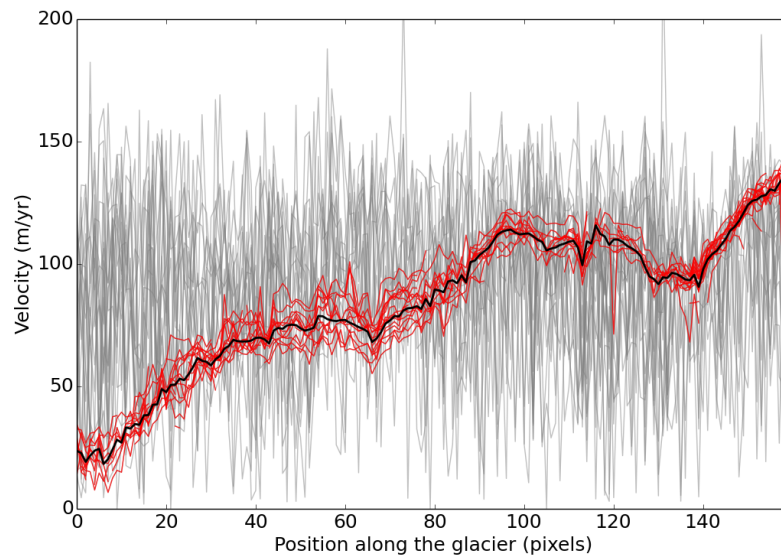


Figure 6: Velocity profiles along the Baltoro glacier (3542'29"N, 7623'21"E) for the 29 available pairs for years 1999 to 2001: unfiltered (grey), after selecting values with an SNR higher than 4 (red) and applying the spatio-temporal median (black).

476 More quantitatively, figure 7 (left) shows the success rate for each single
 477 pair and the fusion. The best single pair or optimum pair (i.e the pair with the
 478 highest success rate) allows an estimate of the velocity of 71% of the glacierized
 479 regions, main gaps are due to saturation in accumulation areas. Meanwhile, the
 480 result of the fusion returns a velocity estimate for 94% of the points. The fu-

481 sion outperforms all individual pairs by exploiting the complementarity between
 482 different pairs.

483 Figure 7 (right) shows the MAD in stable areas for each pair individually
 484 and for the result of the fusion. The MAD for the optimum pair is $5.5m/yr$
 485 and the mean MAD for all single pairs $5.4m/yr$, mainly due to orthorectification
 486 errors. The fusion has the advantage of reducing this noise that is not correlated
 487 between successive pairs. As a consequence, the MAD for the fusion is $1.4m/yr$,
 488 gaining a factor of almost 4 on the optimum pair.

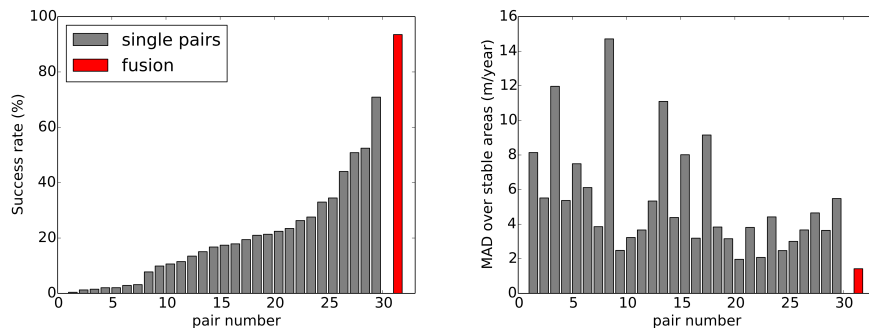


Figure 7: Left : Success rate for each individual pair, in ascending order and for the result of the fusion (red). Right : MAD in stable areas for same pairs in same order.

489 4.2. Uncertainties

490 In this section we show how the fusion approach allows to reduce the uncer-
 491 tainty of the final velocity fields with the example of the Karakoram subregion
 492 (74-78E, 34.5-37N). Figure 8 shows the dispersion of the single velocities around
 493 the median (cf Eq 6). It highlights the two main sources of uncertainties. The
 494 first source of uncertainty is coregistration errors that are visible in the shape
 495 of large rectangles displaying the contours of the Landsat frames or correlated
 496 with the topography. Despite the coregistration with the GLS images, the mean
 497 dispersion over stable areas is $4.1m/yr$. The second source of uncertainty is the
 498 variability in glacier flow over the three year period. Glaciers are clearly visi-
 499 ble on the figure in the shape of yellow or red tongues. In particular, a large

500 variability is observed on the central Rimo glacier (annotated with a *) of approx-
 501 imately 40m/yr . This is coherent with the reported surging behavior of this
 502 glacier during that period (Bhambri et al., 2013). The mean dispersion over
 503 glaciers is 6.4m/yr .

504

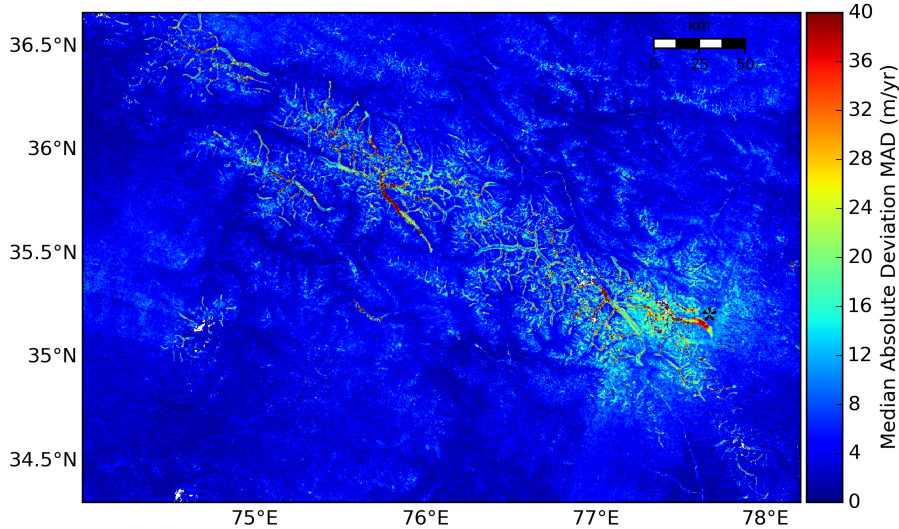


Figure 8: Dispersion of the velocities estimated from all pairs for the Karakoram and period 1999-2001

505 The uncertainty of the final velocity, i.e the median velocity, is impacted
 506 by the dispersion of the velocities but is reduced with an increasing number of
 507 observations. Figure 9 (left) shows the 95% confidence interval t_{95} of the final
 508 velocity in stable areas as a function of the number of points used to compute
 509 the median. When few velocity estimates are available, i.e the measurement
 510 is spatially isolated or very few pairs allows for a measurement, the residuals
 511 reach over 20m/yr but as the number of merged velocity estimates increases, the
 512 confidence in the measurements reaches a few m/yr . Figure 9 (right) shows the
 513 linear relationship between $\log(t_{95}/\sigma)$ and $\log(N)$. The relationship is strong
 514 except for N below 5 ($\log(N) \leq 0.7$). Actually, for a low number of samples, the
 515 median and MAD are more difficult to estimate and their distributions diverge

Table 3: Parameters for the linear regression between $\log(t_{95}/\sigma)$ and $\log(N)$

Component	α	k	R^2
x	0.44	4.0	0.94
y	0.46	4.1	0.94

516 from the normal distribution. For these values, our method underestimate the
 517 uncertainty and we recommend to remove these points. For $N \geq 5$, the param-
 518 eters of the regression are summarized in Table 3.

519

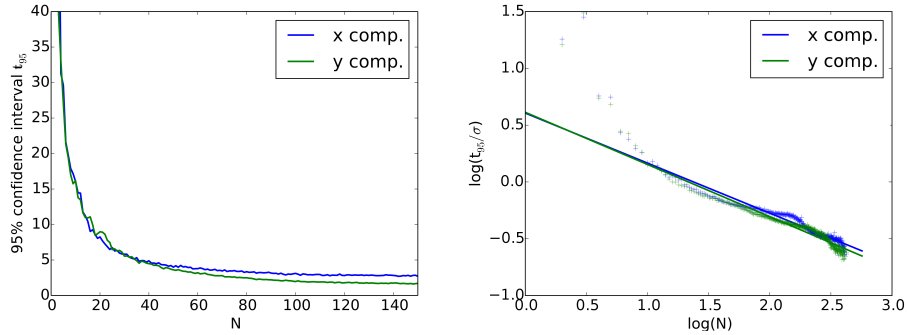


Figure 9: Residuals in stable areas as a function of the number of available velocity estimates for the Karakoram subregion

520 This allows us to compute a 95% confidence interval as a function of σ and
 521 N . Figure 10 shows the result for the Karakoram region. The uncertainty map
 522 has a similar shape as σ (Figure 8), but is weighted by N ; in particular, on
 523 stable grounds where there are generally more measurements (less problems of
 524 saturation), the uncertainty is reduced whereas in snow covered areas, the low
 525 contrast reduces the number of measurements and uncertainty remains relatively
 526 high. The median uncertainty is $2.0m/yr$ in stable areas. Over glaciers, the
 527 median uncertainty is $4.4m/yr$, from a few m/yr on some glaciers tongues to
 528 $10m/yr$ in some accumulation zones. The uncertainty is also higher on glaciers
 529 edges (as visible in the inset of Figure 10), due to higher strain rates and thus

530 a more variable velocity within the reference window. Some grid patterns are
 531 also visible : they are due to the fact that the UTM and Lambert conic grids
 532 are not superposed and the number of neighbors varies periodically.

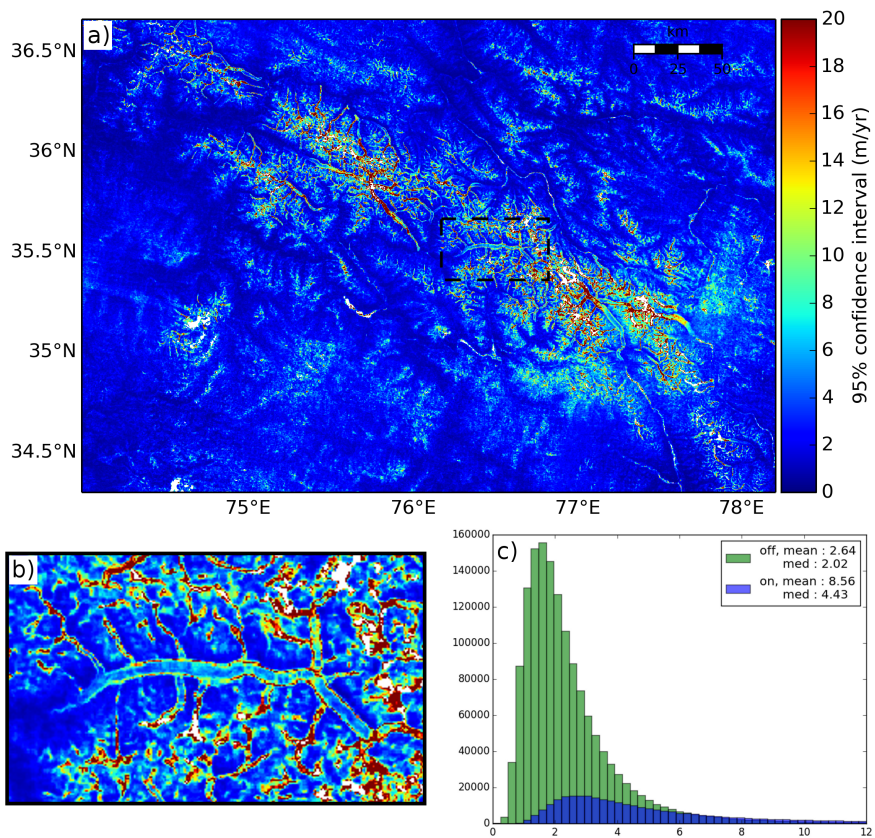


Figure 10: (a) Uncertainty of the final velocity for the Karakoram and period 1999-2001, (b) zoom over the Baltoro glacier (dash line), (c) histogram of the uncertainty on and off glacier

533 At last, the velocity vector coherence is illustrated in Figure 11 for the
 534 Karakoram region. Frame patterns or features correlated with topography re-
 535 main in stable areas and are indicative of coregistration errors. Nevertheless,
 536 the coherence is much higher on glaciers which mean that the merged velocity
 537 vectors are well aligned and that we can be confident in the direction of the

538 velocity field.

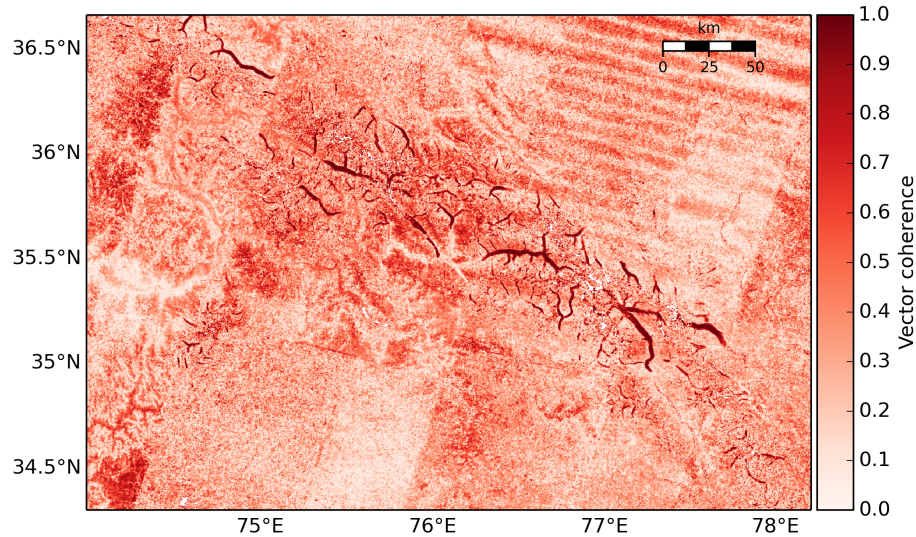


Figure 11: Velocity vector coherence for the Karakoram region. A value of 1 means perfect alignment of all the vectors contributing to the median velocity, 0 means completely random directions.

539 5. Conclusions

540 In this paper, we present a processing strategy to estimate mountain glacier
541 velocities from a complete satellite archive. We select all possible pairs for a spe-
542 cific time span, avoiding the lengthy task of manually selecting the best available
543 images. The pairs are then submitted to the same preprocessing steps and a
544 feature-tracking algorithm is performed to produce surface velocity fields. Suc-
545 cessful measurements are selected solely based on the quality of the correlation,
546 and merged together. First, the most aberrant displacement values are rejected
547 based on the confidence function returned by the feature-tracking algorithm; all
548 points below a certain threshold are removed. Secondly, the results are filtered
549 based on the spatial and temporal consistency of the displacement. A median
550 filter is applied to the resulting stack of velocities on a pixel by pixel basis within

551 a spatio-temporal neighborhood to obtain the final glacier velocity field.

552 This strategy has been applied to produce glacier annual velocity fields from
553 a data set of 1536 pairs of Landsat 5 and 7 images acquired within a 3 year period
554 and covering the Pamir-Karakoram-Himalaya region extending over 3000km.
555 Results on a single Landsat frame shows that the percentage of successful mea-
556 surements increases from 71% of glacierized area for the best available pair, to
557 94% for the merged results. In overall, it allows us to obtain a velocity estimate
558 for $76000km^2$ or 92% of the glacierized areas of this region. We then estimate
559 the impact of the coregistration errors and variability of glacier flow on the final
560 velocity over the Karakoram region (300x200km). The median 95% confidence
561 interval is reduced to $2.0m/yr$ in stable areas and $4.4m/yr$ over glaciers thanks
562 to the redundancy in the measurements.

563 The strategy has been applied to Landsat images but is flexible and could
564 easily be applied to various sensors with different pixel resolution or wavelength,
565 including radar. This would be particularly valuable for the upcoming Sentinel
566 1-2 missions of the European Space Agency that will provide repeated images of
567 the Earth surface. This strategy can also be applied to derive not only annual
568 but seasonal velocities using set of pairs with shorter time span. More complex
569 postprocessing strategy as for example time series inversion (Lanari et al., 2007)
570 to select the coherent displacements along the time serie could be implemented,
571 potentially allowing to derive the seasonal velocity variations.

572 The analysis of complete satellite archives open new perspectives for the
573 study of glacier's dynamic against physical parameters such as length, slope
574 and debris cover, for the study of glacier response to climate changes, glacial
575 geomorphology, erosion (Scherler et al., 2011a), glacial hazards (Bolch et al.,
576 2008) and the estimation of the contribution of surface mass balance and ice
577 fluxes to the observed glacier thinning/thickening (Berthier and Vincent, 2012).

578

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