Determination of glaciers’ velocity fields at the scale of the Himalayas from the Landsat archive

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Why do we study Himalayan glaciers?

Climate change and Sea Level Rise

→ Response time of a few decades ⇒ indicator of climate changes
→ Potential contribution to SLR: 0.41 m
→ 1st contributor to current SLR ⇒ 2100 (Meier et al. 2007)

Water needs:

→ 1.4 billion people depends on the water supply from 5 rivers sourcing in Himalaya
→ flow reductions could threaten 60 million people by 2065 (Immerzeel et al 2010)

Glacial Lakes Outburst Floods:

Halji village, western Nepal after a GLOF
Current knowledge

**Field campaign:**
- Long archive, ground truth
- Very sparse data

**Satellite altimetry:**
- Large spatial extent shows contrasting patterns
- Short time scale (since 2000)
Great lack of information on the Himalayan glaciers for different reasons:

- large extent: > 3000km
- geographical situation: high altitude, access difficult to glacial valleys
- geopolitical situation: Indian-Pakistani conflict in Karakoram, Chinese-Tibetan conflict

⇒ This is a task for Earth Observation satellites!

Measure velocity instead of mass balance:

- velocity is easier to measure from satellite data
- there is a link between ice flow and mass balance
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Glacier flow

→ SAR interferometry
→ Feature tracking from optical images or radar amplitude

Quincey et al., 2009
Copand et al., 2009

All previous studies focus on specific regions at small time scales.
No one take benefit of the large archive.
Objectives

→ Apply existing methods for the Landsat archive, at the scale of the mountain range (>3000km)
→ Take advantage of the longevity of Landsat missions to widen the time span up to 40 years
→ Try to understand the link between extent, mass balance and glacier flow

Challenges

→ Over 10 000 images : how to automatically extract the relevant data ?
→ Multi-spectral images : what is the best fusion of this multiple information ?
→ Redundant information : how to merge the results into a syntetical velocity field while preserving the variability of the phenomenon ?
Data

MSS : 4 bands (visible + NIR) at 60m resolution
TM : 6 bands (visible + IR) at 30m resolution
ETM+ : 6 bands (visible + IR) 30m + panchromatic 15m
Combine multibands information

Which one to use?
Principal Component Analysis of visible and IR bands = ETM+ bands 1-5? (Scambos et al, 1992; Berthier et al 2003)

Band 4 (0.76-0.90 \(\mu\)m) Fraction of good matches: 30%
Combine multibands information

⇒ Which one to use?
Principal Component Analysis of visible and IR bands = ETM+ bands 1-5? (Scambos et al, 1992; Berthier et al 2003)

Band 5 (1.55-1.75 μm)  Fraction of good matches: 34%
Combine multibands information

⇒ Which one to use?
Principal Component Analysis of visible and IR bands = ETM+ bands 1-5? (Scambos et al, 1992; Berthier et al 2003)

PCA 4-5

Fraction of good matches: 40%
Feature tracking algorithm

Oriented correlation (Fitch et al., 2002) ⇔ Correlation of the gradient orientation:

\[ Z = \begin{cases} 
\frac{g_x + ig_y}{\sqrt{g_x^2 + g_y^2}} & \text{if } g_x = g_y = 0 \\
0, & \text{otherwise}
\end{cases} \]

Similarity function:

\[ CO = \frac{1}{N} |\sum_{\Omega_r} Z_r Z_s^*| \]

where \( g_x, g_y \) are intensity gradients.

Interesting properties: illumination invariant, insensitive to NULL-stripes (LE7 after 2003)
How to merge the final result?

→ Landsat repeat cycle = 16 days
→ Glaciers velocity depends on the season ⇒ (bi-)annual pairs
⇒ Many pairs are available over a period of a few years ⇒ How to get rid of the wrong matches and take benefit of the redundant observations?
Data selection for each pair

A first selection of the matches based on the Signal-to-Noise Ratio

$$SNR = \frac{\text{maximum of similarity}}{\text{average similarity in search window}}$$
Data selection for each pair

A first selection of the matches based on the Signal-to-Noise Ratio

\[ SNR = \frac{\text{maximum of similarity}}{\text{average similarity in search window}} \]

\[ SNR \geq 5 \]
Fusion

Hypothesis:

\[\rightarrow \text{velocity does not vary quickly from year to year}\]

\[\rightarrow \text{velocity does not vary much in a local neighborhood}\]

\[\Rightarrow \text{We compute the marginal median both in a local temporal and spatial neighborhood}\]

Practically: All annual and bi-annual pairs within a period of 3 years \([T-1;T+1], [T-1;T], [T;T+1]\) and within a 3x3 grid cell

More sophisticated approaches could be investigated:

\[\rightarrow \text{2D median}\]

\[\rightarrow \text{weighted average}\]

\[\rightarrow \text{adaptative neighborhood}\]
Final velocity after selection and fusion for period 2000-2002 (29 pairs)
Introduction

Method

Performance assessment

Conclusion

Comparison individual pairs - fusion
Uncertainties
Comparison with high resolution images
Comparison individual pairs - fusion

Efficiency over glacierized regions

Residuals over stable grounds

Amaury Dehecq
Dynamic of Himalayan Glaciers - Journée ISIS 10/04/2014
→ frequent instrumental or orthorectification errors in the images ⇒ Not coherent artefacts in the estimated single velocity fields

→ the median removes most of this artefacts and allows to reach the theoretical precision of the algorithm of 1/20 pixel
Variability of the velocity?

\[
\sigma(p, q) = \sqrt{\frac{\sum_{t \in T} (V_x(p, q, t) - \bar{V}_x(p, q))^2 + (V_y(p, q, t) - \bar{V}_y(p, q))^2}{M}}
\]
Variability of the velocity?

- Equal performance over rocks and ice
- Uncertainty is dominated by instrumental errors ≠ natural variability
Vector coherence

\[ \text{align}(p, q) = \frac{\| \sum_{t \in T} \vec{V}(p, q, t) \|}{\sum_{t \in T} \| \vec{V}_t(p, q, t) \|} \]
Question: would it be possible to compare or to merge results obtained from images with different resolution?

Comparison Landsat - SPOT over the Mer de Glace (2000-2001)
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Landsat (20 pairs)
Ref window: 16x16 pix = 480x480m
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Comparison Landsat - SPOT over the Mer de Glace (2000-2001)

Landsat (20 pairs)  
Ref window: 16x16 pix  
= 480x480m

SPOT (1 pair)  
Ref window: 16x16 pix  
= 160x160m
Question: would it be possible to compare or to merge results obtained from images with different resolution?

Comparison Landsat - SPOT over the Mer de Glace (2000-2001)

- Landsat (20 pairs)
  - Ref window: 16x16 pix
  - = 480x480 m

- SPOT (1 pair)
  - Ref window: 16x16 pix
  - = 160x160 m

- SPOT at 30m
  - Ref window: 16x16 pix
  - = 480x480 m

⇒ Measured velocity coherent with the size of the reference window
Question: would it be possible to compare or merge results obtained from images with different resolution?

Comparison Landsat - SPOT over the Mer de Glace

Difference: SPOT 30m - average(SPOT 10m, 480m)
We proposed an automatic way of processing large multi-band satellite archive to measure velocities that:

- combine multiple bands information to enhance glacier features thus allowing a better estimate of the velocity
- extract the relevant data while removing useless information (clouds, saturation...) and artefacts (orthorectification errors)
- apply fusion of redundant information into a single, more confident value allowing a more exhaustive estimate of the velocity field

Some challenges still need to be tackled:

- combine information from bands with different resolutions
- adaptative reference window for smaller glaciers
- correct orthorectification errors instead of filtering them out
Any questions/suggestions?