Monitoring Earth Surface Dynamics with Optical Imagery

Sébastien Leprince[(1)], François Ayoub[(1)], Pablo Musé[(1)], Etienne Berthier[(2)], Christophe Delacourt[(3)], and Jean-Philippe Avouac[(1)]

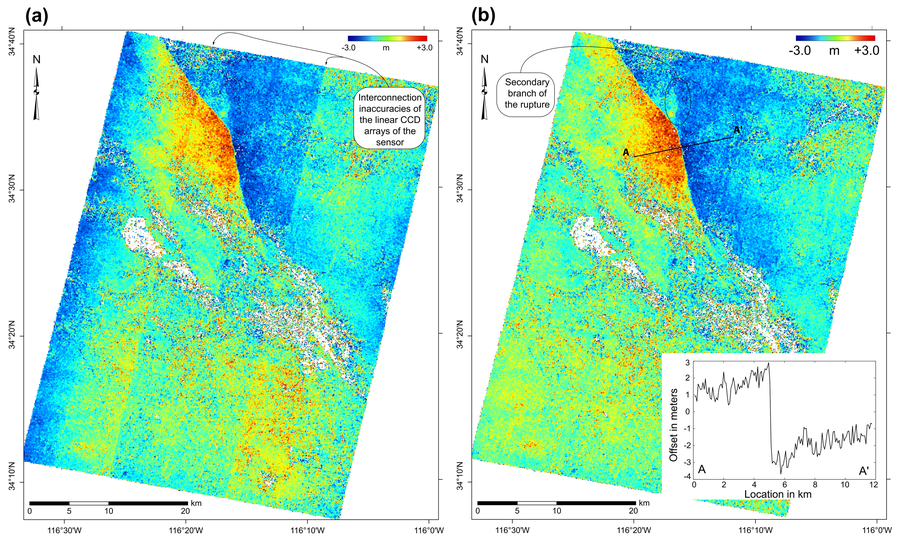
(1) California Institute of Technology, Pasadena, CA 91125, USA, Email: ***leprincs@caltech.edu***

(2) CNRS-LEGOS, 14 av. Ed. Belin, 31400 Toulouse, France

(3) Domaines Océaniques, IUEM, Université de Bretagne Occidentale, Plouzané, France

Despite the increasing availability of high quality optical satellite images, continuous monitoring of Earth's surface changes is still of limited use due to technical limitations. To overcome these limitations, we propose a processing chain, the Co-registration of Optically Sensed Images and Correlation (COSI-Corr), to accurately orthorectify and coregister sets of pushbroom images, which, associated with a precise correlation technique, allows for the measurement of ground deformations with accuracy on the order of 1/20 of the pixel size. Applications related to earthquake ground deformations, ice flow, and landslides, are presented.

The 1999, Mw 7.1 Hector Mine earthquake, California

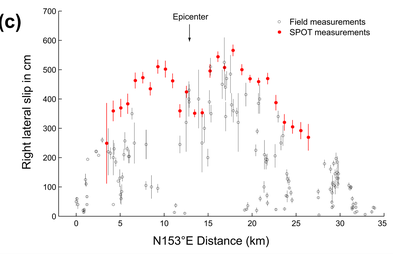


North-South component (northward positive) of the coseismic displacement field due to the 1999 Hector Mine earthquake, California. The pre-earthquake image is a 10m SPOT 4 acquisition from 08/17/1998, and the post-earthquake image is a 10m SPOT 2 acquisition from 08/10/2000.

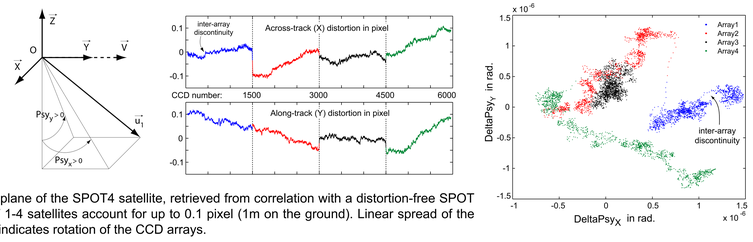
(a) Linear Artifacts due to CCD misalignement are clearly visible in the satellite along-track direction

(b) After CCD calibration, artifacts are not visible anymore. It is found that the four CCD arrays of the SPOT 1-4 satellites are misaligned and rotated in the focal plane (see below)

(c) Comparison of the right lateral slip from ground survey and from this remote sensing study. Our results measure the envelop of the slip distribution along the fault, showing areas where the distributed slip could not be measured, although it has been acknowledged, during field survey.



CCD Distortion Calibration for Pushbrrom Satellites



Residuals in CCD position in the focal plane of the SPOT4 satellite, retrieved from correlation with a distortion-free SPOT 5 image. CCD distortions of the SPOT 1-4 satellites account for up to 0.1 pixel (1m on the ground). Linear spread of the CCD pointing errors in the polar plane indicates rotation of the CCD arrays.

References:

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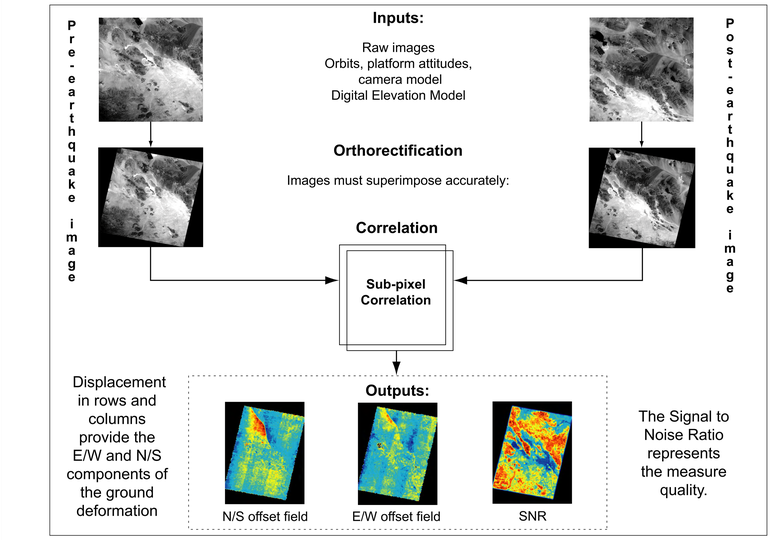
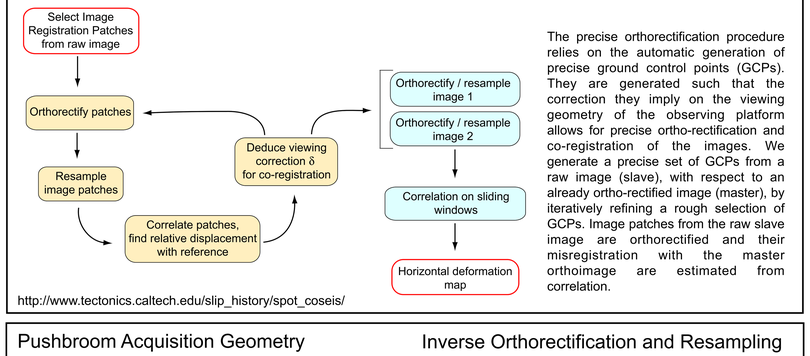
The COSI-Corr Flow Chart and Methodology

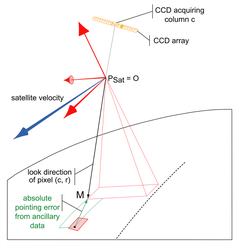




http://www.tectonics.caltech.edu/slip_history/spot_coseis/

The precise orthorectification procedure relies on the automatic generation of precise ground control points (GCPs). They are generated such that the correction they imply on the viewing geometry of the observing platform allows for precise ortho-rectification and co-registration of the images. We generate a precise set of GCPs from a raw image (slave), with respect to an already ortho-rectified image (master), by iteratively refining a rough selection of GCPs. Image patches from the raw slave image are orthorectified and their misregistration with the master orthoimage are estimated from correlation.

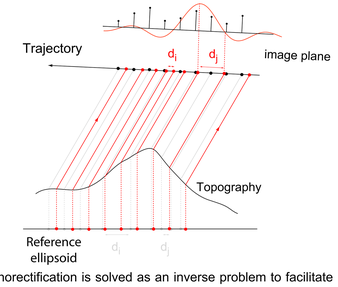
Pushbroom Acquisition Geometry



- O, optical center in space
- M, ground point seen by pixel p
- $\vec{u}_1$ pixel pointing model
- $R(p)$ 3D rotation matrix, roll, pitch, yaw at p
- $T(p)$ Terrestrial coordinates conversion
- $\vec{\delta}$ correction on the look directions to insure coregistration
- $\lambda > 0$

$$M(p) = O(p) + \lambda\left[T(p)R(p)\vec{u}_1(p) + \vec{\delta}(p)\right]$$

Inverse Orthorectification and Resampling



Orthorectification is solved as an inverse problem to facilitate rigorous resampling of the raw image and to avoid introduction of aliasing.

Image Correlation

- Fourier Shift Theorem

$$i_2(x,y) = i_1(x-\Delta_x, y-\Delta_y)$$
$$I_2(\omega_x,\omega_y) = I_1(\omega_x,\omega_y)e^{-j(\omega_x\Delta_x+\omega_y\Delta_y)}$$

- Normalized Cross-spectrum

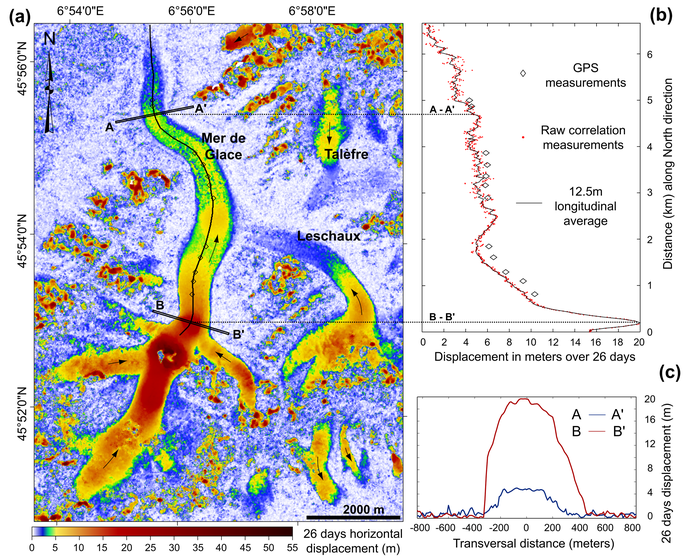
$$C_{i_1 i_2}(\omega_x,\omega_y) = \frac{I_1(\omega_x,\omega_y)I_2^*(\omega_x,\omega_y)}{|I_1(\omega_x,\omega_y)I_2^*(\omega_x,\omega_y)|} = e^{j(\omega_x\Delta_x+\omega_y\Delta_y)}$$

- Finding the relative displacement

$$\phi(\Delta_x,\Delta_y) = \sum_{\omega_x=-\pi}^{\pi}\sum_{\omega_y=-\pi}^{\pi} W(\omega_x,\omega_y)|C_{i_1 i_2}(\omega_x,\omega_y) - e^{j(\omega_x\Delta_x+\omega_y\Delta_y)}|^2$$

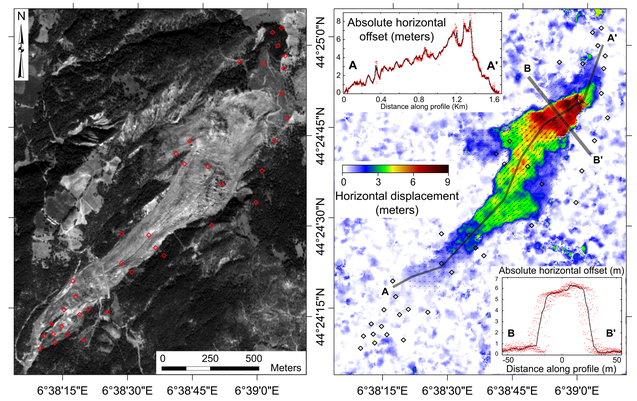
W weighting matrix. (Δ_x,Δ_y) such that ϕ minimum.

Ice-flow monitoring using SPOT5: the Mer de Glace glacier



(a) Amplitude of horizontal displacement over the Mer de Glace area from 08/23/2003 to 09/18/2003, from two 2.5m SPOT 5 images. Displacements below 2.5m appear in blue to highlight the subpixel capabilities and the low noise level of the measurements. Displacements as high as 55m (about 800 m/yr) are recorded over this 26-day period.
(b) Displacements along a central flow line of the Mer de Glace measured from SPOT5 images and from GPS campaign. The time period covered by the GPS (08/12/2003 to 09/03/2003) starts slightly earlier in the summer and includes the August 2003 European heat wave, explaining the faster velocities observed over this period.
(c) Displacement along transverse profiles AA' and BB'. No topography or baseline artifacts are noticed.

La Valette landslide (French Alps) monitoring using SPOT5



(left) Orthorectified SPOT image of the La Valette landslide. The red diamonds show the geodetic benchmarks for field survey.
(right) Absolute horizontal displacement and displacement vectors as imaged from the correlation of two 2.5m SPOT 5 images acquired on 09/19/2003 and 08/22/2004. The black diamonds indicate the geodetic benchmarks. The displacement field revealed from the correlation would have been unnoticed in the geodetic measurements.