Monitoring Earth Surface Dynamics With Optical Imagery

The increasing availability of high-quality optical satellite images should allow, in principle, continuous monitoring of Earth’s surface changes due to geologic processes, climate change, or anthropic activity. For instance, sequential optical images have been used to measure displacements at Earth’s surface due to coseismic ground deformation [e.g., van Poppelbeek et al., 2010], ice flow [Scambos et al., 1992, Berthier et al., 1991], and landslides [Kääb, 2012; Delacourt et al., 2004].

Surface changes related to agriculture, deforestation, urbanization, and erosion—which do not involve ground displacements—might also be monitored, provided that the images can be registered with sufficient accuracy. Although the approach is simple in principle, its use is still limited, mainly because of geometric distortions of the images induced by the imaging system, biased correlation techniques, and implementation difficulties.

These obstacles have been overcome through recent methodological advances and the development of a user-friendly software package called Co-Registration Of Optically-Sensed Images and Correlation (COSI-Corr) [Leprince et al., 2007]. The software makes it possible to coregister images and to measure surface displacements with unprecedented ease and accuracy. This article describes some applications of the technique and pinpoints some key thematic questions that can benefit from this approach.

Increase of Data Set Availability

The application of the technique depends primarily on the availability of high-quality optical images, for which there exist considerable archived data to mine. Aerial surveys by the U.S. Geological Survey have covered the United States since the 1950s, the Institut Géographique National has surveyed the French territory since the 1930s, and similar archives exist around the world. Multiple satellite programs have delivered worldwide coverage such as Landsat since 1972, SPOT since 1986, and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrument, on board the NASA satellite Terra, since 1999. Many high-resolution satellite programs have been launched more recently, including IKONOS, QuickBird, WorldView, EOS-1, and FORMOSAT.

Images acquired by these programs have been essential in assessing temporal changes induced by large-scale natural disasters like earthquakes, tsunamis, floods, and volcanic eruptions. Such images are particularly crucial in detecting temporal changes between series of images, possibly acquired by different instruments and at different resolutions, remains a considerable challenge.

COSI-Corr Software Package

The COSI-Corr software package allows for automatic and precise orthorectification, coregistration, and subpixel correlation of satellite and aerial images [Leprince et al., 2007]. The procedure does not require external information such as GPS measurements of ground control points, and it is based solely on topographic knowledge and on the ancillary data provided with the observing platform.

In particular, the software package takes advantage of the availability of accurate digital elevation models with global coverage ( Shuttle Radar Topography Mission - SRTM, 4-arc-second resolution). COSI-Corr makes it possible to measure local displacements between temporal series of images, possibly acquired by different instruments and at different resolutions, with measurement accuracy of the order of a small fraction of the nominal images’ resolution. A plugin for Environment for Visualizing Images (ENVI) registered on Google Earth, COSI-Corr is freely available from the California Institute of Technology’s Tectonics Observatory (http://www.tectonics.caltech.edu).

Coseismic Deformation

Coseismic deformation is generally studied through field surveys of surface ruptures or geodetic or interferometric synthetic aperture radar (InSAR) measurements. However, even these techniques often fail to provide detailed maps of the near-field surface strain, which may consist of a complex of surface ruptures and cracks with a fault zone of finite width. Consequently, InSAR and field measurements are not efficient approaches to estimating the total slip across a fault zone and its along-strike variability.

The distribution of slip, which is critical to understanding earthquake dynamics and the damaging near-field seismic waves, might be best assessed from cross-correlating optical images. Optical-image correlation has proven to be efficient in mapping fault ruptures and in measuring both the fault-parallel and fault-perpendicular components of coseismic displacements [Hooke et al., 2006]. Several studies indicate success in correlating images in the same season and with nearly equal incidence views [e.g., van Poppelbeek et al., 2008; Dominguez et al., 2009].

COSI-Corr now allows the processing of images acquired sequentially by correlating them with different incidence views, considerably broadening the technique’s potential. Figure 1a shows one component of the coseismic-displacement field induced by the 1995 M7.1 Hector Mine earthquake, California, measured by correlating a 10-meter SPOT 4 image with a 15-meter ASTER image. Although the deformation field is not as well resolved as the one measured by correlating two SPOT images with 10-meter resolution [Leprince et al., 2007], the fault trace is effortlessly delineated and the fault slip vectors can be measured and the displacement discontinuities. A secondary branch of the rupture that accounts for a right-lateral displacement of about 1 meter is also visible. This example also demonstrates the subpixel capabilities of COSI-Corr. Even with images from different sensors, uncertainties on the fault slip measurements are very low, 0.15 meter to 0.8 meter.

Ice Flow

In the current climatic context, monitoring continental ice and better understanding glacier dynamics are crucial. Rignot and Scambos [2006] recently detected that the rapid increase in ice velocities is the major cause of mass reduction of polar ice sheets, but the seasonal and interannual variability of glacier flow remains poorly known. Cross-correlation of optical images can address these issues [Kääb, 2012; Berthier et al., 2005].

Figures 1b, 1c, and 1d show horizontal displacements in the Mer de Glace area (Alps) over 26 days (23 August to 18 September 2003), derived from 2.5-meter-resolution SPOT 5 images. Our study reveals details of the ice velocity field with exceptional accuracy. Very few areas of decorrelation are observed, and when such areas are present, they result mainly from changes in length and orientation of mountain shadows between the two dates. Around the main glaciers, many small, disconnected regions (subkilometric size) have measurable motion. This complete and homogeneous ice flow field measured with COSI-Corr is valuable to validating and calibrating ice flow models, which can then be used to predict the fate of mountain glaciers and ice sheets under global warming scenarios.

"Slow" Landsliding

The mechanics of slowly moving landslides, a common phenomenon in mountainous areas, also remains poorly understood. The dynamics are complex and highly sensitive to climatic factors [Middle et al., 2007], making it difficult to assess how slow landslides evolve with time. Conventional geodetic measurements (tacheometry, leveling, kinematic GPS) are commonly used to monitor the temporal evolution of landslides, but they cannot capture the spatial heterogeneities of mass movement, which may be best assessed with multitemporal images.

Figures 2a and 2b show cumulative horizontal displacement over about 11 months, measured from the subpixel correlation of two 2.5-meter-resolution SPOT 5 images. This displacement field is consistent with InSAR measurements [Squarzoni et al., 2013], but it provides a better spatial resolution. Interestingly, the velocity field does not coincide with the geomorphic expression of the landslide and is highly heterogeneous. A network of benchmarks had been installed for repeated geodetic measurements. Although the targets were correctly placed according to the morphology of the landslide, they missed the most active areas. These areas were revealed by our technique and may otherwise have remained undetected.

A Technique Ready for Operational Use

Investigating and monitoring Earth’s surface evolution through coregistration and...
correlation of multitemporal and multisensor imagery is promising, especially given the existing archives of satellite and aerial imagery systems, and their improving resolution. The COSI-Corr methodology correctly points in the direction of both push-broom satellites and aerial imagery to achieve accurate subpixel coregistration. In addition, the subpixel correlation of precisely co-registered images allows for the accurate extraction of horizontal displacements between multitemporal images.

The accuracy of the technique may be limited by the following: availability of accurate digital elevation models, especially in urban areas; the quality of ancillary data provided with the images (altitude records should be well-sampled); radiometric noise, sensor saturation, and aliasing; shadow length and orientation differences between multitemporal images; snow, cloud or vegetation cover; or man-made changes such as new buildings.

Despite these limitations, COSI-Corr is an efficient and versatile tool for investigating a variety of geophysical and seismic-morfotectonic processes such as faulting, the mechanics of ice flow and the effects of climate, and landslides. This approach has myriad potential applications. For instance, it has also been used to accurately measure sand dune migration. Correlation of optical images is a valuable contribution to understanding the displacements at Earth’s surface where it directly provides the two components of the horizontal displacement field, it is more robust against decorrelation, and it does not saturate with high areas.

Furthermore, because COSI-Corr also allows for accurate coregistration of multispectral bands, applications that require high-quality band-to-band coregistration, such as vegetation monitoring, also can be investigated.

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References


The 1634 eruption was only partially known to describe the ongoing eruption, providing significant and continuous exposure to scientific elements to two-rate, and also previously unknown, accompanying written reports. In addition, the maps attest to the period of the time location from Catania and other villages around Mount Etna, a large concave area where lava accumulated. The report only describes four of the seven flows stem directly from the active crater. A further description of tephra and the volcanic lava, which no one has investigated, is included close to the active crater. Along with the report, there is a drawing with a map of the area around the Etna, in a somewhat elementary watercolor drawing, lava is red, the ground is ocher, and the then perennial snow zone—which is now sporadic—is white. Seven locations are described with a black dot, but only four toponyms are reported.

The report only describes four of the seven lava flows portrayed in the drawing, and the map and toponomy are different from each other with different information. The report notes that only one flow emerged from the crater and that this flow reached as far as the Piano della Rosselle (Rosselle Plain). This is a very important area where lava accumulated for several days because the path to the south and to Catania was blocked by a hill called Salto del Cane (Donkey’s Leap). All of the secondary branches of lava flow from the report are thought to have originated from this hill. In the painting, however, some of the former flows stem directly from the crater that had opened. The easternmost flow stretched as far as the territory of Acireale, southeast of Mount Etna; this volcano had been known in volcanic literature. In the map, Etna is represented from a Riccian perspective. The volcano’s surface is projected approximately on the flat surface.

The Most Ancient Maps of Erupting Mount Etna

Mount Etna, in eastern Sicily, Italy, is an active volcano whose slopes are the city of Catania and adjacent towns. The volcanic eruptions are noted in written sources dating back to the thirteenth century B.C., continues to hold surprises for researchers who examine its eruptive history. During extensive historical research for a new catalog of Etna’s eruptions (E. Gaudioso and E. Boschi, manuscript in preparation), 2002, maps have been found that were previously unknown in the literature. These maps, which are the most accurate and representative of the Etna’s eruptive phase, provide new elements to evaluate the correlation of the Etna’s eruption and continued until June 1636.

The two maps are important iconographic sources that help scientists understand the nature of that eruption, providing significant and continuous exposure to scientific information; he provided is correct, since he had been helped by a local expert, who was an expert on the volcanology. According to the report, handwritten in Italian in early January 1636, the Etna’s eruption and the 1634 earthquake are accentuated close to the active crater.

Along with the report, there is a drawing with a map and a drawing in Latin of one of the eruptions in 1634, and a map is included close to the active crater. The volcano’s surface is projected approximately on the flat surface.

Ancient Maps

Map 1. An Apparently Elementary Drawing

Fig. 1. Map 1 is a watercolor sketch showing Mount Etna erupting. 1634. Red indicates lava, ocher indicates ground, white indicates the so-called zone of the perennial snow, which no longer exists. Courtesy Biblioteca Nazionale Centrale di Roma.