Revisiting Past Earthquakes and Seismo-Volcanic Crises Using Declassified Optical Satellite Imagery

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Abstract

Recent development of the user-friendly software package "Co-registration of Optically Sensed Images and Correlation" (COSI-Corr), which allows for automatic and precise ortho-rectification, co-registration, and sub-pixel correlation of pushbroom satellite and aerial images, has enabled Earth's surface dynamics to be accurately monitored using optical imagery [1]. This technique compares two images of the Earth's surface that were acquired at different times, and estimates any potential pixel shifts between them with an accuracy typically better than 1/10 of the pixel size. Correlation of both satellite and aerial images has been successfully used to identify coseismic ground ruptures and quantify fault offsets during large earthquakes [2]–[4], as well as monitoring sand dune migration, landsliding, ice flow [5] [6], and volcanic activity [7] [8]. In this study, we demonstrate that recently declassified US spy satellite images can be used to measure ground deformation resulting from seismotectonic and volcanic events using optical sub-pixel correlation. KH-9 Hexagon satellite images, with a swath size of 250×125 km, were acquired by the US government between 1971 and 1980, and are available for purchase from the United States Geological Survey (USGS) at small cost ($30 per image). During this period, around 29,000 images were acquired globally [9], providing a comprehensive record of the Earth's surface at 6–9 m resolution.

Knowledge of the camera calibration information is required to determine the interior orientation parameters of the camera, which are in turn needed to successfully orthorectify and co-register the images using COSI-Corr. Because information on the camera system used during the KH-9 missions remains classified, we follow the approach in [9], who conclude that the KH-9 Hexagon camera system is similar to the later NASA Large Format Camera (LFC) system, for which the camera calibration information is known. Each image measures 23×46 cm and the KH-9 Hexagon camera is estimated to be a standard frame camera with a focal length of 30.5 cm. A regular grid of reseau marks spaced every 1×1 cm^2 allows film distortions, which have accumulated since the moment the film was exposed, to be potentially corrected. Therefore, KH-9 Hexagon images may be treated as regular aerial photographs for orthorectification purposes, with the corner fiducial points given by the corners of the reseau grid. Because the KH-9 image negatives are large, with a length of 46 cm, the USGS scans each image in two halves. To correct for film distortions and stitch the two halves of the image together, we initially used the 'KH_Tools' software from [9], which automatically detects and corrects reseau points that deviate from the initial 1×1 cm^2 reseau-grid. However, we found, in some cases, the processing to be not robust enough and large distortions were introduced during the resampling stage, which obscured any tectonic signal. Therefore, we manually stitched the two-halves together and did not correct for the film distortions prior to the image matching. To minimize potential stitching artefacts, we selected KH-9 Hexagon images in which the area of interest was entirely contained within one of the image halves.

We tested the approach on the 1999.10.16 Hector Mine, earthquake (Ms 7.4), which occurred in the Mojave desert region of California, USA. Existing measurements of the surface deformation from image matching between two SPOT satellite images [10] allow us to test whether KH-9 Hexagon images can be used to successfully estimate the co-seismic surface deformation resulting from this earthquake. Figure 1 shows the N-S deformation map from a pre- and post-event SPOT image correlation [10], and a pre-event KH-9 Hexagon and post-event SPOT image correlation. Long wavelength deformations unrelated to the tectonic signal in the KH-9 Hexagon-SPOT correlation are probably the result of both film and optical distortions, which have not been removed prior to orthorectification. Furthermore, the lower signal to noise ratio of KH-9 Hexagon images (compared with SPOT 5 satellite images), and the many surface changes which have occurred over the 27 year period between pre- and post-event image acquisition, results in a more noisy correlation. Nevertheless, the location of the fault rupture and the magnitude of the displacement in the KH-9 Hexagon-SPOT correlation are in very good agreement with those measured from the SPOT-SPOT correlation.

KH-9 Hexagon image acquisition began in the early 1970's, and consequently they offer huge potential for investigating tectonic deformation in the period 1970–1990, for which InSAR and GPS measurements are not available. By correlating a KH-9 Hexagon image from 15th September 1977 with a SPOT 5 image from 3rd October 2002, we have been able to measure the surface deformation associated with the 1975–1984 Krafla rifting crisis in NE Iceland. The SPOT 5 image was orthorectified at 7 m resolution relative to a sunshaded ASTER GDEM (30 m resolution) using COSI-Corr. Optimization of the 34 ground control points (GCP's) used to register the SPOT 5 image to the ASTER GDEM, yielded a normalized mis-registration of 0.26 m, and a standard deviation of 14.5 m. The KH-9 Hexagon image was then registered to the SPOT 5 orthoimage using 18 tie points, which were optimized via sub-pixel correlation, yielding a normalized mis-registration of 0.025 m and a standard deviation of 1.94 m. The KH-9 Hexagon image was orthorectified at 7 m resolution using the same ASTER GDEM as was used for the post-event SPOT 5 image. The KH-9 Hexagon and SPOT 5 orthoimages are correlated using a multi-scaling window size of 64 and 32 pixels, and a sliding step of 8 pixels (56 m). Finally, we experiment with removing long-wavelength, non-tectonic deformation in the correlation resulting from film distortions, by subtracting a best fitting polynomial trend to the data (we use a 2nd order polynomial trend, as it is not sensitive to surface displacements produced by dike injection or fault slip). The magnitude of the displacements resulting from optical distortion can be as much as 20 m, over a variety of wavelengths ranging from a few to tens

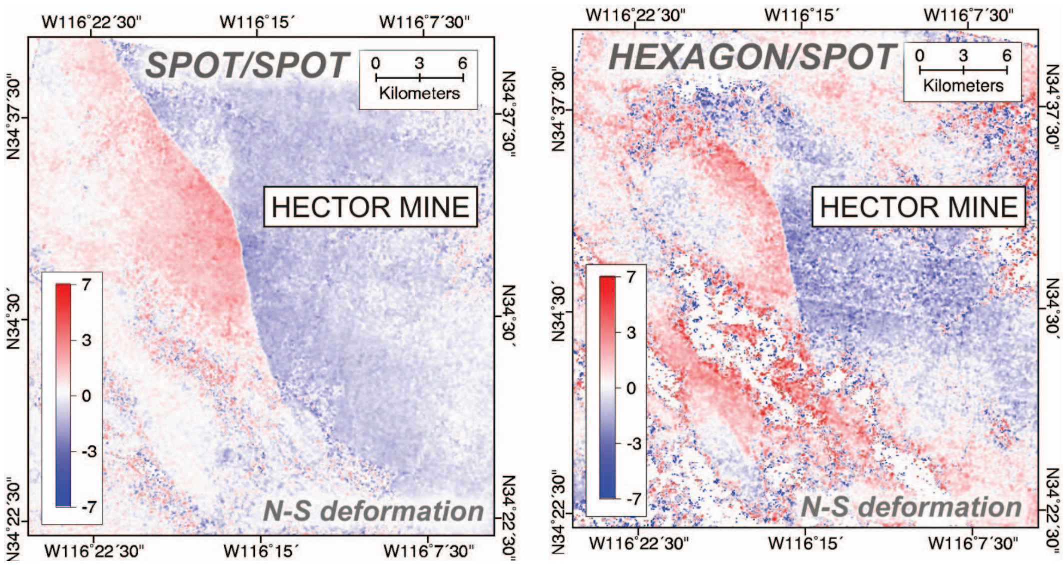

Fig. 1. N-S component of the deformation field induced by the 1999 Hector Mine earthquake, as measured from SPOT/SPOT and KH-9/SPOT correlations. The pre-event SPOT 4 image (10 m resolution) was acquired on 1998, and the post-event SPOT 2 (10 m resolution) image on 8th October 2002, and they were correlated using a window size of 32 pixels, and a sliding step of 8 pixels. The KH-9 image was acquired on the 9th June 1975 (9 m resolution), and was correlated with the 2002 SPOT 5 (5 m resolution) image with a multiscale window size of 64 and 32 pixels, and a sliding step of 8 pixels. This correlation has also been destriped to remove scanning artefacts, and detrended to remove the longest-wavelength film distortions.

of kilometers. Therefore, although our detrending method removes the longest wavelength distortions, it is not able to remove shorter wavelength distortions produced by more localized film distortions.

During the period 1977–2002 we find an average E-W surface extension of 3±0.5 m across the rift, which extends NNE from Lake Myvatn in the south to Ásbyrgi canyon in the north (a distance of over 40 km). The location of surface extension correlates with known structures visible within the Krafla fissure swarm, as well as the location of earthquakes produced by a single dike injection in 1978 [11]. Although our measurements do not begin until 1977, thereby missing the onset of rifting in 1975, they cover ∼80% of the remaining rifting period. The amount of extension across the rift determined from optical image correlation is slightly less than measurements made with Electric Distance Meters between late 1978 and 1989 [12]. Nevertheless, our measurements are consistent with the background plate spreading rate of ∼20 mm/yr across NE Iceland [13], and an approximate dike injection repeat time of ∼250 years (estimated from the historical record of eruptions at Krafla).

To complement our study, and better constrain deformation during the early stages of the rifting crisis (i.e. 1975-1977), we follow the procedure in [10] and [14] and correlate a series of aerial photos of the Krafla rift, acquired in 1990, with older aerial photos acquired in 1957 and 1976. The 1990 aerial photos are orthorectified at 1 m resolution, relative to the SPOT 5 orthoimage (resampled at 2.5 m), and using the 30 m ASTER GDEM. For both the 1956 and 1976 aerial photos, which span the majority of the northern part of the rift, we collect 10–15 tie points from each side of the rift. Although this forces the east and west edges of each aerial photo to be non-deforming, thereby preventing us from resolving long-wavelength tectonic deformation related to the depth of diking, we preserve the co-rifting extension produced across the various structures within the fissure swarm (which lie within the center of each aerial photo). By measuring the extension which has occurred between 1957–1990 and 1976–1990, we are able to solve for the 1957–1976 deformation field, thereby providing the first detailed constraints on surface deformation during the early stages of this rifting crisis. We find that in the central part of the Krafla fissure swarm, the total E-W extension between 1957-1990 is no more than 5 m, and rather less than the 9ṁ previously reported [12].

Therefore, image matching using regional-scale KH-9 Hexagon and SPOT 5 satellite images, and local-scale aerial photos, allows us to determine which faults and fissures were activated during the 1975-1984 Krafla rifting crisis, and how much they moved by. The various examples discussed above highlight the potential for using inexpensive declassified Hexagon images and aerial photos to investigate tectonic deformation dating back to the onset of the KH-9 Hexagon program in 1971, and even earlier for aerial photos. Furthermore, this technique could benefit change detection studies in general by providing accurate observations for periods that have, until now, been out of reach.

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