Pure Appl. Geophys. 174 (2017), 2295–2310

DOI 10.1007/s00024-016-1403-z

Pure and Applied Geophysics

Radar Determination of Fault Slip and Location in Partially Decorrelated Images

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Abstract—Faced with the challenge of thousands of frames of radar interferometric images, automated feature extraction promises to spur data understanding and highlight geophysically active land regions for further study. We have developed techniques for automatically determining surface fault slip and location using deformation images from the NASA Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR), which is similar to satellite-based SAR but has more mission flexibility and higher resolution (pixels are approximately 7 m). This radar interferometry provides a highly sensitive method, clearly indicating faults slipping at levels of 10 mm or less. But interferometric images are subject to decorrelation between revisit times, creating spots of bad data in the image. Our method begins with freely available data products from the UAVSAR mission, chiefly unwrapped interferograms, coherence images, and flight metadata. The computer vision techniques we use assume no data gaps or holes; so a preliminary step detects and removes spots of bad data and fills these holes by interpolation and blurring. Detected and partially validated surface fractures from earthquake main shocks, aftershocks, and aseismic-induced slip are shown for faults in California, including El Mayor-Cucapah (M7.2, 2010), the Ocotillo aftershock (M5.7, 2010), and South Napa (M6.0, 2014). Aseismic slip is detected on the San Andreas Fault from the El Mayor-Cucapah earthquake, in regions of highly patterned partial decorrelation. Validation is performed by comparing slip estimates from two interferograms with published ground truth measurements.

Key words: Radar, interferometry, fault slip, computer vision, Canny algorithm.

1. Introduction

While earthquake mainshocks often break the surface in sliding events with offsets of several meters, the smaller surface fracture events that are often created in the vicinity of large earthquakes (including silent slip events) are also of importance. They are important to society, commonly requiring road resurfacing; more extreme damage to infrastructure is also well known, such as the 1963 fault-triggered failure of the Baldwin Hills reservoir, whose flood resulted in the destruction of hundreds of homes in Los Angeles (Hudson and Scott 1965). Northridge earthquake (M6.9, 1994) triggered co-motion on the nearby Mission Hills fault (Johnson et al. 1996). The Landers (Fialko 2004) and Hector Mine (Fialko et al. 2002) earthquakes triggered deformation on nearby faults, detected by satellite repeat-pass InSAR. Rymer et al. (2011) recount eight prior triggered earthquake events detected in the Salton Trough, California, found by field investigations. They document dozens of field verifications of triggered slip detected in interferometric phase jumps in UAVSAR repeat-pass images (uavsar.jpl.nasa.gov) In this work "fault" refers to semi-permanent, deeply rooted crustal structures that support slip, "surface fracture" to a detectable lineation displaying slip on the surface, often associated with a neighboring earthquake event. There can also be localized shear, detectable in the interferogram but not by field investigation and typically associated with subsurface fault slip; for convenience such localized shear (near-surface fracture) will be lumped with "surface fracture," when the two are indistinguishable to the computer vision algorithm. Note that surface fractures near a mainshock may be due to immediate (elastic) or delayed (afterslip, relaxation) processes; and these fractures may or may not be associated with local seismicity.

Examples in this work rely on UAVSAR data, although they can be extended to satellite InSAR as well (repeat-pass interferometry, or RPI). UAVSAR is an airborne system, and the RPI data relies on the same principles as satellite InSAR, but with differing strengths and weaknesses. Advantages of UAVSAR

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include a public data policy, high resolution (roughly 7 m pixel size in released ground-range geolocated phase maps, that reflect surface deformation), and flight-path flexibility (direction and visit time vary according to experiment design). Also, UAVSAR data quality is not affected by ionospheric disturbance. Weaknesses are that the width of an imaged swath is limited to roughly 20 km (typical satellite swaths are 70–350 km); also RPI ground-range phase images are affected by limitations of the aircraft: distortions due to unplanned aircraft motions can be but partially compensated in data processing. The wide range of incidence angle in UAVSAR makes the data somewhat more difficult to interpret: the near edge of a swath has a zenith incidence angle of about 20°; the far edge angle is about 70°. Both are affected by radar propagation delay due to spatial variability of atmospheric water vapor, and by decorrelation that results in a steady decrease in useful image pixels as repeat-pass time increases.

Data images from the UAVSAR program are freely available from two sources, http://uavsar.nasa.gov and http://geo-gateway.org. The latter has been developed to create web service-based tools that rely on the UAVSAR data. For example thumbnail images of the unwrapped ground range data are overlain with Google Maps, with a variety of features to enable navigation to data strips of interest (Parker et al. 2015; Wang et al. 2012). Also, the tools support line plots of line-of-sight deformation values on user-specified lines. As of this writing there are 1250 available RPI data images, concentrated in California (where the aircraft is based) but including locations as far as Japan and Iceland.

This large number of high-resolution images presents a need for feature extraction, automated by computer vision algorithms. Since unwrapped phase images correspond to the component of deformation (between the repeat visits) in the line of sight of the instrument, detectable boundaries corresponding to phase discontinuities correspond (much of the time) to surface expression of fault slip. Note we do not find that InSAR can see the surface fault itself, as the feature size is smaller than the imaging pixel scale; but it is often easy to observe fault-induced discontinuities in phase in the unwrapped image, because one side of a fault has moved (relatively) toward the instrument, and the other side has moved away. Image processing detects a coherent motion of many pixels defining regions on both sides of the fault.

Surface fracture detection is a highly favorable feature to explore early in developing feature detection. Its pattern is nearly orthogonal to typical instances of image distortion due to atmospheric water vapor (which tends to vary slowly across an image) and uncompensated aircraft motion. Features that may be confused with faults, such as the edge of a vegetated area (a farm may be wetter in one pass than in another one months later, affecting the radar phase and mimicking a fault slip at its edge), are commonly easy to identify by comparing with optical images and maps.

Phase gradient approaches have been used to find surface fractures following the Landers (Price and Sandwell 1998) and Hector Mine (Sandwell et al. 2000) earthquakes in the Mojave Desert, and near the 1995 Nuweiba earthquake in the Gulf of Aqaba (Red Sea) (Baer et al. 2001). A phase gradient product is produced by the GMTSAR package (http://topex.ucsd.edu/gmtsar/). Their approach computes a phase gradient from the real and imaginary part of the complex interferogram, avoiding reliance on phase unwrapping, which is problematic in complex scenes. To use the computer vision algorithm directly, this work operates on phase gradients created directly from an unwrapped phase product of UAVSAR, and therefore is limited to interferogram portions where this phase unwrapping is reliably produced. Both approaches use a combination of Gaussian smoothing with a numerical derivative filter, resulting in similar combined filter response functions.

The computer vision subject corresponding to detection of surface fractures in RPI images is edge detection. Some prior well-developed work in this field (Canny 1986) has been implemented in open-source software. To make our work easy to share, we apply the opencv Python library, which is easy to obtain and integrate into free Python development environments.

Because there is scientific and emergency response value in detecting triggered or silent fault slip, the method described here is valuable in its own right; estimation of fault slip amplitude and mechanism (often requiring additional information) can be