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## GPS and Remote Sensing Study of Slope Movement in the Berkeley Hills, Ca.

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**ABSTRACT:** Recent advances in geodetic technologies, allow for analysis of spatial and temporal deformation of landslides that was previously not possible. Technologies such as continuous GPS and Interferometric Synthetic Aperture Radar (InSAR) need to be incorporated in the current state of practice for landslide characterization. This landslide risk assessment project aims to characterize slope movement at Lawrence Berkeley National Laboratory (LBNL) and in the Berkeley Hills as a result of static and dynamic forces, first using a comprehensive network of continuously streaming GPS stations that measure active ground surface displacement with sub-centimeter precision and accuracy. The intent is to combine the GPS observations with InSAR time series analyses to help develop a method for the determination and evaluation of landslide hazards remotely. Since the implementation of our GPS observation program in January 2012, landslide related surface displacements have been recorded as an effect of precipitation.

### INTRODUCTION

The objective of this study is to characterize slope deformation as a result of static and dynamic forces, using the most current geodetic technologies that measure active ground surface displacement. New and improved methods for geodetic and remote data collection, such as continuous GPS, and Interferometric Synthetic Aperture Radar (InSAR) allow for a level of primary site characterization and eventual risk assessment due to landsliding that was previously not possible. These technologies need to be incorporated in current practice and tested. Active landsliding across the Lawrence Berkeley National Laboratory (LBNL) site and the greater Berkeley Hills region, California, has been the object of many investigations over recent decades, though the mechanisms of currently mobile, slow moving slides are still poorly understood. Previous studies suggest a trend in landslide mobility is associated with regional climate and active tectonic conditions in addition to the local geologic

setting. A first focus of this project is therefore to study the spatial and temporal distribution of active Berkeley Hills landsliding in relation to local precipitation and ground shaking events by a careful observational program. This program includes the instrumentation of individual landslides with permanent continuously streaming GPS stations, and regional monitoring of slope surface deformation by InSAR time series analysis. Subsequently, the mechanisms of some of these slow moving landslides will be modeled, integrating our surface observations with previous subsurface investigations and monitoring. This is a presentation of preliminary GPS findings.

## **SETTING**

As part of the northwest trending California Coast Range geomorphic province, the Berkeley Hills are an uplifted block of Jurassic to Tertiary sedimentary, volcanic and metamorphic rocks that formed during regional transpression related to the active plate margin 1-2 million years ago. Now largely overlain by Quaternary colluvial and alluvial deposits, this highly fractured, intensely weathered, moderately soft rock is prone to landsliding. In addition to the geologic setting, studies suggest that Berkeley Hills landslide mobility is driven by precipitation and regional active tectonic conditions (Hilley et al. 2004, Quigley et al. 2010). Today, several hundred landslide-related geologic and geotechnical investigation reports are available for LBNL and the Berkeley Hills alone, and form a solid background to this project.

## **METHODOLOGY**

Two state of the art geodetic sensing technologies form the primary modes of data acquisition in this project: high rate, continuously streaming, Global Positioning Systems (GPS) and space-borne Interferometric Synthetic Aperture Radar (InSAR). These methods are complimentary in that GPS provides real time, direct ground surface displacement measurements with millimeter scale accuracy and precision, where InSAR time series analysis produces spatial averages at decameter resolution with sub-centimeter precision. Combining these methods allows for spatial and temporal distribution analysis of ground surface displacements due to landsliding in relation to local precipitation and ground shaking events. By incorporating these surface observations with previous investigations and monitoring, the landslide mechanisms can then be modeled.

## **PROJECT STATUS**

The first phase of this project has been to instrument individual landslides with autonomous, continuously streaming GPS stations, collecting readings at 1Hz for average daily solutions and a 25Hz buffer in the case of seismic activity. Each station has been specifically designed for permanent, stand-alone installation and built to capture landslide displacement at depth. Anchored on a deep seated reinforced concrete foundation to limit the effects of surficial disturbance, the stations are solar powered and equipped with a wireless antenna for remote access. Since January 2012, 5 such stations have been successfully installed at LBNL and one at the

University of California Blake Garden on the Blakemont Landslide. Four additional sites in the Berkeley Hills are in the process of being developed.

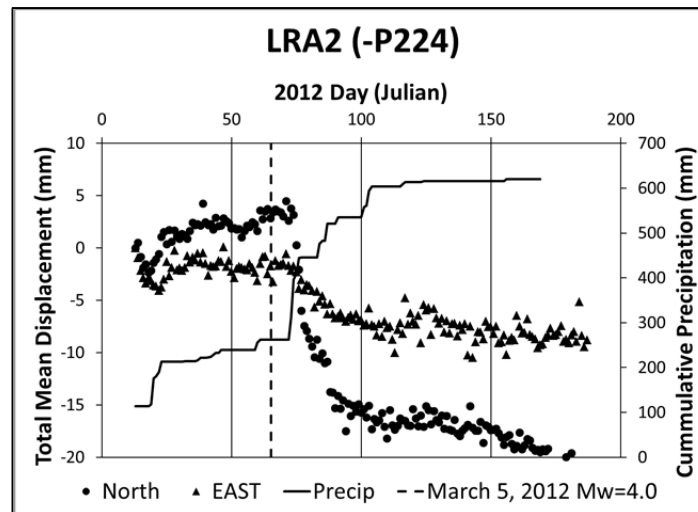
With the concurrent development of this GPS network, analysis of InSAR time series has also begun, though is not presented here. Satellite based Radar images are available for the Berkeley Hills region dating back to 1992 and have already been the object of several InSAR studies, as in Hilley et al. (2004) and Quigley et al. (2010).

## PRELIMINARY GPS RESULTS

Since January 2012, the first 6 continuously streaming GPS stations have been producing daily solutions. Highlighted here are stations “LRA 1-3” located on the same landslide at LBNL as depicted in Figure 1, a 1935 air photo (Alan Kropp and Associates 2009). While historical ground surface displacement related to this landslide has yet to be characterized and quantified, extensive field investigations have described it as an approximately 230m long, 75m wide and 24m deep translational soil and rock landslide with nested rotational failures (Alan Kropp and Associates 2009). Already, a clear signal at each of these 3 stations is apparent, showing down-slope displacements of up to 2cm and directly related to local precipitation. As an example, Figure 2 illustrates the time history of daily solutions for station LRA 2 from January through June 2012, plotted against cumulative rainfall. Daily solutions for the station’s North and East baselines are taken with respect to a fixed station (P224) several kilometers to the South and are shown to be moving down-slope to the West and South-West, accelerating during large rainfall events. Also illustrated in Figure 2 is the March 5, 2012  $M_w = 4.0$  Hayward fault seismic event with epicenter in El Cerrito, CA, approximately 10 km North of the site. While no clear seismically driven permanent slope displacements can be discerned, this may be due to the “dry” state of the landslide as well as the event’s size and distance.



**FIG. 1 1935 Oblique view of LBNL landslide with current GPS station locations.**



**FIG. 2 GPS Displacement time history of station LRA 2 with respect to reference station P224 showing deviation from North (circles) and East (triangles) baselines, cumulative precipitation (solid) and seismic event (dashed).**

## CONCLUSION

After a mild wet season, the GPS instrumentation of several landslides in the Berkeley Hills CA, has recorded well defined precipitation triggered slope movement. In contrast, the occurrence of one measureable seismic event did not appear to have produced a measurable effect. Overall, the system has already demonstrated its capability to record events that otherwise would not have been observed with such level of detail and it continues to function and collect new data.

## ACKNOWLEDGEMENT

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