KISS Technical Development Progress Summary

Monitoring Earth Surface Changes from Space

Caltech lead: Jean-Philippe Avouac

JPL lead: Paul Rosen

Progress summary completed on: November 29, 2012

Prepared by S. Leprince and J. P. Avouac

Introduction

This report gives an overview of the activities which have been undertaken as part of the technical follow-on to the large study "Monitoring Earth Surface Changes from Space". In addition to the support provided by the Keck Institute for Space Studies, these activities have been supported by matching funds from the Gordon and Betty Moore Foundation, from UAE and Kuwait, and from the MDAP NASA program.

Activities were organized under five different themes, each lead by a different PI:

1- Optical Image Time-Series (PI: Sebastien Leprince). These activities aim at developing techniques to analyze optical images acquired by different imaging systems and at different times to look at general landscape evolution (evolutions due to tectonic activity, glacier flow, landslides, sand dunes migration, etc.). They also aim at building a framework for large scale processing to look at global changes.

2- SAR Time-Series Analysis (PI: Mark Simons). These activities aim at developing techniques to analyze radar image time series, in particular via interferrometric techniques. These activities involve close interactions with JPL via the ARIA project (PI: Susan Owen).

3- Seismic Waves Imaging (PI: Pablo Ampuero). These activities aim at developing techniques for seismic inversion with dense measurement in time and space, such as measurement that would be provided by a space seismometer. These activities involve close interactions with JPL, which received a matching R&TD funding to investigate the development of a space optical seismometer (PI: David Redding).

4- Sub-surface Imaging (PI: Essam Heggy). These activities involve close interactions at testing the possibility of an Earth orbiting Ground Penetrating Radar (GPR). Within the scope of this project, only airborne applications will be sought after, with study for space applications.

5- Science Applications (PI: Mike Lamb). These activities involve taking advantage of the techniques developed by the other groups. It also drives the technical developments and foresees the external visitor program.

We detail below these activities. Each sub-section has software products, publications, and/or conference posters/talks as outcome. All publications and presentations in international meetings are listed again at the end of the report together with a few other publications produced by collaborators who have participated in the KISS study but did not receive funding from us. Regarding the 'seismic waves imaging' project, we have explored different designs and mission concepts for a 4 m-class Seismic Imager Geostationnary satellite system. We are currently working on estimating the cost and preparing a draft GSI Mission Whitepaper.

On-Going Activities

1- Optical Image Time-Series (PI: Sébastien Leprince)

1.1 *Adaptive Resampling (S. Leprince, P. Tan):* Project Completed Sept 2011

We developed a rigorous resampling method where the resampling kernel can locally adapt to the local warping. This allows images with steep topographic slopes and high incidence angles to be rectified without losing information, which is particularly important for high resolution imagery. Prototypes have been designed, tested, and implemented into the COSI-Corr software.

References:

P. Tan, S. Leprince, J.P. Avouac, "Image Warping," Technical Report California Institute of Technology, Sept. 2011.

1.2 *Automatic and robust tie-points detection and matching (S. Beckouche, S. Leprince, F. Ayoub, N. Sabater, JP Avouac):* Project Completed April 2011

Automatic processing and analysis of large quantity of images requires automatic and robust estimation of similar features between image pairs. We proposed an algorithm that mixes random sampling of transformation coefficients (we use an affine constraint on the image mapping), and robust clustering of underlying coefficient transforms. The method robustly identifies matching points between image pairs with no error up to a proportion of 90% of outliers in the initial matching.

References:

S. Beckouche, S. Leprince, N. Sabater, F. Ayoub, "Robust outlier detection in image point matching," IEEE ICCV, Nov. 2011, pages 180-187.

1.3 ***USGS Lidar analysis (S. Leprince, K. Hudnut, S. Ackiz):*** **Project completed August 2012**

Collaboration with the USGS allowed accurate analysis of the April 2010, El-Mayor Cucapah earthquake, by analyzing pre and post- event LiDAR acquisitions. A complete high resolution 3D map of the rupture was produced, making it the first successful attempt at extracting 3D fault rupture displacement from LiDAR data.

References:

S. Leprince, K. Hudnut, S. Akciz, A. Hinojosa-Corona, and J. Fletcher, “Surface rupture and slip variation induced by the 2010 El Mayor-Cucapah earthquake, Baja California, quantified using COSI-Corr analysis on pre- and post-earthquake LiDAR acquisitions," American Geophysical Union, Fall Meeting 2011, San Francisco.

GRL paper in preparation, 2012.

1.4 Three dimensional measurement of ground deformation using mutli-angle imagery and LiDAR point clouds (S. Leprince, B. Conejo, F. Ayoub, J. Lin)

This project aims at developing new software tools to use multi-angle high resolution optical imagery to recover the 3D ground deformation of the ground. Comparative studies with the 3D ground deformation measured from LiDAR above the El-Mayor Cucapah earthquake from April 2010. In addition, we explore the use of using LiDAR point clouds to measure the deformation of smooth surface such as sand dune surfaces. Sand dune studies are carried above the White Sand Dunes in New Mexico thanks to a collaboration with Ryan Ewing, University of Alabama, who provided the LiDAR data.

References:

S. Leprince, J. Hollingsworth, F. Ayoub, J.-P. Avouac, and J. Dolan, “Quantifying 3D ground deformation using multi-angle high resolution optical imagery,” SCEC meeting, Palm Springs, 2012

S. Leprince, F. Ayoub, B. Conejo, and J.-P. Avouac, “Emerging techniques to quantify 3D ground deformation using high resolution optical imagery and multi-temporal LiDAR,” American Geophysical Union, San Francisco, Fall Meeting 2012, invited

S. Leprince, F. Ayoub, J. Lin, J.P. Avouac, “The COSI-Corr Tools: Emerging techniques to quantify ground deformation using high resolution optical imagery and multi-temporal LiDAR,” GRSG workshop, London, December 2012.

1.5 ***Advanced image correlation techniques (N. Sabater, S. Leprince): Project completed January 2012***

The aim of this project is to study a generalized version of optical flow which improves the accuracy of other more basic approaches. The classic formulation of optical flow assumes intensity invariance in a simple translation model. To overcome these limitations we are studying a formulation of optical flow with eight parameters to allow for affine transformations and

variations in illumination. Since the optical flow equation is a first order approximation, displacements of more than one pixel are not allowed. For this reason the algorithm is multi-scale. Furthermore, at each scale, the optical flow equation may not be solvable for a few pixels. In this case, a bilateral filter interpolates the displacement field. Finally, the choice of the costs functions and the optimization methods are crucial for the success of the method.

References:

N. Sabater, S. Leprince, J.P. Avouac, “Contrast Invariant and Affine Optical Flow for DEM extraction”, ASPRS Conference, March 2012.

N. Sabater, S. Leprince, J.P. Avouac, “Contrast Invariant and Affine Optical Flow”, ICIP Conference, October 2012.

1.6 *Cluster distributed processing (J. Lin, M. Aivazis, A. Fang, F. Ayoub, S. Leprince)*

Building on the first year progress in terms of code development, we pushed the effort further to improve on the COSI-Corr code structure, execution speed, and parallelization capabilities:

We brought in modern software engineering practices to establish a flexible and sustainable development environment, including a distributed source control system, a build system, an automatic testing system, a trac site, and a development procedure.

We ported existing C++ code so that we have one single source code for all platforms we plan to support.

We explored C++ libraries to be utilized by core engines of COSI-Corr. The main goal was to find one or more libraries that can help ease the development of core functionalities, but also make it easier to optimize the speed of the implementation. We weren't able to identify any off-the-shelf library that would satisfy our constraints, imposing further development on our part.

We started to create Python bindings for the COSI-Corr C++ libraries and implemented a layered architecture for the COSI-Corr Python package.

We started building the necessary infrastructure for supporting batch processing of large numbers of images concurrently on high performance computing clusters. The goal is to make this capability available in a way that is transparent to the user. The system will be able to take advantage of multiple machines at the same time, and dynamically direct job requests wherever computational cycles become available.

Of particular importance, we recently finalized our first beta version of a web interface to the new distributed tool we are building, which will allow external users to use our technology.

2- SAR Time-Series Analysis (PI: Mark Simons, with P. S. Agram)

This activity is essentially the result of the work of Piyush Agram, a KISS postdoctoral fellow. See his annual report for details.

2.1 Continued development of Multi-scale InSAR Time-series (MInTS) package. It is now available for download at:

https://secure.geo.lsa.umich.edu/groups/lithosphere/wiki/eb455/MInTS.html

2.2 Development of other time-series InSAR related packages for improving the quality of time-series including:

- Variable Resolution Sampler (http://code.google.com/p/varrespy) to reduce redundancy in interferograms for more efficient geophysical modeling.

- Development of tools to convert ECMWF, NARR and MERR-A weather model data into water vapor phase delay screens for correcting interferograms in collaboration with Romain Jolivet.

2.3 Production of an inter-seismic surface displacement map from the San Francisco Bay Area to south of Parkfield in California. The data has already been used in a publication titled "Geodetic Constraints on the Parkfield Seismogenic Zone: Implications for the Earthquake Prediction Experiment" to be submitted to JGR in collaboration with Sylvain Barbot, Nadia Lapusta, Jean-Philippe Avouac and Mark Simons.

2.4 Development of a theoretical noise covariance model for InSAR. The work was presented at ESA's FRINGE 2011 meeting in Frascati, Italy. The model is also being written up to be submitted to JGR.

2.5 Development of a Kalman-filter approach to modeling time-series observation in model space. Combining data in model space with the correct covariance structures allows us to seamlessly use data from various sources like GPS, tiltmeters and InSAR each of which are characterized by different spatial and temporal resolution.

References:

P. Agram and M. Simons, “Noise Covariance model for time series InSAR analysis,” FRINGE InSAR workshop, FRINGE 2011 at Frascati (Italy), Sep 2011.

B. Minchew, M.Simons et al., “Airborne and satellite-based InSAR observations of Icelandic Ice Caps,” FRINGE InSAR workshop, FRINGE 2011 at Frascati (Italy), Sep 2011.

E. Hetland, M. Simons et al., “Multiscale InSAR Time Series (MInTS) analysis of surface deformation,” In Press. JGR (Earth).

P. Agram and M. Simons, “Noise models for time-series InSAR analysis,” In Preparation.

B. Minchew, M. Simons et al., “Surface Velocity Field of Temperate Ice Cap Hofsjökull Using UAVSAR Repeat Pass Interferometry,” AGU Fall Meeting 2011.

S. H. Yun et al., “Damage Proxy Map from InSAR Coherence Applied to February 2011 M6.3 Christchurch Earthquake, 2011 M9.0 Tohoku-oki Earthquake, and 2011 Kirishima Volcano Eruption,” AGU Fall Meeting 2011.

M. Simons, P. Agram et al., “Exploiting ALOS observations as a guide to what will be possible with DESDynI,” AGU Fall Meeting 2011.

S. Barbot, N. Lapusta et al., “Geodetic Constraints on the Parkfield Seismogenic Zone: Implications for the Earthquake Prediction Experiment,” In Preparation.

3- Seismic Waves Imaging (PI: Pablo Ampuero)

3.1 Scalable Source Model Inversion (P. Ampuero, N. Lapusta, S. Somala, P. Galvez):

We developed a source inversion algorithm that can handle ground motions recorded by thousands of sensors. We implemented a conjugate gradient method based on an adjoint computed by time-reversal wave propagation simulations, using the 3D spectral element method (SPECFEM3D) and high performance computing (Caltech clusters Fram and Garuda). With this tool we started assessing the performance of the extremely dense observations that could be provided by a space-based optical telescope. In particular we quantified the capability to resolve source details as a function of density of sensors and as a function of signal to noise ratio. We considered kinematic and dynamic earthquake scenarios, but only in homogeneous media. Extension of this work to more realistic scenarios is in progress. We also gained insight into the effect of sensor density on the quality of source imaging from a more fundamental approach, by studying the anatomy of the null space in an axisymmetric source inversion problem, a mathematically tractable "toy model". The analysis confirms the intuition that the optimal network for earthquake source imaging requires a sensor spacing a few times smaller than the shortest wavelength. As a corollary of our efforts, we are now poised to do the first source inversion of the 2011 Tohoku-Oki earthquake that incorporates all the thousands of Japanese cGPS, strong motion and broadband recordings for this mega-event.

References:

Ampuero, J.-P., S. N. Somala, N. Lapusta, R. Michel, Proof of Concept for Seismic Wave Imaging, *Monitoring Earth Surface Changes from Space II*, Caltech, Mar. 2010.

Ampuero, J.-P., R. Michel, S. N. Somala, N. Lapusta, J.-P. Avouac, Towards Earthquake Source Imaging by a Space based Strong Motion Seismometer, *Workshop on Earthquake Source Dynamics : Data and Data-constrained Numerical Modeling*, Slovak Republic, June 2010

Ampuero, J.-P., S. N. Somala, N. Lapusta, Adjoint Inversion for Extended Earthquake Source Kinematics from very dense Strong Motion Data, AGU Fall Meet. Suppl., Abstract S53C-1992, 2010.

Somala, S. N., J.-P. Ampuero, N. Lapusta, Earthquake source inversion with very dense seismic data, "Workshop of quantitative estimation of earth's seismic sources and structure", Iceland, July 2011

Somala, S. N., J.-P. Ampuero, N. Lapusta, Effects of parameterization on finite source inversions with dense local data, *SCEC Annual Meeting*, Palm Springs, CA, Sept. 2011.

Somala, S. N., P. Galvez, A. Inbal, J.-P. Ampuero, N. Lapusta, Towards Adjoint Finite Source Inversion: Application to the 2011 M9 Tohoku Earthquake, AGU Fall Meet. Suppl., Abstract S43C-2248, 2011.

Somala, S. N., Z. Duputel, J.-P. Ampuero, N. Lapusta, Quantity Vs. Quality: Effect of Sensor Density and Sensitivity on Earthquake Source Inversion , "*IUGG Conference on Mathematical Geophysics (CMG)*", Edinburgh, June 2012

Somala, S. N., J.-P. Ampuero, N. Lapusta, Earthquake source inversion with dense networks, *SCEC Annual Meeting*, Palm Springs, CA, Sept. 2012.

Somala, S. N., J.-P. Ampuero, N. Lapusta, Earthquake source inversion with dense networks, *AGU Fall Meeting*, 2012.

3.2 Optical Seismometer (PI: David Redding, and JPL team. Also includes from Caltech P. Ampuero, N. Lapusta, S. Leprince, J.P. Avouac):

This year's activities have focused on fundamentals of the optical-flow measurements of displacements, and how they are impacted by the space telescope design, especially the aperture size and shape. This work shows that telescopes as small as 2 m aperture can measure large earthquakes, but that 3.6 to 4 m apertures give far superior performance. We have begun to examine mission cost, using astronomical telescope design studies to ground predictions based on parametric cost models. Indications are that incorporating lightweight optics technologies, such as silicon carbide mirrors, can help keep costs under $2B for a 4 m-class GEO Seismic Imager mission. We will be working with the JPL Team-X design group to develop more detailed estimates, and conclude our activities this year with a draft GSI Mission Whitepaper.

References:

R. Michel, J.-P. Ampuero, J.-P. Avouac, N. Lapusta, S. Leprince, D.C. Redding, and S. N. Somala, “A Geostationary Optical Seismometer, Proof of Concept,” IEEE TGRS, in press, 2012.

3.3 *Full-field laboratory earthquake experiment using digital image correlation* (A. Rosakis, N. Lapusta, Vito Rubino, S. Leprince, JP Avouac)

Full-field measurements of displacement and strains have been performed in the laboratory earthquake setup developed by A. Rosakis and coworkers, using digital image correlation. Images of the specimens are taken before and after dynamic rupture propagation with a 4 Megapixels CCD camera. The digital images are analyzed with two software: VIC-2D (Correlated Solutions Inc.) and COSI-Corr (Leprince et. al, 2007). The full-field displacement clearly shows relative motion on the two sides of the fault. In one case, due to the presence of secondary mode I cracks, VIC-2D correlation does not converge. In contrast, COSI-Corr discards

subsets where the correlation does not converge. As a result, COSI-Corr analysis accurately shows (i) the propagation of the dynamic rupture along the frictional interface, (ii) the rupture arrest on the glued boundaries, (iii) the presence of two wing cracks. Images were also taken before and during deformation with a gated-intensified high-speed camera. The analysis performed on these preliminary tests shows that useful dynamic measurements are indeed feasible.

References:

Rubino, V, N. Lapusta, and A.J. Rosakis, The feasibility of dynamic full-field earthquake measurements from space: a laboratory study, 2011 Annual Tectonic Observatory Meeting, Pasadena, CA, 2011.

Rubino, V, N. Lapusta, and A.J. Rosakis, The feasibility of dynamic full-field earthquake measurements from space: a laboratory study, Caltech Solid Mechanics Symposium, Pasadena, CA, 2012.

Rubino, V, N. Lapusta, and A.J. Rosakis, Full-field laboratory earthquake measurements with the digital image correlation method, 2012 SSA Annual Meeting, San Diego, CA, 2012.

Rubino, V, N. Lapusta, A.J. Rosakis, S. Leprince and J.P. Avouac, Full-field laboratory earthquake measurements with the digital image correlation method, Manuscript in preparation, 2012.

Rubino, V, N. Lapusta, and A.J. Rosakis, Laboratory earthquake measurements with the high-speed digital image correlation method and applications to super-shear transition, 2012 AGU Fall Meeting, San Francisco, CA, 2012.

4- Sub-surface Imaging (PI: Essam Heggy)

4.1 Airborne Radar Probing of Desert Environments: Understanding the Role of Earth Dry Regions as a Key Element in Monitoring Earth global Environmental Changes (Essam Heggy, M. Lamb, J.P. Avouac):

Our knowledge of the shallow subsurface (0-10s of meters) is very limited although it is a key element of the critical zone that determines the interactions between the atmosphere and the solid Earth, as well as the availability of life-sustaining resources, including food production and water quality. As part of this project, we have explored the possibility of imaging the shallow subsurface using radar remote sensing systems. We focused on arid areas where the applicability of the technique is less challenging. The research carried during this first year of funding allowed the following: (1) performing a four-week airborne survey in Kuwait in Mai 2011; (2) procure radar sounding transmitter, digital unit and two software packages and computational platforms for radar data processing; (3) fund four graduate students and two visiting scientists to work in the field and on data analysis in Caltech; (4) fund travels for ground data validation and to future test sites in UAE and Kuwait; (5) Formulation of an Orbital and airborne mission concept for mapping aquifers in desert areas.

We performed the first experimental large scale airborne mapping of an aquifer using 40 MHz low-frequency sounding radar technology. Results obtained suggest the utility of sounding radars to locate and map Earth's desert aquifers within few meters of vertical resolution. During the survey we flew with a helicopter equipped with the radar on 12 low-altitude passes (305 meters) over two well-known freshwater aquifers, probing the desert subsurface down to the water table at depths ranging from 20 to 65 meters. We successfully demonstrated that the radar could locate subsurface aquifers with 30m horizontal resolution, probe variations in the depth of the water table within 1 meter vertical resolution, and identify locations where water flowed in and out of the aquifers. Such unmatched accuracy (compare to 300 km by GRACE gravity experiment) over large areas is crucial for understanding of ground water dynamic, recharge mechanisms as well as current and past hydrological conditions in Earth's deserts and assessing how climate change is impacting them.

The results and collaborations that resulted from this activity have contributed to preparing an Orbital sounding radar mission proposal for NASA Earth Venture -2 call. The suggested mission: "Orbiting Arid Subsurface and Ice Sheet Sounder (OASIS)" aims to Explore desert aquifers and polar ice sheets and their role in current and paleo-climate evolution. In addition we have formulated an airborne mapping project that is being submitted to the Kuwait Foundation to build and operate dual-band sounding radar to map for 5 years the fossil aquifers in the Arabian peninsula and north African Sahara. The airborne platform will also carry a LiDAR, a transient Electromagnetic sounder and a high resolution Visible –IR camera. This unique effort will be the first groundwater large scale mapping in the Sahara and the Arabian Peninsula (~10 % of the earth land surface). It is expected to provide unique knowledge on the deserts evolution and response to climate change.

References:

Heggy et al., 2011, Probing Shallow Aquifers in Northern Kuwait Using Airborne Sounding Radars, Abstract P13G-06, Fall Meeting, AGU, 2011, San Francisco, Calif., 5-9 Dec.

Heggy, Fadlemawla, Avouac, Al-Rashed, Normand, Sultan et al., 2012, Exploring Fossil Aquifers Using Sounding Radars: Implication to Understand large-scale Ground Water Dynamic and Desert Paleo-Climatic conditions. In preparation for Nature Geoscience.

S. Leprince, F. Ayoub, P. Vermeesch, J.-P. Avouac, "Monitoring Desert Sand Dunes from Space," UN conference on Climate Change, Qatar, Nov 28, 2012

E. Heggy, "Exploring Fossil Aquifers Using Sounding Radars," UN conference on Climate Change, Qatar, Nov 28, 2012

5- Science Applications (PI: Mike Lamb)

5.1 Earth flows (J. Scheingross, Ben Mackey, R. Ewing, M. Lamb, A. Booth):

Earthflows are slow-moving landslides that creep at approximate rates of meters per year causing hazards and significant sediment fluxes. We used COSI-Corr to produce an unprecedented, decadal-scale time-series of earthflow movement in northern California spanning 1944-2009. This ongoing study illustrates the complex and dynamic behavior of a large, slow-moving landslide and its relationship to meteorological forcing. In addition, we acquired Ground Penetrating Radar (GPR) across an active earthflow in the same study area to determine earthflow depth and internal structure, which is needed to invert the remotely sensed kinematic data for sediment flux and earthflow rheology. In a related study, we have used a combination of airborne InSAR, high resolution aerial photographs, and digital elevation models to map the distribution of earthflows along the central portion of the San Andreas Fault, CA. We find that landslides are more abundant near the San Andreas Fault where seismicity has reduced rock strength.

References:

Mackey, B.H., Lamb, M.P., Roering, J., 2011, Automated optical image correlation to constrain dynamics of slow-moving landslides, EOS Trans. AGU EP52C-02. Invited.

Scheingross, J.S., B. Minchew B., B.H. Mackey, M. Simons, and M.P. Lamb, " Fault zone controls on the spatial distribution of slow moving landslides," *Geological Society of America Bulletin,* in press, 2012

Scheingross, J.S., Minchew, B., Mackey, B.H., Simons, M., Lamb, M.P., Hensley, S., 2012, The influence of large-magnitude earthquakes and fault zone damage on the spatial distribution of slow-moving landslides, *AGU Fall Meeting* 2012.

Mackey, B.H., Lamb, M.P., Roering, J., in prep., Automated optical image correlation to constrain dynamics of slow-moving landslides.

Adam M. Booth; Joshua J. Roering; Michael P. Lamb, 2012, Surface roughness manifestations of deep-seated landslide processes. American Geophysical Union Fall Meeting (Invited).

Michael P. Lamb, 2012, Bedrock hillslopes to deltas: New insights into landscape mechanics. Robert P. Sharp Lecture, American Geophysical Union Fall Meeting (Invited).

Booth, A.M., J. Roering, and A. Rempel, "Topographic signatures of deep-seated landslides and a general landscape evolution model," AGU Fall Meeting, 2012.

5.2 Exploration of arctic permafrost melting on river channel migration (O. Mark, M. Lamb, S. Leprince, J.P. Avouac, M. Thomas)

The presence or degradation of permafrost may significantly influence landscape evolution and response to climate change, yet little is known about how river planform stability is affected by ground ice content. Herein we use a new semi-automatic algorithm to extract river morphometrics, including the degree of anabranching, from satellite images of the artic Lena River, Siberia. This data set is combined with MODIS thermal mapping to detect whether ground-ice changes correlate with river plan form changes. We find that the Lena River transitions from a single-thread channel to an anastamosing river with multiple threads at the ~-10 degree C mean-annual land-surface isotherm, which corresponds approximately to the onset of continuous permafrost and ground-ice contents that exceed 40%. The change in river

morphology implies a reduction of bank strength in the zone of high ground-ice contents, suggesting a high vulnerability to thermo-erosion in Arctic terrains.

Reference:

Marc, O., Lamb, M.P., Thomas, M., Leprince, S., Avouac, J.-P., "Permafrost as a bank weakening process: Insights from remote sensing of the central Lena river, Siberia," Earth Surface Processes and Landforms, in review.

5.3 Sand dunes on Mars (F. Ayoub, N. Bridges, S. Leprince, J.P. Avouac, A. Lucas):

Partly funded by a NASA proposal with Nathan Bridges, this study expands our processing techniques, already validated on Earth, to planetary images of Mars. Strong and sustained winds on Mars have been considered rare. The abundant dunes and evidence for wind erosion seen on the planet have commonly been interpreted as reflecting past climatic conditions. Using HiRISE NASA imagery we have demonstrated that the sand ripples and dune lee fronts at Nili Patera are active and measured their migration. We were thus able to constrain the sand flux at this site related to reptation and saltation. We found unexpectedly high sand fluxes similar to those reported from some sites on Earth such as Victoria Valley, Antartica. We additionally showed that the dunes are near steady state, with their entire volumes composed of mobile sand. This study allowed quantifying eolian activity on Mars, thus providing key constraints on the main geomorphic process currently active on this planet, and opens new ways to assess current conditions and keys to assess its past geologic activity as recorded in its stratigraphy.

References:

N. Bridges, F. Ayoub, J.P. Avouac, S. Leprince, A. Lucas, S. Mattson, "Earth-like Sand Fluxes on Mars," Nature, 485, pages 339–342, May 2012.

F. Ayoub, N. Bridges, J.P. Avouac, S. Leprince, A. Lucas, S. Mattson, "Measuring sand flux on Mars using HiRISE Images," AGU Fall Conference - San Francisco, December 5-9, 2011.

Bridges N. T., F. Ayoub, J.-P. Avouac, and S. Leprince, "Measurement of High Martian Sand Fluxes: Implications for Landscape Modification," EPSC Division for Planetary Sciences of the American Astronomical Society (DPS) EPSC-DPS Joint Meeting 2011 - Vol. 6, EPSC-DPS2011-793-1, Nantes, France, October 2011.

N. Bridges, F. Ayoub, J.P. Avouac, S. Leprince, A. Lucas, S. Mattson, "High Sand Fluxes and Abrasion Rates on Mars Determined from HiRISE Images" Lunar and Planetary Science Conference, paper #1322, March 2012.

N. Bridges, F. Ayoub, J.P. Avouac, S. Leprince, A. Lucas, S. Mattson, "Measuring Sand Flux on Mars using HiRISE imagery", American Society of Photogrammetry and Remote Sensing Annual Conference, Sacramento, March 2012.

F. Ayoub, J.P. Avouac, A. Lucas, C. Newman, S. Leprince, N. Bridges, "Calibrating Mars atmospheric models through sand flux measurement," in prep., 2012

F. Ayoub, N. Bridges, J.P. Avouac, S. Leprince, A. Lucas, "Measuring Mars sand flux and its seasonality using HiRISE imagery," Third International Planetary Dunes Workshop, Flagstaff, June 2012.

F. Ayoub, N. Bridges, J.P. Avouac, S. Leprince, A. Lucas, "Measuring Mars sand flux and its seasonality using HiRISE imagery," AGU Fall meeting, San Francisco, December 2012.

F. Ayoub, N. Bridges, J.P. Avouac, S. Leprince, A. Lucas, "Measuring Mars sand flux seasonality from a time series of images," GRSG, London, December, 2012.

F. Ayoub, J.P. Avouac, A. Lucas, S. Leprince, N. Bridges, "Tracking topographic changes from multitemporal stereo images, application to the Nili Patera Dune field," AGU Fall Meeting, December 2012, invited.

5.4 Sand Dunes on Earth (J. Prancevic, M. Lamb, F. Ayoub)

Measuring aeolian sediment transport rates is essential to understanding the pattern of dune formation and desertification. We have studied the feasibility of using aerial photographs and precise image co-registration and correlation software (COSI-Corr) to calculate ripple migration rates and estimate sediment flux by wind transport. Monitoring sand dunes on Earth is challenging because terrestrian wind ripples are smaller scale than on Mars (with wavelengths of typically a few tenths of centimeters). They cannot be resolved from available satellite imagery. Preliminary work relied on the analysis of aerial photography of dune fields from a kite and generating a digital elevation model (DEM) from the images. This approach yielded promising results. If successful this would be the first technique available to measure the flux of sand transported by either reptation or saltation. Such en information should be critical to test models of eolian transport and erosion.

5.5 Krafla rifting crisis (J. Hollingsworth, S. Leprince, F. Ayoub, J.P. Avouac):

Very little was known about the surface deformation caused by the Krafla crisis, the largest seismic-volcanic crisis to have occurred on a rift system over the last 40 years. This crisis took place from 1975 to 1984. Thanks to the techniques developed as part of this KISS study we were able to measure the displacement field resulting from this rifting crisis from the correlation of SPOT, KH-9 spy satellite, and aerial photos. Correlation of declassified KH-9 spy and SPOT5 satellite images reveals extension between 1977-2002 (3.7 m average opening), while correlation of aerial photos between 1957-1990 provide measurements of the total extension (average 6.2 m opening). We combined these measurements with EDM data and high resolution topographic data to better constrain the 3D deformation associated with the 1975-84 Krafla rifting crisis, NE Iceland. Inversion of the combined datasets provides constraints on the volumes of material injected into the crust during the crisis. Our results are significant as they provide new information on how past dike injection events accommodate long-term plate spreading, as well as providing new details on the Krafla rift crisis in particular.

References:

J. Hollingsworth, S. Leprince, F. Ayoub, J-P. Avouac, “Deformation during the 1975-84 Krafla rifting crisis, NE Iceland, measured by optical image correlation,” American Geophysical Union (AGU) Fall Meeting 2011.

J. Hollingsworth, S. Leprince, F. Ayoub, J-P. Avouac, “Measuring earthquake and volcanic deformation using correlation of spy satellite images,” ASPRS - American Society for Photogrammetry and Remote Sensing (ASPRS) 2012.

J. Hollingsworth, S. Leprince, F. Ayoub, J-P. Avouac, “Deformation during the 1975-84 Krafla rifting crisis, NE Iceland, measured from historical optical imagery,” in press JGR, 2012.

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5.6 Deformation of the Asal Rift, Djibouti – UCLA project (J. Harrington, G. Peltzer, J. Hollingsworth, F. Ayoub, S. Leprince):

The project is the research topic of a UCLA graduate student, Jon Harrington. The goal of this project is to improve our understanding of the faulting and magmatic processes involved in a major rifting episode, which occurred in the Asal-Goubbet Rift in November 1978. Only sparse, ground-based geodetic measurements exist for this event. The idea is to exploit historical aerial photographs and declassified satellite images of the area to correlate with post-event images and measure the horizontal movements associated with the event.

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