Geodetic Imaging for SDI and DRR: Post Earthquake Research & Education

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SUMMARY
Technological advances in LiDAR (Light Detection and Ranging) during the past decade or so have provided an unprecedented opportunity to geodesists to acquire accurate 3D images which provide never-before-available quantitative information for Spatial Data Infrastructure (SDI) and Disaster Risk Reduction (DRR) management in the geosciences community and related fields of science. Airborne LiDAR observations, and such derived products as “bare earth” digital elevation models, are being used to study: earthquake deformation fields, fault slip rates, folding mechanisms, landscape response to tectonics, landslide dynamics, forestry, channel network evolution, marsh evolution, archaeological sites, and many more (Carter et al., 2001, Fernandez-Diaz eta al., 2014, Shrestha et al., 2005). LiDAR technology is still developing rapidly, with high priority being given to multicolor systems that can map hundreds of kilometers of swaths in hours with XYZ point density of 10 - 25 per square meter with vertical accuracy of better than 5 cm.

1. NCALM: THE NATIONAL CENTER FOR AIRBORNE LASER MAPPING

The National Center for Airborne Laser Mapping (NCALM), founded in 2003, is jointly operated by the University of Houston (UH) and University of California, Berkeley. NCALM is funded by the National Science Foundation (NSF) to provide research quality geodetic images, and a variety of derived products, to NSF Principal Investigators. In addition to the research and operational base funding provided by NSF, NCALM receives funding from other federal agencies (e.g., USGS, NASA, NOAA, and the US Park Service), state and local governmental agencies, academic institutions, and private sector companies. During the past 12 years NCALM has completed some 150 projects plus 90 “seed projects” proposed by graduate students as part of their research to earn graduate degrees.

In the last five years NCALM has extended its operations to collect airborne LiDAR observations well beyond the continental United States, including remote projects in Hawaii, New Zealand, Central America (including a project in Guatemala funded by a Japanese group), and Antarctica. As the locations of the projects have become more globally distributed, the research applications have become more diverse, including such activities as management of natural resources and reaction to natural and human induced disasters.

2. AIRBORNE LIDAR TECHNOLOGY

Until technological advances realized largely during the past decade, the spatial and temporal resolutions of geodetic observations simply were not adequate for many applications in related fields of earth science and engineering (Carter et al., 2007). However, the development of geodetic imaging by LiDAR, which can produce decimeter resolution three-dimensional bare-earth images of the surface of the earth covering hundreds of square kilometers from observations collected in hours or days, has brought previously unreachable problems within reach of geomorphologists, geologists, hydrologists, biologists, archaeologists, and engineers, and provided quantitative information to those managing forests, fighting forest fires, responding to flooding and other natural and human-induced disasters (Carter et al., 2013; Gutelius et al., 1998; Shrestha et al., 1999). Optimizing the collection, processing, filtering and interpretation of geodetic imaging data clearly cuts across the traditional boundaries of many areas of engineering and science, including most specifically: electrical, mechanical, and optical engineering; physics; computer science; and geodetic science. Extracting new scientific results from geodetic imaging data requires in-depth communications between the suppliers and users of such data, placing a premium on individuals with sufficient knowledge and skills broad enough to grasp the issues at each step of the process and contribute to a team approach of solving and moving beyond problems encountered (Chase et al. 2011).

The evolution of LiDAR technology can be traced back to early nineteen-seventies, but its explosive growth began in mid-nineties (Figure 1). Despite skepticism of the new technology by personnel in such agencies as state Departments of Transportation (DOT) and Environmental Protection (DEP), the authors in this paper were able to conduct a LiDAR demonstration project in 1996 using a 5kHz LiDAR system and the results were undeniable (Carter & Shrestha, 1998). Both agencies were compelled to recognize the potential savings and increased productivity they could derive by using airborne LiDAR to plan new highway right-of-ways, detect areas of highways potentially subject to landslides and sinkholes, define flood zones, compute loss of sand on beaches, and determine damage to forest from fires. Just as the users of personal computers are always seeking faster CPUs and higher capacity data storage units, users of airborne LiDAR data immediately began to seek ever higher laser pulse rates, and the LiDAR manufacturers have responded as rapidly as advances in laser technology, and the supporting electronics and data storage technologies, have allowed.

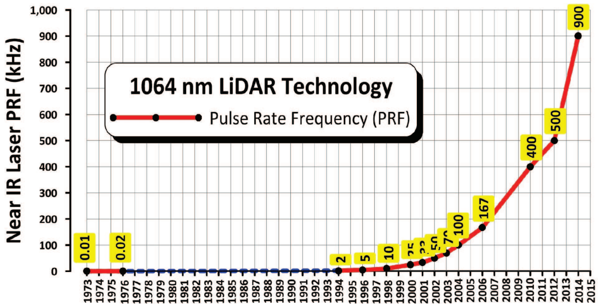

Figure 1. Explosion of laser Pulse Rate Frequency in LiDAR during the last decade. (Data source: Teledyne Optech)

3. NCALM OPERATION

The initial cost of purchasing a LiDAR system is substantial: roughly a million US dollars for a 10 kHz system, in 1998. Since then NCALM has secured three LiDAR systems (Table 1) with increasing PRF, the last being the three color LiDAR - TITAN MW in 2014 with a total PRF of 900 kHz. The Titan unit also contains a high resolution 60 mega-pixel digital aerial camera (Figure 2). Maintaining and operating the system, and processing the observations to extract high resolution geodetic images, can run into the hundreds of thousands dollars per year, depending on the locations and extents of the areas mapped. In addition to the fixed costs there is also a significant learning curve involved in mastering the collection and processing of the observations.

Table 1. NCALM Airborne LiDAR Systems.

Year	Model	λ (nm)	Color
1998	ALTM 1210	1064	Near IR (RED)
2006	GEMINI	1064	Near IR (RED)
2010	AQUARIUS	532	Green
2014	TITAN MW	532, 1064, 1500	Multi-color

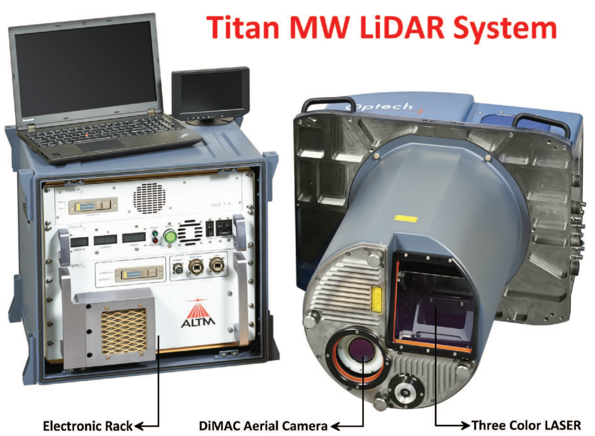

Figure 2. Titan MW three color LiDAR system with a total PRF of 900 kHz.

The approach taken by NSF in establishing NCALM has returned rapid advances in science. During the first decade of operation NCALM has mapped more than 35,000 square kilometers in over 100 locations in 27 States in the United States including Alaska and Hawaii, and seven foreign countries. (Figure 3). These projects have resulted in an ever increasing number of theses and dissertations, and close to 300 papers published (as of May 2015) in refereed journals, including Nature, Science, Proceedings of the National Academy of Sciences, and Physics Today. In 2014, one refereed paper utilizing LiDAR observations collected by NCALM was published, on average, every 6.5 days (Figure 4) (http://ncalm.cive.uh.edu/s). NSF recently approved a proposal to extend the operation of NCALM for an additional five years, beginning September 1, 2013. The data for all of these projects are made freely available to interested researchers, through NCALM's partnership with Open Topography (Crosby et al., 2011), through the web portal www.opentopography.org.

4. NCALM MISSION

NCALM'S three missions are:

(1) Provide research quality data, (2) Advance emerging new sensing technology, and
(3) Educate and train graduate students.

4.1 Research Quality Data: Producing research quality LiDAR observational data and derived products begins with using a well calibrated state-of-the-art sensor, which is necessary but not sufficient to guarantee good results. Even more important factors are the knowledge, experience, and skills of the personnel who carry out each step of the process, which include calibrating the instrument, flight planning, flying the aircraft, operating the LiDAR sensor and supporting instruments, reducing and editing the raw point clouds, examining the data for artifacts and reprocessing to remove or minimize artifacts, filtering the observations, and inspecting the filtered data to make sure that important information has been retained. We use the term ‘‘research quality’’ to characterize LiDAR data collection and reduction procedures that meet the high (and evolving) standards of the scientific research community, as necessitated by their applications of LIDAR data (Slatton et al., 2007). It is not a term that necessarily implies a particular spatial sampling or processing algorithm since the scientific value of the data ultimately depends on all aspects of the collection and reduction procedures and the degree to which those procedures are openly shared with the scientific community.

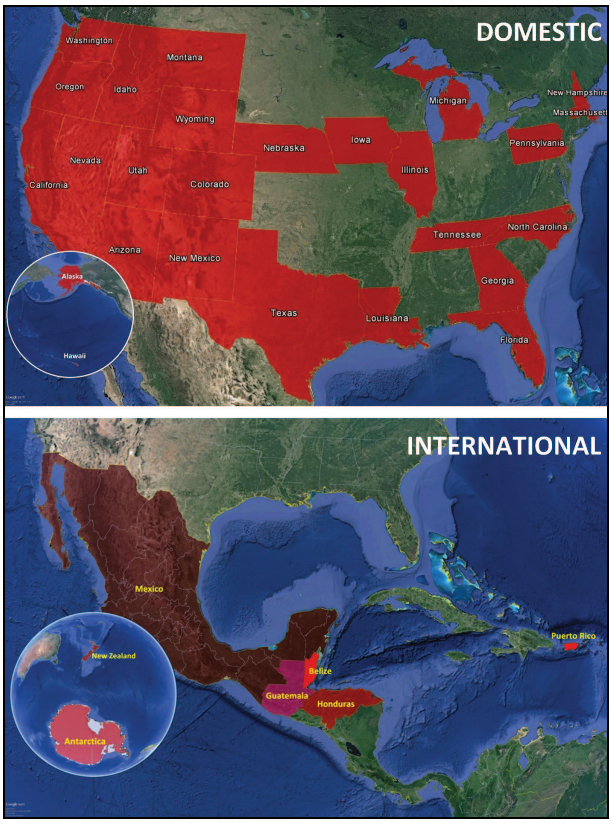

Figure 3. NCALM funded project site locations in 27 States in US (including Alaska and Hawaii) and 7 foreign countries (including New Zealand and Antarctica).

4. 2 Advancing Technology: NCALM has played key roles in advancing the new sensing technology. Although we do not manufacture hardware, our collaboration with the manufacturers we had significant innovative inputs in all of the four LiDAR units we acquired to meet our specific specifications.

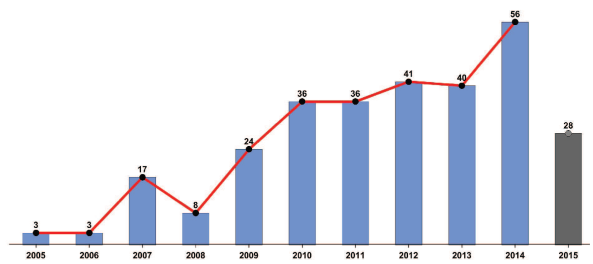

Figure 4. Refereed journal publications using NCALM LiDAR data. A total of 292 as of May 2015. One journal parer every 6.5 days in 2014.

4.3 Education and Training: In 2007 US Department of Labor conducted a comprehensive study, concluding that:

> *"The geospatial technology sector has been selected as one of 14 targeted industries in the High Growth Job Training Initiative primarily because it currently meets many of the criteria for an emerging market sector, and is growing in additional areas as well.... The worldwide market for geospatial technologies has enormous potential. The most frequently quoted growth figures estimated the geospatial market at $5 billion in 2001, with projected annual revenues of $30 billion by 2011. This growth is due to many factors, including the sector's importance to national economic and security interests." The study forecasts a shortage of 3000 to 4000 geospatial professionals in U.S. alone, and even greater outside the United States."*

In addition, American Society for Photogrammetry and Remote Sensing (ASPRS) reports a shortage of geospatial professionals, and that *"the educational community is not meeting the industry need for master's and Ph.D. level graduates with technical training in geospatial technologies."*

4.3.1 Geosensing Graduate Research and Education Program: To address the global need of appropriate educators and professional, NCALM at University of Houston has developed a new Geosensing Graduate Research Program which provides doctoral level education in Geosensing Systems Engineering and Sciences (GSES) to prepare graduates with geospatial background and research skills to successfully embark on academic, national laboratory, or industrial research careers in engineering and sciences here in the United States and abroad. It integrates fundamental principles in engineering, the natural sciences and mathematics to address problems in engineering, geo-spatial information in earth sciences, and related studies in other disciplines that rely on knowledge about the surface of the earth. Under this new program two new degrees have been approved by the State of Texas; (1) MS in Geosensing Systems Engineering and Sciences (GSES), and (2) PhD GSES.

5. SCIENTIFIC FINDINGS DERIVED FROM LiDAR OBSERVATIONS

There are far too many projects and scientific findings to provide a comprehensive overview of the impact that the LiDAR observations collected by NCALM during the past decade have had on various branches of science, in the limited space available here. A more in-depth overview, with an extensive list of references, is presented in (Glennie et al., 2013).

In mountainous areas landslides are generally the dominant form of erosion, but the terrain is often covered with forest, making it difficult to locate and accurately map the extent of past or pending landslides. Monitoring areas subject to landslides using ground survey or aerial photographic techniques is too time consuming and costly to be practical. As a result, in populated areas landslides (including so called mud slides) often result in loss of life and extensive property damage.

Figure 5 is an example of how landslides, even in areas covered with pine forests, can be mapped with LiDAR. Because the 3D coordinates of all points in the geodetic images are known, the perimeter, area, and volume of such landslides can be calculated with better accuracy than ever before. Recently extensive mapping of the Eel River, in California, led to the discovery of the site of a landslide that temporarily blocked the Eel River some 2500 years ago, resulting in a genetic mixing of native anadromous fish (Mackey et al., 2012).

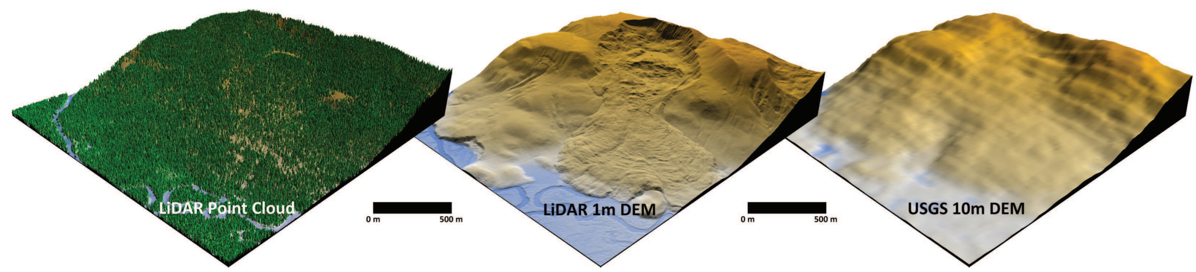

Figure 5. False color geodetic images of an area near the Flathead River, Montana, created with LiDAR data collected by NCALM, revealing a large landslide hidden beneath a forest

Natural disasters such as the April 25 M7.8 earthquake in Nepal cause catastrophic loss of life and property damage. Many earthquakes are located along or very near existing fault lines, but in many places their locations are either unknown, or it is simply not possible to map them by traditional surveying methods. During the past decade NCALM has mapped a majority of the major fault lines in California, including sections that are covered with vegetation varying from desert scrub, to brush, to redwood forests. A total of 5,400 km of fault lines have been mapped by LiDAR and hundreds of researchers and students have used, and continue to use, the observations and derived products to better understand the faulting mechanisms (Figure 6). When future earthquakes occur along those faults it will be possible to re-map the vicinity of the affected fault line and quickly determine the magnitude and pattern of the surface ruptures. Figure 7 represents a small section of the San Andreas fault in Wallace Creek, CA. As seen in the right image, major slip and fault deformation can easily be measured and extracted from the LiDAR observations without ever setting foot on the ground, providing critical information in areas not navigable by foot.

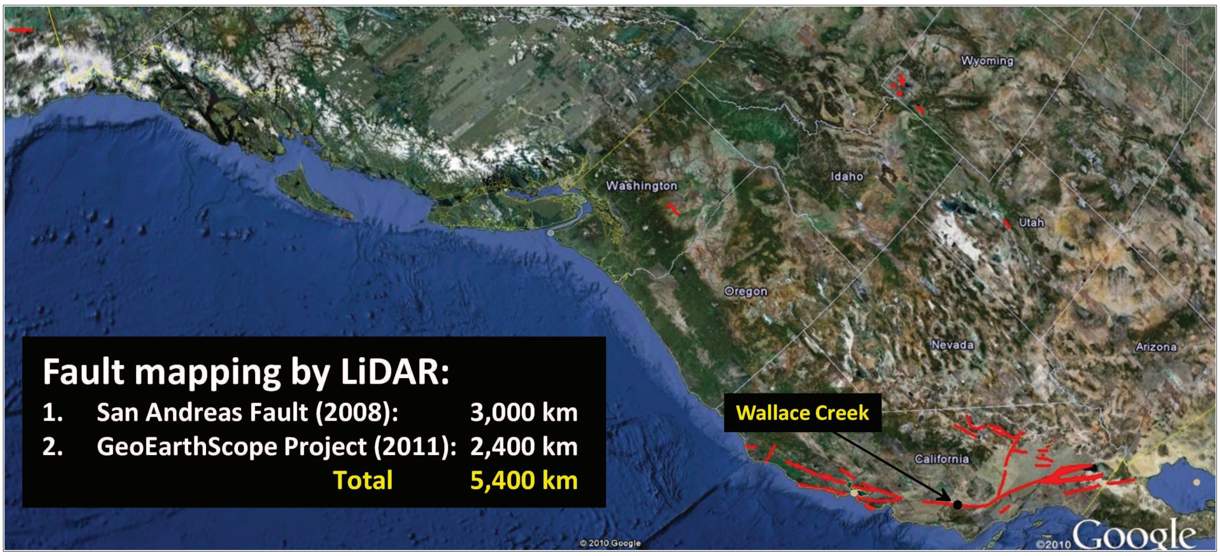

Figure 6. Mapping of San Andreas and other faults in California and beyond.

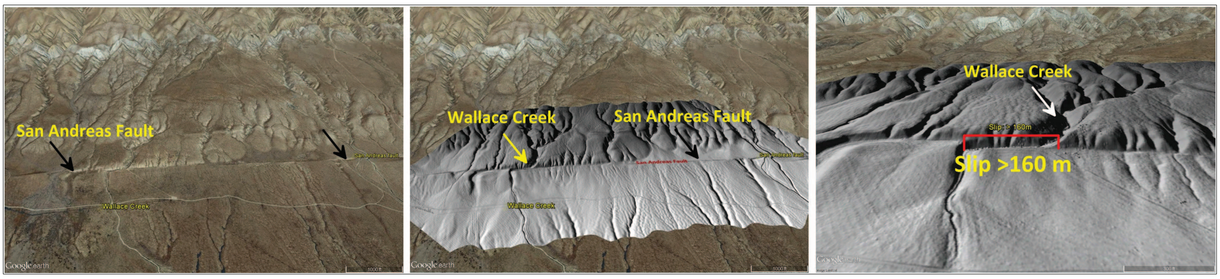

Figure 7. A section of San Andreas Fault near Wallace Creek, CA by LiDAR.

6. HIGHER MAGNITUDE EARTHQUAKES ARE EXPECTED IN NEPAL IN THE FUTURE

The April 25, 2015 M7.8 Nepal earthquake displaced the surface by about 3 meters, killed close to 10,000 people (deadliest in record for Nepal), and displaced millions. But many scientists believe that it did not release all the pent-up seismic stress and it has been estimated that 10 to 15 meters of motion may be required to release the stress, which will cause even more catastrophic loss of life and devastating damage to Nepal's fragile economy (http://www.livescience.com/50638-nepal-bigger-earthquake-risk.html). The consequences of such powerful earthquakes can only be understood by research and education in faulting mechanisms. LiDAR observations can be effectively used to study the nature of faults as it has done for the San Andreas faults. Because of the availability of accurate and timely 3D DAR data sets collected by NCALM, hundreds of scientists and students have gained a better understanding of the mechanism and movement of the San Andreas Fault, and that understanding will enable scientists and managers to better prepare for the next disaster, which will happen sooner or later. Similar effort should be undertaken in Nepal to save lives.

7. POST EARTHQUAKE RESEARCH AND EDUCATION

Nepal extends about 850 km (530 mi) East-West and 225 km (140 mi) North- South, and most faults are along the east-west direction in southern Nepal (Figure 8). Many of the largest earthquakes occur in close proximity to known fault lines. At this moment we don't know the actual total lengths of the faults in Nepal, but since hundreds of kilometers of fault lines (with a swath width of 0.5 km or more) can be mapped by LiDAR within days, the entire network of Nepal faults could be mapped within one year. The data could be immediately made publicly available to research, scientist, planners, managers and decision-makers worldwide, and our experience with San Andreas LiDAR data tells us that countless researchers and students would mount a concerted effort to understand the faulting mechanism in this part of the world. Such a program would undoubtedly result in the savings of llives in the future (Oskin et al., 2012). NCALM has the capability and resources to undertake such an endeavor and would welcome the opportunity to work with the

Government of Nepal and its academia, as well as international agencies to develop such a program at the earliest opportunity.

8. NEPAL HIGHWAYS AND ROADS

Nepal has approximately 3,500 km linear length of 15 National Highways and 2,000 km of 51 Feeder Roads (Figure 9), which are the primary transportation corridors to move goods and people in the most mountainous country in the world. Any disruption in the major highways due to disasters such as earthquakes and frequent landslides during the monsoon seasons brings the transportation system to a grinding halt, causing enormous economic losses. Working with extremely limited resources, Nepal must keep the transportation corridors open, to alleviate the suffering. Access to better geospatial information of the infrastructure by the planners and decisions makers can provide much needed relief that is lacking in Nepal. We would recommend that Nepal undertake a program to map all National Highways and Feeder roads by LiDAR and aerial digital photography (pixel resolution <10 cm). The mapping should be at lease 2 km wide, centered along the transportation corridors. The program should include not only the geospatial data information, but also research and analysis to identify hot-spots for landslides. The proposed data sets would provide much needed geospatial data sets to Nepal for next decade or two and it would provide the framework for the economic development in the future.

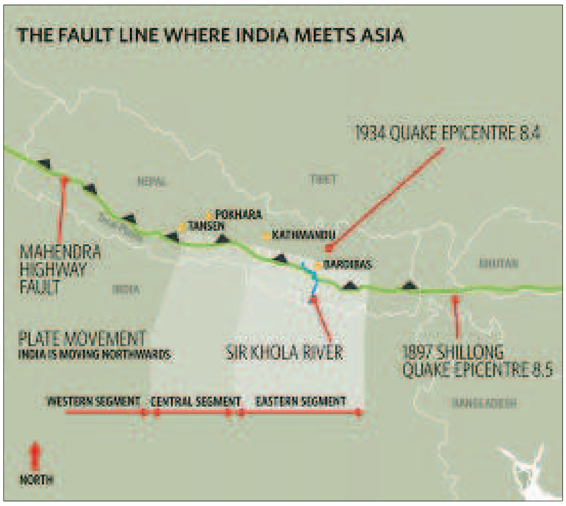

Figure 8. A sample of Nepal Fault.

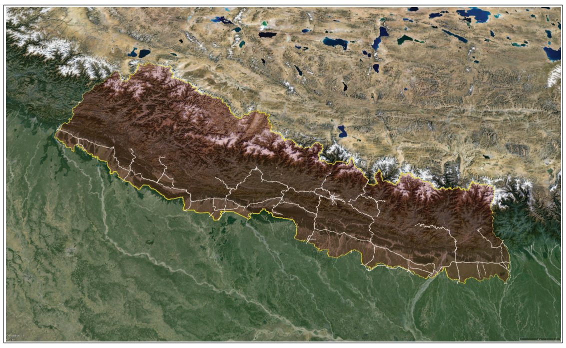

Figure 9. Transportation Corridor Major Highways in Nepal.

9. EARTHQUAKE EARLY WARNING

Earthquake early warning (EEW) systems have been shown to reduce harm to people and infrastructure by providing advanced warning of tsunamis and earthquakes. Unfortunately, EEW systems have not been implemented in most areas of high seismic risk due to the prohibitive cost of installation and maintenance of these systems. The ubiquitous nature of smartphones, currently 1.9 billion worldwide and projected to be ~5.6 billion by 2019 (Fitchard, 2013), identifies them as an alluring target for earthquake detection and warning systems through a crowd-sourced approach. The majority of consumer smartphones now contain an integrated Global Navigation Satellite System (GNSS) chipset that contains a variety of sensors including tri-axial accelerometers and gyroscopes, magnetic compasses and pressure and temperature sensors. In fact, limited initial testing (Minson et al., 2015) has shown that these consumer devices would be able to detect larger magnitude (>Mw 7) earthquakes. Based on these promising initial tests, the USGS and the University of Houston are currently installing an array of ~250 low cost smartphone based earthquake early warning sensors (Figure 10) in Chile.

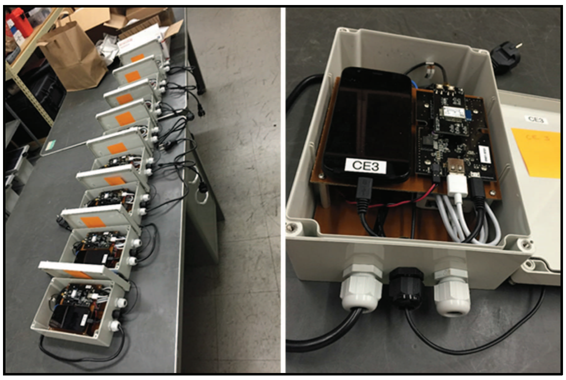

Figure 10. Smartphone based Earthquake Early Warning sensors being deployed in Chile.

10. SYNTHETIC APERTURE RADAR

NCALM research capabilities and resources extend beyond just LiDAR. These include space-based and airborne Synthetic Aperture Radar (SAR), airborne and terrestrial Hyperspectral imaging, GPS, kinematic and terrestrial LiDAR. Glacier velocity and its gradient information of the Himalayas in Nepal are important for the ice mass balance estimation, but the needed ground-based measurements of the glacier velocity are practically impossible to derive. However the space-based SAR enables us to derive ice flow velocity remotely (Strozzi et al., 2008). Figure 11 shows the glacier velocity over the Novaya Zemlya Island in Russian Arctic, generated by the offset-tracking technique with two L-band PALSAR images obtained on 12/13/2008 and 01/28/2009 (Sun et al., 2015). Similar ice velocity maps over the Himalayan glaciers can be obtained using the offset-tracking technique in order to monitor the glacier melt, which directly affects the freshwater availability, under anthropogenic climate change.

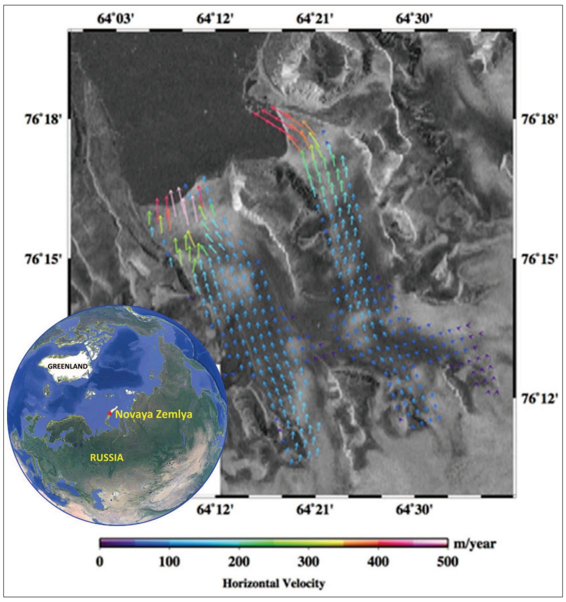

Figure 11. Glacier velocity over Novaya Zemlya in Russian Arctic obtained from SAR offset-tracking technique.

11. CONCLUDING REMARKS

High resolution and accurate Spatial Data Infrastructure by geodetic imaging for Disaster Risk Reduction for Nepal is within reach now, but requires cooperation, collaboration and partnerships between National and International organizations, governments and academia. In this paper we have presented only the use of Airborne LiDAR and aerial digital photography geodetic imaging technology, but the NCALM research and education program has other research expertise and resources that can be utilized to better serve the needs of Nepal for SDI, DRR and other areas such as climate change, flood risk vulnerability assessment, early earthquake warning and land slide. We are committed to do our part, but we can't do it alone. We seek support from the Government of Nepal as well as academia and professionals to help us to establish a sustainable long term research and education needs in SDI and DRR for Nepal.

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BIOGRAPHICAL NOTES

Dr. Ramesh L Shrestha is a Distinguished Professor, University of Houston and the PI & Director of the National Center for Airborne Laser Mapping (NCALM) funded by the National Science Foundation which is the largest non-military research funding agency of the US Government. His research interests are in geodetic imaging using space, airborne and terrestrial geodetic imaging technologies.

Dr. Bill Carter is a Research Professor and Co-PI of NCALM, University of Houston whose research interests are in the development and implementation of new technologies such as Very Long Baseline Interferometry (VLBI) and LiDAR. He was the Chief of the Geosciences Laboratory, NOAA, and led research programs in VLBI, absolute gravimetry and GPS.

Dr. Craig Glennie is an Assistant Professor and Co-PI of NCALM, University of Houston. He conducts research in LiDAR and he has been active in the design, development and operation of kinematic remote sensing systems for 15 years.

Dr. Hyongki Lee is an Assistant Professor University of Houston. He conducts research in the application of space based technologies such as SAR and Satellite Altimeter. He is the recipient of 2015 NASA New Investigator Early Career Award.

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