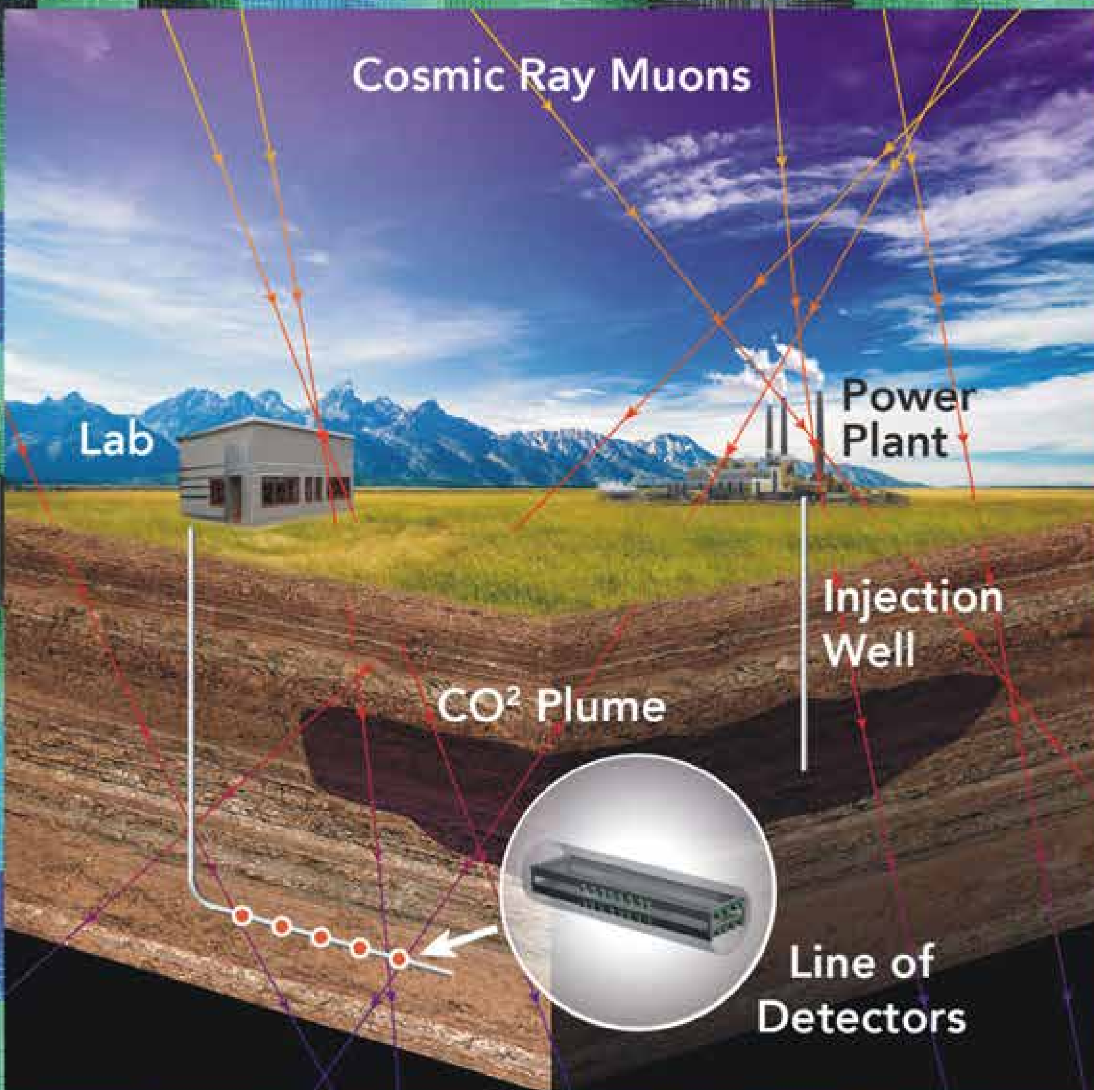
FastTIMES

Special Issue (4 Articles):

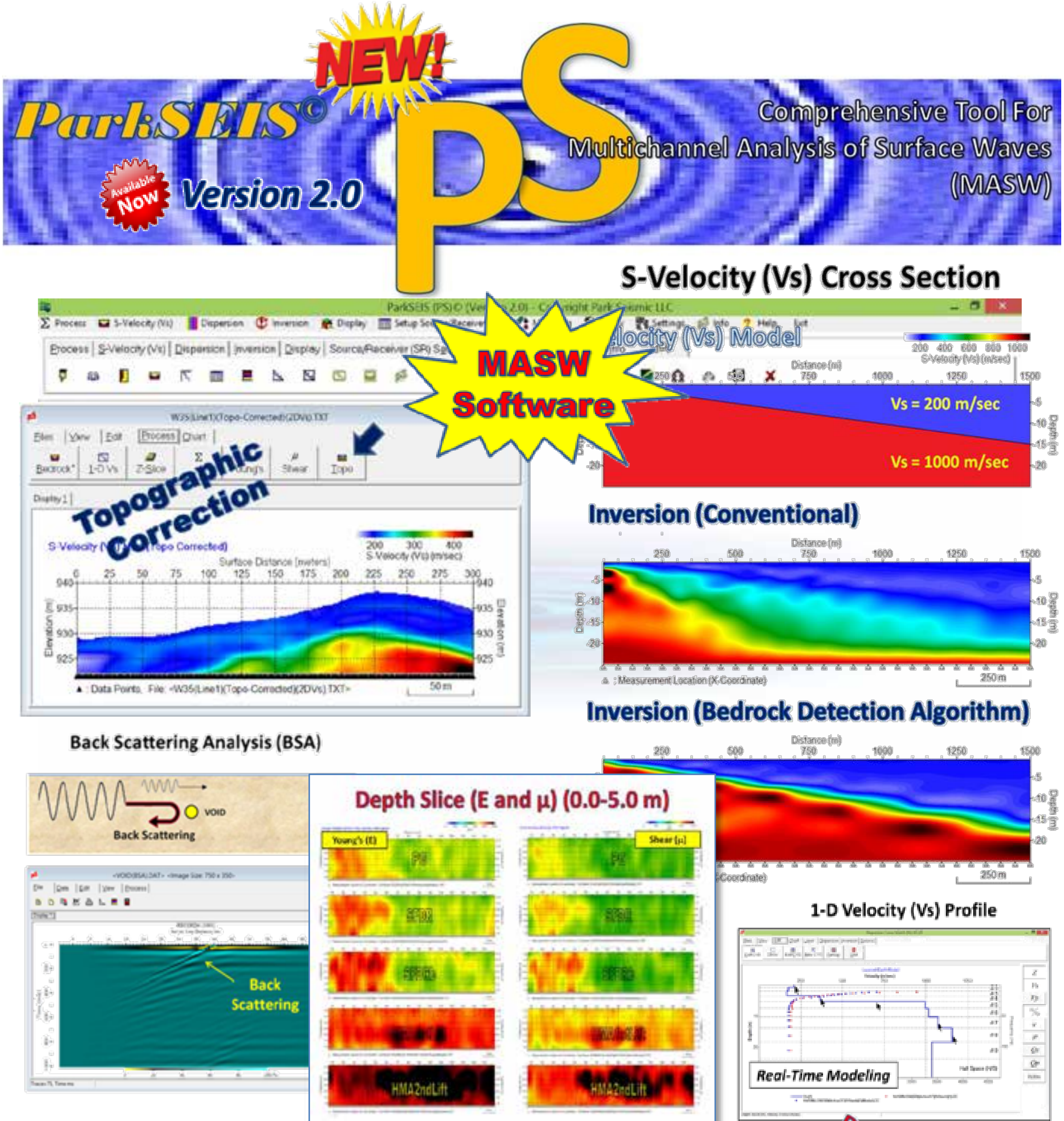
Geophysical Investigations Using Muon Measurements



Also: Drone Topographic Mapping of Great Sand Dunes National Park

December 2016

Volume 21, Number 4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The current issue of *Fast*TIMES is focused on geophysical investigations using muon measurements and includes four articles on this cutting edge topic. There is also a new section on "Drone Geoscience" with an article on the use of an unmanned aircraft system to map topography of the Great Sand Dunes National Park.

Contents

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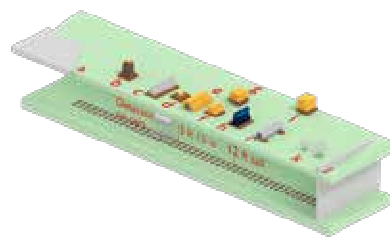

Geophysical Investigation Using Muon Measurements

Also:

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*Fast*TIMES

*Fast*TIMES (ISSN 1943-6505) is published by the Environmental and Engineering Geophysical Society (EEGS). It is available electronically (as a pdf document) from the EEGS website (www.eegs.org).

ABOUT EEGS

The Environmental and Engineering Geophysical Society (EEGS) is an applied scientific organization founded in 1992. Our mission:

"To promote the science of geophysics especially as it is applied to environmental and engineering problems; to foster common scientific interests of geophysicists and their colleagues in other related sciences and engineering; to maintain a high professional standing among its members; and to promote fellowship and cooperation among persons interested in the science."

We strive to accomplish our mission in many ways, including (1) holding the annual Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP); (2) publishing the Journal of Environmental & Engineering Geophysics (JEEG), a peer-reviewed journal devoted to near-surface geophysics; (3) publishing *Fast*TIMES, a magazine for the near-surface community, and (4) maintaining relationships with other professional societies relevant to near-surface geophysics.

JOINING EEGS

EEGS welcomes membership applications from individuals (including students) and businesses. Annual dues are $105 for an individual membership, $50 for introductory membership, $50 for a retired member, $50 developing world membership, complimentary corporate sponsored student membership - if available, and $310 to $4010 for various levels of corporate membership. All membership categories include free on-line access to JEEG. The membership application is available at the back of this issue, or online at www.eegs.org.

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*Fast*TIMES is published electronically four times a year. Please send contributions to any member of the editorial team by February 28, 2017. Advertisements are due to Jackie Jacoby by February 28, 2017.

CALENDAR

2017

February 23 - 24	SurfSeis - Multichannel Analysis of Surface Waves (MASW) Workshop Lawrence, Kansas, USA http://www.kgs.ku.edu/software/surfseis/workshops.html
March 19 - 23	Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP) Denver, Colorado, USA http://www.eegs.org/sageep-2017 (Note: See page 65 for additional information.)
June 28 - 30	9th International Workshop on Advanced Ground Penetrating Radar (IWAGPR2017) Edinburg, Scotland http://www.iwagpr2017.org/
July 24 - 27	AGU-SEG Hydrogeophysics Workshop - Imaging the Critical Zone Stanford, California, USA http://workshops.agu.org/hydrogeophysics/ (Note: See page 68 for additional information.)
August 14 - 15	19th International Conference on Engineering Geophysics (ICEG 2017) Venice, Italy https://www.waset.org/conference/2017/08/venice/ICEG
September 3 - 7	EAGE 23rd European Meeting of Environmental and Engineering Geophysics Malmö, Sweden http://www.eage.org/event/index.php?eventid=1516
September 24 - 29	Society of Exploration Geophysicists (SEG) Annual Meeting Houston, Texas, USA http://seg.org/events/annual-meeting
October 9 - 12	SEG International Conference on Engineering Geophysics (ICEG2017) Al Ain, United Arab Emirates http://seg.org/Events/ICEG2017
December 11 - 15	American Geophysical Union (AGU) Fall Meeting New Orleans, LA, USA http://fallmeeting.agu.org/2017/

Please send event listings, corrections or omitted events to any member of the *Fast*TIMES editorial team.

PRESIDENT'S MESSAGE

Bethany Burton, President

(blburton@usgs.gov)

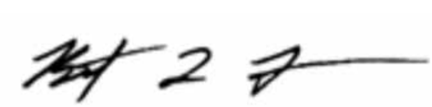
It's hard to believe that 2016 has already passed us by. I hope you had an enjoyable holiday season and wish you a healthy and productive 2017!

With the start of the new year, the 30th Anniversary Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP), to be held in Denver March 19 – 23, 2017, co-located with the National Ground Water Association's (NGWA) Conference on Characterization of Deep Groundwater, is now right around the corner. I'd like to take this opportunity to thank the planning and technical committees, chaired by Dale Werkema and Elliot Grunewald, respectively, for their hard work in putting this conference together. As a volunteer-driven society, SAGEEP wouldn't be possible without the dedication and commitment of the committee members, session chairs, speakers, and student volunteers.

Online registration for SAGEEP is now open. We encourage you to take advantage of the early bird registration rates. EEGS has secured competitive rates at the conference hotel, Denver Marriott City Center. By booking your stay at the conference hotel, you are helping EEGS 1) control the costs of producing SAGEEP, 2) offer registrants the lowest registration rates possible and 3) avoid possible penalties if we fall short of our guarantee. Please consider making your hotel reservation at the Denver Marriott City Center while attending SAGEEP 2017.

As we begin the new year, I'd also like to remind you to renew your EEGS membership for 2017 if you haven't done so already. As you know, every organization must remain financially healthy to function well and to serve its membership. EEGS works hard to operate efficiently and to keep membership costs low. Since 2006 - for 10 years - EEGS has held the line on dues increases for standard individual members in recognition of economic pressures on our membership – the student category dues were reduced to $0 as an investment in EEGS' future. However, operating costs increase, and we must periodically increase membership rates to not only maintain the same level of service but to provide additional benefits. In order to meet the financial demands associated with publishing the Society's Journal, individual members who choose a printed, mailed issue will notice an increase in dues. EEGS has configured its membership categories to allow this choice, but the costs of continuing to offer a print issue have increased. Additionally, the standard (or non-printed JEEG version) EEGS membership category dues have been raised by $15. I hope you will continue to support EEGS by renewing so it can continue to support you and move the near surface geophysics community forward.

Wishing you the best in the new year!



Bethany L. Burton, EEGS President

EEGS Foundation News

30 December 2016 by R. Bell (rbell@igsdenver.com)

Guiding Technologies Today.
Preparing for a World of Needs Tomorrow.

- **Donating to the EEGS Foundation**
- **Seeking Items for Silent Auction at SAGEEP 2017**
- **SAGEEP 2017: Support The Student Event**
- **Richard J. Wold Memorial Scholarship**
- **Geophysical Instruments for Humanitarian Projects**

There has never been a greater need for non-invasive technology capable of obtaining an accurate and precise understanding of what lies beneath our feet near the surface of the earth. The growing global population continues to ratchet up the demand for clean potable water, while simultaneously creating the need to detect, delineate, and mitigate natural geologic hazards and environmental contamination that threaten human lives and property. Drastic changes in the local and global economies are providing the impetus to return contaminated land to productive use and construct infrastructure on difficult geologic conditions. These are just a few of the challenges that geoscientists and engineers tackle today. In order to meet the environmental and engineering challenges of the future, the routine use of near surface geophysical technology must also expand while at the same time the geophysical industry at-large must continue to improve the efficacy of near-surface geophysical technology, enhance the competency of near-surface geophysical practitioners, and expand the knowledge of the customers of near surface geophysics.

The EEGS Foundation is a 501(3)c charitable organization through which individuals and corporations provide financial support for programs designed to encourage the use of geophysics as well as enhance the knowledge of those interested in applying near-surface geophysical technology. The foundation receives funding primarily through the generous tax-deductible donations received from individuals and EEGS members along with donations from EEGS Corporate Members and un-affiliated corporations. In addition, the EEGS foundation holds a Silent Auction fund raiser at the SAGEEP, the Annual Meeting of EEGS.

If you are an EEGS member, or even if you are not an EEGS member, please consider a gift to the EEGS Foundation. A typical gift from an individual is $50. EEGS Corporate members typically provide an annual gift of $2500.00. Of course, giving a larger amount is quite acceptable and much appreciated. Please keep in mind that you also have the option of designating if you wish to have your gift applied to the EEGS Foundation Student Scholarship Fund or the EEGS Foundation General Fund.

Annually, money from the General Fund supports the venue for the Student Event at SAGEEP. The objective is to foster networking between students interested in near surface geophysics, professionals working in the industry, and representatives from industry who might be a future employer. The Student Event has grown to become the "must attend" social gathering of the EEGS Annual Meeting.

If you wish to make a donation via check, please mail it to the following address:

EEGS Foundation
1720 South Bellaire, Suite 110
Denver, CO 80222-4303

If you wish to make a donation via a credit card, please call the EEGS business office at **303.531.7517.** For more information, visit http://www.eegsfoundation.org/. Of course, EEGS Members can always add a donation when they renew their annual membership.

The EEGS Foundation Board of Directors sincerely thank you for your generous donation. It will make a difference and result in positive impact on the future of near surface geophysics.

Seeking Items for Silent Auction at SAGEEP 2017

The EEGS Foundation Silent Auction adds significantly to the foundation's ability to support programs such as the Student Event. Through the generous donations of items from individuals and companies, the foundation has continued build up its General Fund. The foundation is seeking items to auction off during SAGEEP in March 2017. If you have a working but under-utilized geophysical instrument, rock specimens, books, electronics, or any other item that would appeal to a decidedly geo-oriented attendee of SAGEEP, please consider donating it for the Silent Auction. US citizens and corporations are able to take tax deduction for the donation. To learn more or to donate, visit the following link.

http://media.wix.com/ugd/5b5cd8_20d65cb9057f4733bce621e4636e62c0.pdf

or email Doug Laymon (doug@collierconsulting.com).

SAGEEP 2017: Support the Student Event

The Student Event, held every year at SAGEEP, is the "must attend" social gathering at the EEGS Annual Meeting. Students interested in near surface geophysics are able to meet and network with their peers and potential work mates. Geoscience professionals gain the opportunity to exchange thoughts and ideas with the next generation of geoscientists. And company representatives are able to engage and interact with potential employees in an informal, fun setting.

For SAGEEP 2017, the EEGS Foundation will continue its long running tradition of providing financial support for the Student Event. The Foundation is seeking industry partners to help us make the Student Event for SAGEEP 2017 the most enjoyable and successful to date. To learn more about how you can contribute, please email Doug Laymon (doug@collierconsulting.com) or Ron Bell (rbell@igsdenver.com).

Richard J. Wold Memorial Scholarship

A former President of EEGS and my good friend, Richard Wold passed away in 2015. Dick began his geophysical career in the 1950's and obtained a PhD for the development of the first digitally recording airborne magnetometer. Throughout his long and varied career, Dick always maintained a keen interest in better ways to make geophysical measurements. He was instrumental in helping many geophysicists and engineers in their respective efforts to develop and commercialize innovative geophysical technologies. He often did so by connecting the researcher with sources of funding. Dick had a broad array of contacts in the research centers of geophysical research in industry, academia, and government. As many found out, although quiet and assuming, he was a not only one of the "good guys", he was a good guy to know.

I am working with the EEGS Foundation to establish a scholarship in Dick's memory. The scholarship will focus on providing financial support for graduate students who are working on new geophysical measurement or sensor technologies. My goal is to present one or more $5000.00 scholarships on an annual basis to a MS or PhD candidate in geophysics or engineering or related field of study. I plan to award the first scholarship in the Spring of 2018 at SAGEEP 2018.

A selection committee comprised of qualified scientists and industry donors will evaluate applicants and recommend award recipients. Donors making a donation of $25,000 or more will be given the opportunity to participate in the review and selection process. I am seeking individual and corporate donations as well as one or more individuals willing to assist with the development and guidance of the scholarship fund.

If you wish to support this initiative, all you have to do is designate your donation to the EEGS Foundation be applied to the Richard J. Wold Memorial Scholarship Fund.

If you wish to learn more about this initiative, please contact call me at 303-462-1466 or email me at rbell@igsdenver.com.

Geophysical Instruments for Humanitarian Projects

One of the most engaging and exciting initiatives presently under discussion by the EEGS Foundation Board is the concept of a repository of geophysical instruments to be used for humanitarian projects at little or no cost. As one can imagine, there are a bunch of details to be worked through, not the least of which is how to facilitate the access to the gear.

The EEGS Foundation is seeking your input on the concept. If you have any thoughts, ideas, suggestions or perhaps wish to help with the formation of the repository, please email Dennis Mills (dmills@expins.com).

EEGS Foundation Board of Directors (December, 2016)

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NOTES FROM EEGS

Renew your EEGS Membership for 2017

Be sure to renew your EEGS membership for 2017! In addition to the more tangible member benefits (including the option of receiving a print or electronic subscription to JEEG, *Fast*TIMES delivered to your email box quarterly, discounts on EEGS publications and SAGEEP registration, and benefits from associated societies), your dues help support EEGS's major initiatives such as producing our annual meeting (SAGEEP), publishing JEEG, making our publications available electronically, expanding the awareness of near-surface geophysics outside our discipline, and enhancing our web site to enable desired capabilities such as membership services, publication ordering, and search and delivery of SAGEEP papers. You will also have the opportunity to donate to the EEGS Foundation during the renewal process. Members can renew by mail, fax, or online at www.eegs.org.

Lifetime Membership

In a move to enable those who wish to join EEGS once and support the organization and receive benefits without renewal, the EEGS Board of Directors approved the formation of a membership category "Lifetime Member." Longtime EEGS member Professor Oliver Kaufmann became the first Lifetime Member in January 2016. Past EEGS President, Lee Slater, welcomed Prof. Kaufmann and said "learning about our first Lifetime Member was one of the high points of my one-year tenure as president of EEGS." President Slater also commended Prof. Kaufmann for his commitment to EEGS and his role in assuring the long-term health and value of EEGS.

Sponsorship Opportunities

There are always sponsorship opportunities available for government agencies, corporations, and individuals who wish to help support EEGS's activities. Specific opportunities include development and maintenance of an online system for accessing SAGEEP papers from the EEGS web site and support for our next SAGEEP. Make this the year your company gets involved! Contact Bethany Burton (blburton@usgs.gov) for more information.

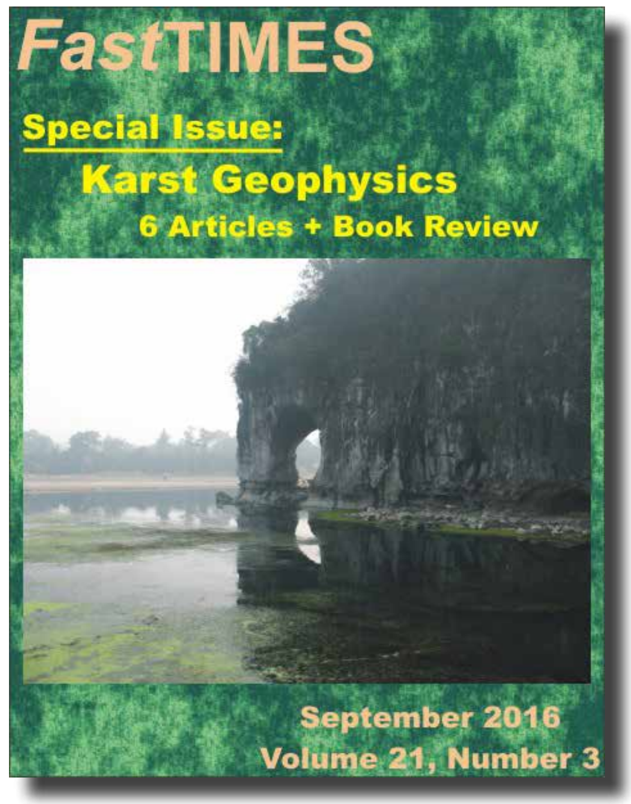
From the *Fast*TIMES Editorial Team

*Fast*TIMES is distributed as an electronic document (pdf) to all EEGS members, sent by web link to several related professional societies, and is available to all for downloading from the EEGS *Fast*TIMES web site (http://www.eegs.org/fasttimes). Past issues of *Fast*TIMES continually rank among the top downloads from the EEGS web site. Your articles, advertisements, and announcements receive a wide audience, both within and outside the geophysics community.

To keep the content of *Fast*TIMES fresh, the editorial team strongly encourages submissions from researchers, instrument makers, software designers, practitioners, researchers, and consumers of geophysics—in short, everyone with an interest in near-surface geophysics, whether you are an EEGS member or not. We welcome short research articles or descriptions of geophysical successes and challenges, summaries of recent conferences, notices of upcoming events, descriptions of new hardware or software developments, professional opportunities, problems needing solutions, and advertisements for hardware, software, or staff positions.

The *Fast*TIMES presence on the EEGS web site has been redesigned. At http://www.eegs.org/fasttimes you'll now find calls for articles, author guidelines, current and past issues, and advertising information.

Special thanks are extended to Nedra Bonal for her leadership in developing this issue of *Fast*TIMES with its focus on geophysical investigations using muon measurements.



Submissions

The *Fast*TIMES editorial team welcomes contributions of any subject touching upon geophysics. *Fast*TIMES also accepts photographs and brief non-commercial descriptions of new instruments with possible environmental or engineering applications, news from geophysical or earth-science societies, conference notices, and brief reports from recent conferences. Please submit your items to a member of the *Fast*TIMES editorial team by February 28, 2017 to ensure inclusion in the next issue. We look forward to seeing your work in our pages. Note: *Fast*TIMES continues to look for Guest Editors who are interested in organizing a *Fast*TIMES issue around a special topic within the Guest Editor's area of expertise. For more information, please contact Barry Allred (Barry.Allred@ars.usda.gov), if you would like to serve as a *Fast*TIMES Guest Editor.

Message from the Organizing Editor of This *Fast*TIMES Issue

Muon use for subsurface imaging has expanded rapidly in recent years. Muons are naturally occurring elementary particles similar to an electron. They can be used to image through objects analogous to x-ray radiography. Unlike x-rays, muons can pass through very large and dense objects. Also, since muons are passive and naturally occurring, they are not harmful like x-rays. Changes in muon flux through an area correspond with differences within that area like voids or changes in geology provided these differences have sufficient contrast in density.

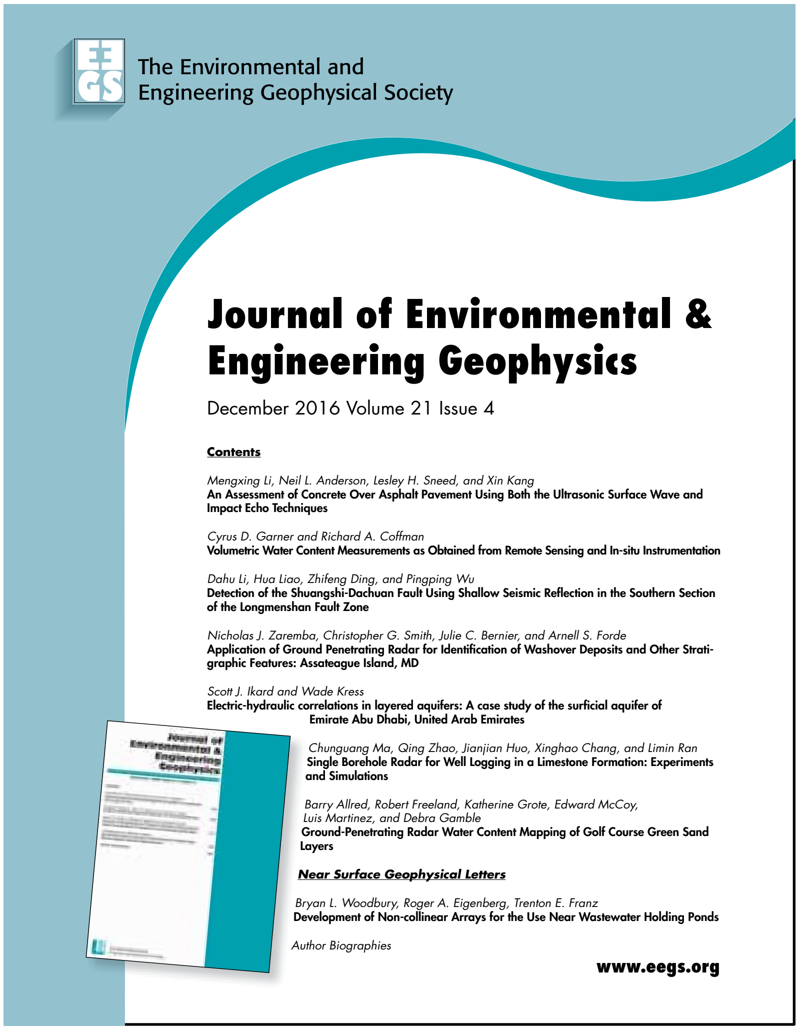
In this special issue of *Fast*Times, muon use for geophysical applications is presented by scientists in academia and government laboratories. **Bonal, Dorsey, Dreesen, Green, and Schwellenbach** explain muon detectors and modes of acquisition used for imaging and demonstrate how muon measurements are affected by density. They show experimental examples of muon images of density contrasts and a simulation of a muon image of a tunnel. **Mellors, Chapline, Bonneville, Kouzes, Bonal, Rowe, and Guardincerri** describe how muon imaging can improve the resolution of other near surface geophysical methods. Muon observations can constrain density estimates consistent with seismic velocity measurements. Joint inversion with gravity should also help constrain density results. **Bonneville and Kouzes** reveal how muon measurements can be used to get a static density image or to identify density variations and fluid content as a function of time. They also present the prototype for their borehole muon detector, which is a novel development for underground muon imaging. **Schwitters and Schreiner** show a wonderful experimental example of how muons can determine the location, shape, and density of various objects and describe techniques to obtain good quality images. Advantages of their unique cylindrical detector are also portrayed.

I hope you enjoy this issue. I look forward to continued advancements in this field.

Nedra Bonal, *Fast*TIMES Associate Editor, nbonal@sandia.gov

JEEG INFORMATION

The Journal of Environmental & Engineering Geophysics (JEEG), published four times each year, is the EEGS peer-reviewed and Science Citation Index (SCI®)-listed journal dedicated to near-surface geophysics. It is available in print by subscription, and is one of a select group of journals available through GeoScienceWorld (www.geoscienceworld.org). JEEG is one of the major benefits of an EEGS membership. Information regarding preparing and submitting JEEG articles is available at http://jeeg.allentrack.net.



The Environmental and Engineering Geophysical Society

Journal of Environmental & Engineering Geophysics

December 2016 Volume 21 Issue 4

Contents

Mengxing Li, Neil L. Anderson, Lesley H. Sneed, and Xin Kang
An Assessment of Concrete Over Asphalt Pavement Using Both the Ultrasonic Surface Wave and Impact Echo Techniques

Cyrus D. Garner and Richard A. Coffman
Volumetric Water Content Measurements as Obtained from Remote Sensing and In-situ Instrumentation

Dahu Li, Hua Liao, Zhifeng Ding, and Pingping Wu
Detection of the Shuangshi-Dachuan Fault Using Shallow Seismic Reflection in the Southern Section of the Longmenshan Fault Zone

Nicholas J. Zaremba, Christopher G. Smith, Julie C. Bernier, and Arnell S. Forde
Application of Ground Penetrating Radar for Identification of Washover Deposits and Other Stratigraphic Features: Assateague Island, MD

Scott J. Ikard and Wade Kress
Electric-hydraulic correlations in layered aquifers: A case study of the surficial aquifer of Emirate Abu Dhabi, United Arab Emirates

Chunguang Ma, Qing Zhao, Jianjian Huo, Xinghao Chang, and Limin Ran
Single Borehole Radar for Well Logging in a Limestone Formation: Experiments and Simulations

Barry Allred, Robert Freeland, Katherine Grote, Edward McCoy, Luis Martinez, and Debra Gamble
Ground-Penetrating Radar Water Content Mapping of Golf Course Green Sand Layers

Near Surface Geophysical Letters

Bryan L. Woodbury, Roger A. Eigenberg, Trenton E. Franz
Development of Non-collinear Arrays for the Use Near Wastewater Holding Ponds

Author Biographies

www.eegs.org

December 2016 - Volume 21 - Issue 4

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Editor's Note

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The Journal of Environmental and Engineering Geophysics (JEEG) is the flagship publication of the Environmental and Engineering Geophysical Society (EEGS). All topics related to geophysics are viable candidates for publication in JEEG, although its primary emphasis is on the theory and application of geophysical techniques for environmental, engineering, and mining applications. There is no page limit, and no page charges for the first ten journal pages of an article. The review process is relatively quick; articles are often published within a year of submission. Articles published in JEEG are available electronically through GeoScienceWorld and the SEG's Digital Library in the EEGS Research Collection. Manuscripts can be submitted online at http://www.eegs.org/jeeg.

SUCCESS WITH GEOPHYSICS

*Fast*TIMES welcomes short articles on applications of geophysics to the near surface in many disciplines, including engineering and environmental problems, geology, hydrology, agriculture, archaeology, and astronomy. The current issue of *Fast*TIMES is focused on geophysical investigations using muon measurements and has four articles devoted to this cutting edge topic. As always, readers are very much encouraged to submit letters to the editor for comments on articles published in this and previous *Fast*TIMES.

USING MUONS TO IMAGE THE SUBSURFACE

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Introduction

Locating and characterizing subsurface structures such as tunnels and underground facilities remains a difficult problem. Muons are subatomic particles produced in the upper atmosphere, which penetrate the earth's crust up to few kilometers. Their absorption rate depends on the density of the materials including fluids through which they pass. Measurements of muon flux rate at differing directions provide density variations of the materials between the sky and detector from those directions, similar to a CAT scan. Therefore, the use of muons for subsurface investigation seems promising.

Alvarez et al. (1970) used muons to search for hidden chambers within the Egyptian pyramids. The results of Alvarez's work proved that the Pyramid of Khafre (the second pyramid) does not have any hidden chambers like those in the Pyramid of Khufu (the first pyramid). Nagamine et al. (1995) pioneered the technique of using muons to investigate volcanoes. Interest in using muons has expanded in recent years (Borozdin et al. 2003, Jourde et al., 2013, Lespare et al., 2010, Tanaka et al., 2003).

Keywords: Muon Flux, Scintillation Counters, Gas Wire Detectors, Tomographic Imaging Mode, Telescopic Imaging Mode, Density Assessment.

Muon Detectors

There are several types of instruments that can detect muons. The ones most commonly used for tracking muons include scintillation counters and gas wire detectors such as drift tubes and cathode strip chambers. When muons and other charged particles hit scintillating materials, photons are emitted through ionization. A photomultiplier is used to amplify the current to a measurable signal. Scintillators are typically used for counting/detecting muons. In gas wire detectors, electrons are knocked off the gas atoms when other charged particles pass through the gas. These electrons then drift toward the positively charged wire in the detector where gas amplification occurs creating a detectable signal. The distance away from the wire that the muon hit the gas can be determined by the time taken for the electrons to drift through the gas to the wire as shown in Figure 1 for the gas wire or drift tube example. A series of drift tubes are needed to increase the resolution of the muon hit location and track its path. Drift tubes are aligned in parallel and stacked in X and Y directions. The intersection between the X and Y tubes hit by a muon helps constrain the hit location. Multiple X and Y layers of tubes provide greater resolution and help eliminate charged particles other than muons. Drift tubes and scintillation counters are commonly used in accelerators for particle physics applications.

Figure 1: Drift tube detector: series of drift tubes in X and Y orientations. The expanded tube show electrons drifting toward the wire after the gas in the tube is ionized by a passing muon. The muon would have hit this tube tangent to the green circle.

Modes of Acquisition

Two modes of data collection are discussed: tomographic and telescopic. Additional methods including stopped tracks are often utilized but not addressed here. The tomographic mode uses two sets of muon detectors (Figure 2) to image objects between the two detectors. Having two detectors enables tracking of individual muons in and out of the volume between them. The tomographic mode of imaging with muons relies on Coulomb scattering of the muons. The scattering angle of the muon is governed by density of the material the muon passed through (Figure 2). This angle can be calculated using the two detectors for each muon and the material between the detectors can then be inferred. Additionally, the location and size of the material can be mapped in three-dimensions. A drawback to the tomographic mode is that access to two sides of the object is required, which may not be practical for many applications and ideally the objects need to be small enough to fit between the two detectors.

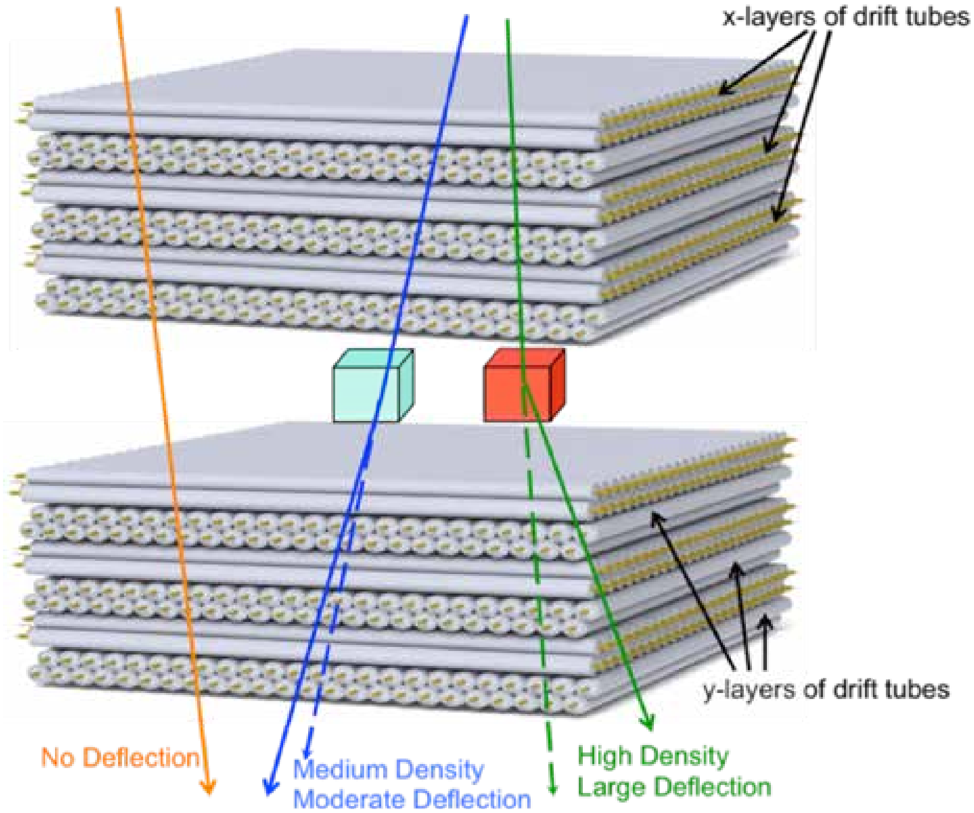

Figure 2: Tomographic imaging mode.

Telescopic mode requires only one detector, so access to only one side of the object is needed (Figure 3). This is sometimes referred to as transmission muon radiography and can produce 2D images of objects, similar to x-ray and gamma ray radiography. Also, very large objects like volcanoes can be imaged using this mode. However, lower resolution images are produced because the scattering angle of the muon through material cannot be measured. Additionally, acquisition times are typically longer since less information (no scattering angles) is obtained. The telescopic mode relies on attenuation of the number of muons (flux) passing through the materials because the incoming cosmic ray muon flux is fairly constant. More muons are attenuated in higher density materials so the flux is lower compared to lower density materials like air for example (Figure 3). Telescopic mode is often used to detect muons that are traveling nearly horizontally, like those needed to image a mountain.

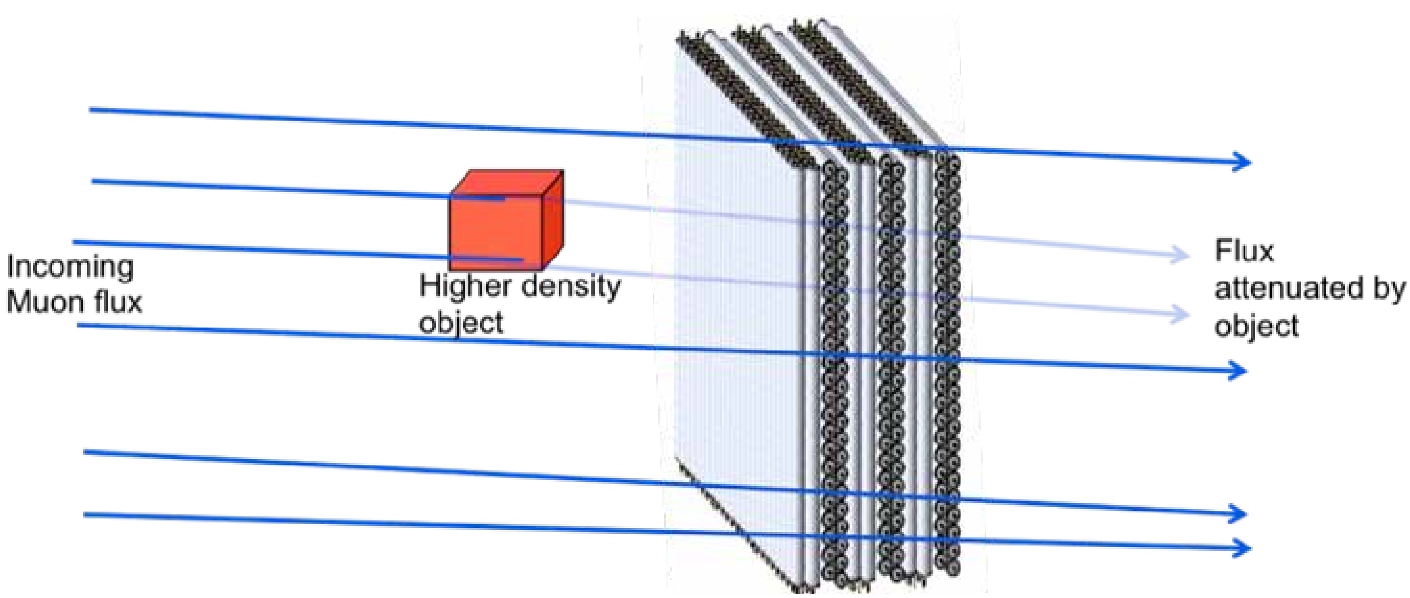

Figure 3: Telescopic imaging mode.

Examples of Muon Imaging

Our current muon work includes density assessment and measuring muon direction. Improving our understanding in these areas will enhance muon images and increase the application space for muon imaging.

Muon fluxes are sensitive to densities. Therefore, muon data can be used to determine relative density differences of objects. Much work has been done using muons to detect high-density materials (Borozdin et al., 2003) but not low-density materials. We conducted a muon tomography experiment to detect a low-density material. A book (low density) and a sphere of tungsten (high density) were placed inside a lead box as shown in Figure 4 on the left. Muon data were collected over 1440 minutes (24 hours) using the tomographic mode. A 3D image of the lead box and contents was constructed from the muon hits and scattering angles. A horizontal slice of the 3D image is shown in Figure 4 on the right. Darker blues and reds in the reconstructed image represent higher density. The outline of the low-density book is also distinguished in the image. Though improvements can be made to further enhance the image in Figure 4, such as increasing acquisition time, this experiment demonstrates the feasibility of muon tomography for detection of low-density materials inside high-density material (e.g. the lead box).

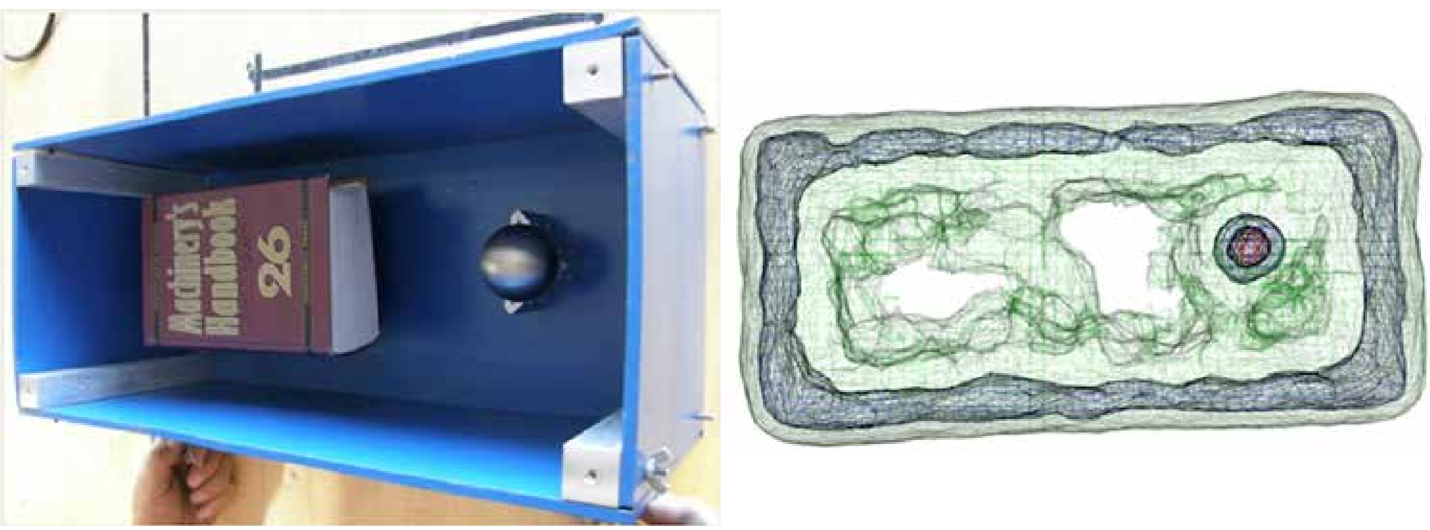

Figure 4: A book (low density) and a sphere of tungsten (high density) inside a lead box (left) with the corresponding muon image in 2D (right).

We also conducted a simulation of muon flux through rock with an air-filled void to demonstrate how muons can be used to map density changes using the telescopic mode. Figure 5 illustrates the layout of this simulation and the resulting muon image. A cube of silica representing standard rock with a density of 2.65 g/cm^3 with an air-filled cylindrical hole in the center is hit with high-energy muons on one side and detected on the opposite side of the cube. The resulting muon image shows higher flux of muons around the cube (red), a moderate flux in the center where the void is located (green), and the lowest flux through the solid cube where there is no void (blue). This result is similar in concept to theoretical studies by Malmqvist et al. (1979). The Malmqvist et al. (1979) study found that density anomalies could be found using muon measurements, which would be applicable for prospecting specifically for massive sulfide and iron explorations.

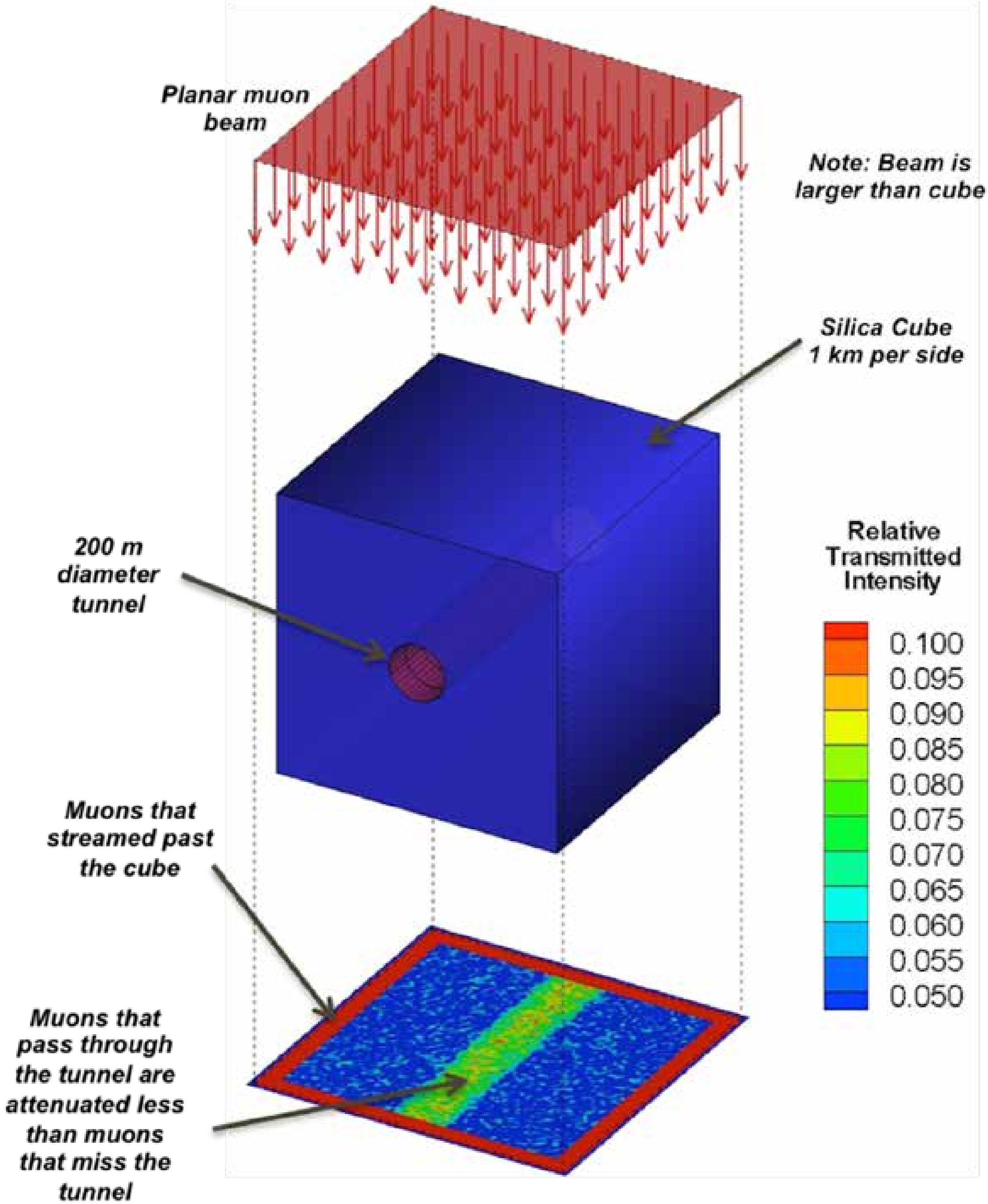

Figure 5: Simulation results of muon flux after passing through a cube of rock (e.g. silica) with an air-filled tunnel.

Determining the direction a muon is traveling is important for some applications. Detectors record muons coming from the direction of the object of interest and from the opposite direction. This is usually not a problem when imaging objects using vertically traveling muons because muons traveling upward are insignificant compared to the large flux of downward traveling muons. Muon flux decreases with zenith angle by approximately $\cos^2$. This means that the greatest flux is from muons traveling vertically downward from a zenith angle of 0° and the flux is significantly lower from muons traveling horizontally with a zenith angle of 90°. Imaging targets like mountains requires use of muons traveling nearly horizontally at high zenith angles. For this case, the flux of muons from the desired direction is on the order of the flux from the opposite direction, resulting in a significant amount of "noise" (Figure 6). Determining the directionality each muon is traveling will eliminate this source of noise. Longer acquisition times will also increase the resolution of the image.

Figure 6: Photo (left) of mountain being imaged (right) from horizontally traveling muons in telescopic mode. The lighter area in the top portion of the figure on the right represent the mountain in the photo on the left. The lighter area in the bottom portion of the figure on the right is due to "noise" from muons detected from the opposite direction.

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MUONS AND SEISMIC: A DYNAMIC DUO FOR THE SHALLOW SUBSURFACE?

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Introduction

Muons were first used to estimate tunnel overburden in 1955 (George, 1955), yet for several decades the technology remained largely unused by geoscientists. Recently, driven by improvements in technology and computing, muon imaging is developing slowly into a useful tool capable of resolving subtle 3D density variations in the subsurface (Lesparre et al., 2010). It has been applied to image magma flow in volcanoes and ore bodies in mines (Tanaka et al., 2015; Bryman et al., 2014). The advent of borehole muon sensors will provide a new realm of potential uses (Bonneville et al., 2015). With further improvements in muon sensors and analysis tools, it is expected that muons may become part of the standard toolkit for specific imaging needs.

Muon imaging uses the constant downward flux of muons emanating from the collisions of cosmic rays with the atmosphere to infer variations in density in the subsurface. As this flux is natural and ongoing, no hazard to the operator is presented (unless you happen to be in a deep mine, numerous muons will pass through you while reading this article). The flux at the surface is approximately 160 muons per meter^2 per second and although most muons travel near vertical paths, some arrive at near horizontal angles. The muons continue in straight lines into the subsurface to depths of 100's of meters, although the flux drops dramatically with depth. Flux decreases to approximately 0.3 muons per meter^2/s at 100 m depth and 0.001 muons per meter^2/s at a depth of 1 km (Robinson et al., 2003; Mei and Hime, 2006). The exact rate of decrease depends on the density along the path. Hence, if the muon flux is measured at depth, an image of the density variations in the material above the sensor can be created. A 3D tomographic image can be created with multiple sensors or by moving one sensor periodically. A key advantage of muon density measurements over other methods of density estimation, such as gravity or borehole density log, is that they are capable of measuring density changes with relatively high spatial resolution away from the sensor.

The resolution of the image is defined primarily by the number of recorded muons, which in turn depends on the deployment length. Longer deployments will provide better resolution, up to the

Keywords: Muons, Density Imaging, Seismic, Void Detection.

limits of the angular resolution of the instrument. An alternate strategy is to use the muon flux over time to measure changes in density due to CO_2 injections or perhaps tunneling.

The propagation of muons in the subsurface is well understood as the muon flux is carefully measured in places such as a former gold mine in South Dakota for underground particle physics experiments (e.g., Mei and Hime, 2006). Consequently, several sophisticated simulation and analysis software routines already exist (such as the GEANT4 package), although these packages are not well-suited for most geoscience use; at least not directly. Several types of muon sensors exist and vary in sensitivity, size, resolution, and cost.

The primary drawback to muon imaging is that the sensor must be below the desired target although not necessarily directly underneath. A secondary problem is that at depths greater than a few hundred meters, the flux is low and weeks or months may be required to achieve reasonable resolution. Therefore, muon imaging is best suited for shallow applications.

As shallow geophysical surveys often employ multiple techniques, the question arises as to how muon imaging can be combined with other geophysical methods to improve the resolution. One possible approach is to combine muon imaging with seismic imaging. Seismic data represents almost the exact opposite of muon imaging: it is a mature technology and is most widely used when the sensors are above the target, although exceptions, such as vertical seismic profiling, do occur. Seismic resolution also depends primarily on the frequency of the seismic waves and hence resolution is independent of deployment time except for improvements in signal-to-noise. However, both seismic waves and muons are sensitive to density and therefore the potential for joint imaging exists.

This paper explores, at a preliminary level, the possibility of merging seismic data, both active and passive, with density constraints inferred from muon measurements. We focus on a theoretical analysis but note that muon experiments are ongoing to test model predictions with experimental data.

Methods

Muon flux at a given depth depends on the energy spectra of the incoming muon flux at the surface, as the distance of penetration depends on the initial energy and the cumulative path density. In the following work, we assume that the muon flux at the surface is known and that we have 'perfect' muon sensors at depth that are capable of measuring the flux to a high level of accuracy. For simplicity, we assume that all muons are traveling in vertical or near vertical paths. This is a reasonable assumption, although we note that off-vertical paths provide much of the potential usefulness of muon imaging. This will be explored in later work.

The basic equation defining muon loss is Equation 1, where Q is the opacity, or the integrated density (ρ) along the path **ε** (Lesparre et al., 2011).

$$Q(L) = \int_L^0 \rho(\mathcal{E})\,d\mathcal{E} \tag{1}$$

Equations 2a and 2b show the velocity for seismic body waves (P and S) in a homogenous non-porous media with elastic constants μ (shear modulus) and λ (Lamé' constant). Vp represents the P wave velocity and Vs is the shear wave velocity.

$$Vp = \sqrt{\frac{\lambda+2\mu}{\rho}} \qquad Vs = \sqrt{\frac{\mu}{\rho}} \tag{2a,b}$$

In this initial study, we do not consider poro-elastic effects, although this will be needed for more sophisticated approaches. It is clear that seismic data alone cannot resolve variations in density and elastic constants as the variables are related. However, muon observations can constrain the density. An estimate of the density combined with the seismic wave propagation velocity (for both P and S) will allow determination of the elastic constants. An exact knowledge of the elastic constants is useful for modeling of rock mechanics as is needed for tunnel design. It may also be useful in imaging variation in lithology.

The next problem is how to combine the two datasets in a quantitative manner. We explore two basic concepts using different seismic data with muon-based path density estimates: 1) seismic travel times, and 2) acoustic impedance. The goal is to present simple example scenarios to guide later experiments. The seismic data may allow other measurements (e.g., amplitude versus offset, anisotropic effects) that permit additional constraints on subsurface structure that we do not address here.

As a first example, we assume a perfect muon sensor that measures all vertically incident muons. We imagine one muon detector on the surface and another at a depth of 500 m. The deep sensor is co-located with a three-component seismic sensor. A seismic source capable of generating both P and S waves is placed on the surface above the deep sensor location. The material is assumed to be homogenous, non-porous and isotropic (Figure 1).

We want to solve for the density and the elastic constants of the intervening layer. Seismic data alone cannot resolve the three unknown values. The muon sensor yields a measure of the path integrated average density between the sensor and the surface. A P-wave travel time cannot independently resolve the two elastic constants even if the density is known; however, an S wave travel time is dependent only on μ, and in conjunction with P wave travel time, therefore allows resolution of the two elastic constants. If both P and S travel times are measured and a muon flux is measured, then all three unknown parameters (μ, λ, and ρ) can be estimated, with an accuracy depending on the observation errors. Therefore, a combination of muon and seismic data is effective at resolving both the density and the elastic constants (μ and λ). Testing of this idea using simple numerical simulation was conducted by Mellors et al. (2016) with good results.

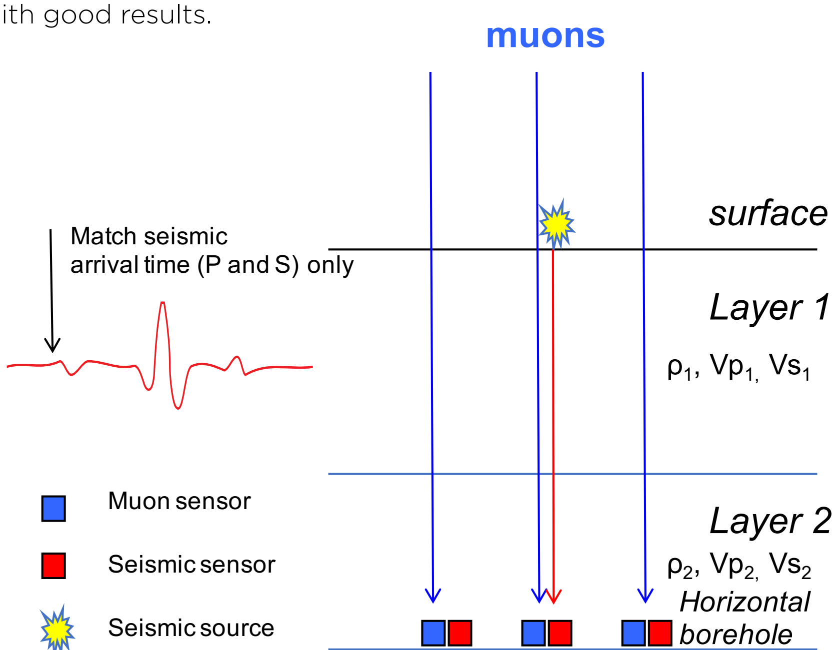

Figure 1: Schematic cartoon showing a possible muon/seismic instrument deployment in a simple two-layer model. Both the seismic and muon sensors are assumed to be col-located in a horizontal borehole (or perhaps tunnel). In this simplified case, a seismic source is assumed on the surface and muons are traveling vertically downwards. Measurements of seismic travel time from the surface combined with the path density derived from the muon measurements allow estimation of the density and elastic parameters in each layer, if both P and S travel times are measured. Note that muons travel at a range of angles and are not restricted to vertical paths.

The second example assumes a set of muon detectors in a horizontal borehole or perhaps a tunnel. A seismic reflection survey has been conducted over the area and reflection coefficients are available for layer boundaries above the muon detectors (Figure 2). The objective is to combine estimates of the acoustic impedance ($Z = (Vp)(\rho)$) where Vp is the seismic P wave velocity and ρ is the density derived from seismic data. The acoustic impedance is useful for distinguishing lithology and also in determining the reflection coefficient (RC) of the seismic waves. For vertical incidence, the reflection coefficient (RC) is:

$$\mathbf{RC} = \frac{\mathbf{Z_2 - Z_1}}{\mathbf{Z_2 + Z_1}} \tag{3}$$

In contrast to the first example, we presume that only the P wavefield (timing and amplitudes) is measured at surface sensors. We do not assume that seismic sensors are coincident with the muon sensors. Measured quantities are the layer boundary depth, two-way zero offset reflection travel times, the reflection coefficient and muon opacity measurements from below the layer.

Testing of this idea using synthetic tests show that combination of both muon data and seismic data improves the estimate of the lower layer density over independent estimates using only seismic or muon data. The increase in resolution is not dramatic, in part due to the indirect dependence of RC on density. It would be possible to implement this for a 2D or 3D model, by matching lateral variations in reflection coefficient with lateral density changes. Adding non-vertical angles for the seismic reflections would further improve the resolution. Density constraints might also improve inversion of acoustic impedance by constraining the longer wavelength variations, which are often poorly resolved if only seismic data is used.

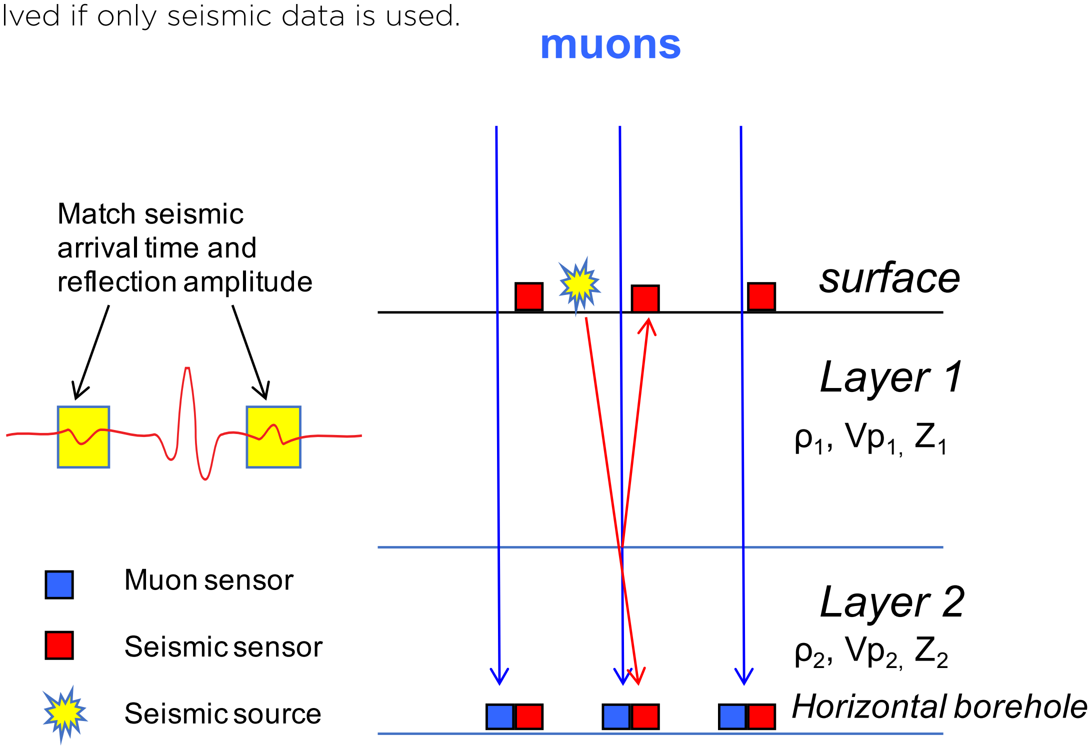

Figure 2: Schematic of imaging using travel-time and reflection coefficients. Here the geometry is as in Figure 1, but with additional seismic sensors on the surface, as in a seismic reflection survey. This allows measurement of the reflection from the layer interface, which provides additional constraints on the layer properties. In this case, S wave travel time are not necessarily measured.

Conclusions and Future Work

Theoretical inferences and preliminary modeling suggests that the combination of seismic and muon observations can be valuable in estimating the density and elastic parameters in the subsurface. Two cases, seismic travel time and P wave reflection, are considered. We find that the simple travel time inversion was adequate, as including the reflection data did not greatly improve estimation of the elastic parameters. Other combinations, such as surface wave based methods or seismic interferometry, may be useful.

Possible applications are in imaging subsurface features with fairly substantial density variations. With current large sensors, the primary value appears to be in characterizing tunnel overburden. If a borehole instrument becomes available, the range of possibilities increases and we see two main categories: flooding of reservoirs with low-density fluids or gas (e.g., CO_2) and voids such as tunnels or solution cavities.

This work has only scratched the surface of possible combinations and we expect significant improvements in the future. One related area is combining simultaneous muon imaging and differential gravity data (Rowe et al., 2015) for a tunnel to map 3D density variations in the overburden. Anticipated future underground experiments will include all three independent data types – seismic, gravity and muon.

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MUON TOMOGRAPHY OF DEEP RESERVOIRS

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Introduction

Imaging subsurface geological formations, oil and gas reservoirs, mineral deposits, cavities or magma chambers under active volcanoes has been for many years a major quest of geophysicists and geologists. Since these objects cannot be observed directly, different indirect geophysical methods have been developed. They are all based on variations of certain physical properties of the subsurface that can be detected from the ground surface or from boreholes. Electrical resistivity, seismic wave velocities, and density are certainly the most used properties. If we look at density, indirect estimates of density distributions are performed currently by seismic reflection methods - since the velocity of seismic waves depend also on density - but they are expensive and discontinuous in time. Direct estimates of density are performed using gravimetric data looking at variations of the gravity field induced by the density variations at depth, but this is not sufficiently accurate. A new imaging technique using cosmic-ray muon detectors has emerged during the last decade and muon tomography - or muography - promises to provide, for the first time, a complete and precise image of the density distribution in the subsurface. Further, this novel approach has the potential to become a direct, real-time, and low-cost method for monitoring fluid displacement in subsurface reservoirs.

Muon Creation, Propagation, and Attenuation

Muons are fundamental particles similar to electrons but much more massive (~207 times an electron mass). They are created when high energy protons entering the upper atmosphere produce pions (kaons) which then decay to muons and neutrinos (Figure 1). High energy muons (6 GeV) propagate in quasi straight lines undergoing minimal scattering and penetrate into the Earth at multiple angles (Thompson and Whalley, 1975). The average flux of Muons at sea level is about 1 muon per square centimeter per minute (5.26 109/m^2/yr). They are then attenuated by the different geologic units depending on their densities. The flux of muons has been measured at different depths and shows a rapid decrease with depth (Mei and Hime, 2006) (Figure 2). The flux can also be predicted by a full multiphysics model (GIANT4) calibrated on these observations and using various density distributions. By measuring the muon flux at different depths, the attenuation of the muon signal due to the different geological units, or the fluids contained within these units, can be determined. These measurements can be performed during a certain period of time to get a static density image or continuously to identify and interpret variations in density and fluid content as a function of time. They can also be processed and interpreted jointly with other geophysical data (passive and active seismic, gravity, etc.), thereby improving spatial resolution and reducing uncertainty.

Keywords: Muon Detection, Subsurface Fluid Injection, GEANT4, Plastic Scintillator, Density Tomography.

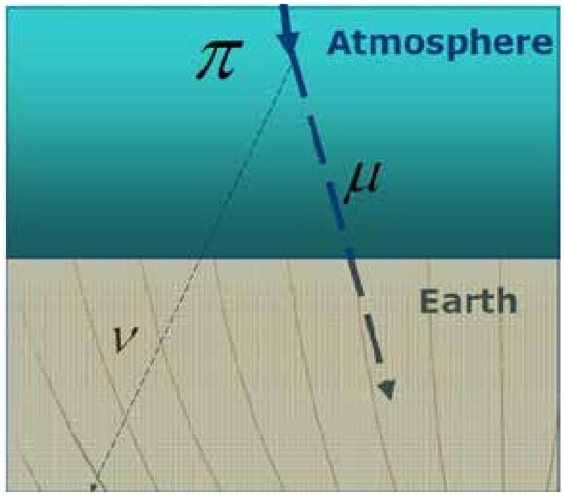

Figure 1: Muons (μ) are generated by the cosmic rays pions (π) in the upper atmosphere.

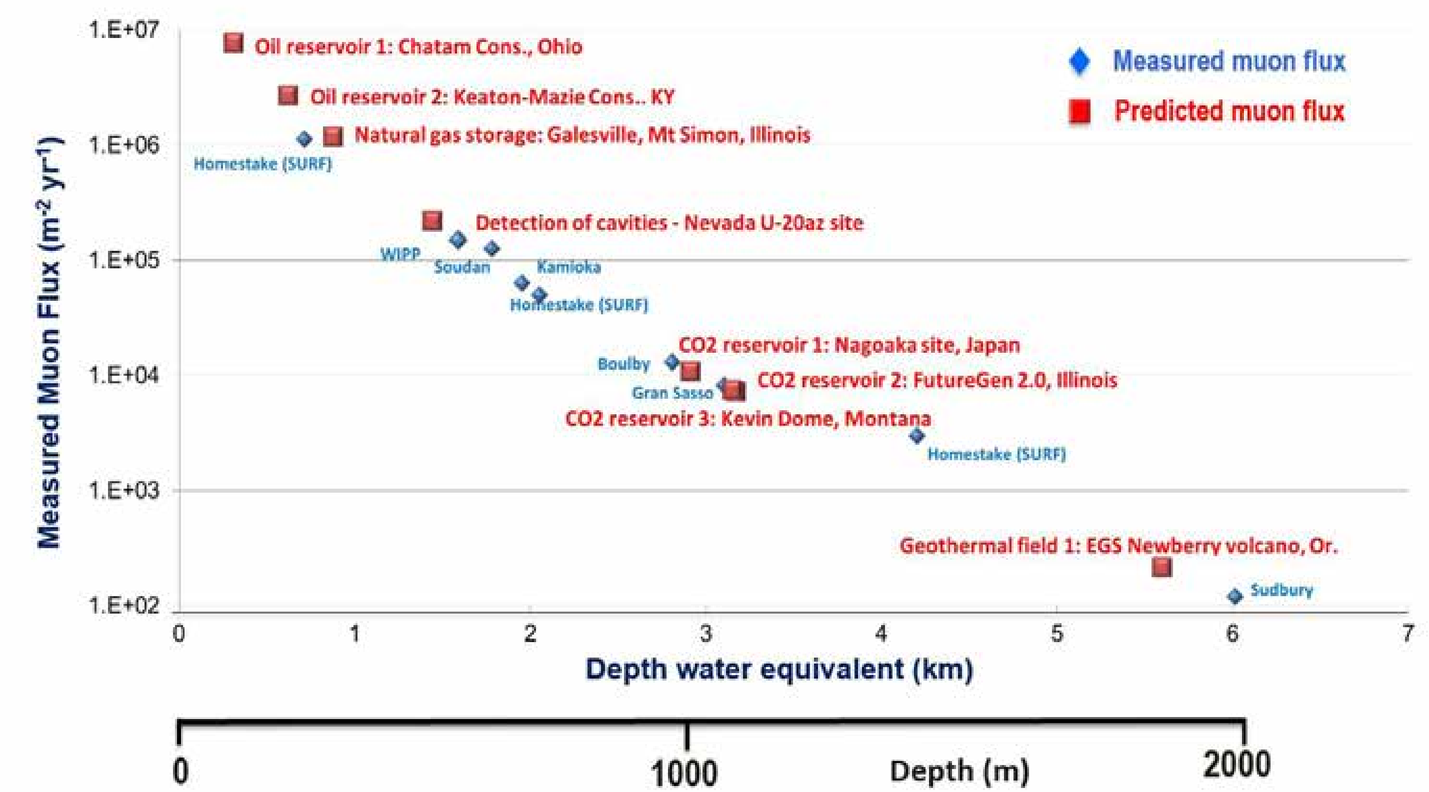

Figure 2: Actual measurements (blue) of muon flux and predicted flux (red) for a variety of geological targets versus depth.

Muon Measurement Geophysical Applications

In the past 10 years, muon tomography has been used to successfully image the displacement of magma in active volcanoes (Tanaka et al., 2007; Lesparre et al., 2012; Marteau et al., 2012) (Figure 3) with unprecedented detail using large detectors deployed at the surface. Applications to mineral exploration have been considered in the 1970's from a theoretical point of view (Malmqvist et al., 1979), and only very recently have actual applications in a mine been accomplished. Bryman et al. (2014) report the results from muon measurements collected in various locations of mine drifts to better characterize the Price volcanic-hosted massive sulfide (VHMS) deposit on Vancouver Island, British Columbia, Canada. The model derived for the muography is satisfactorily compared to a model derived from drill core data.

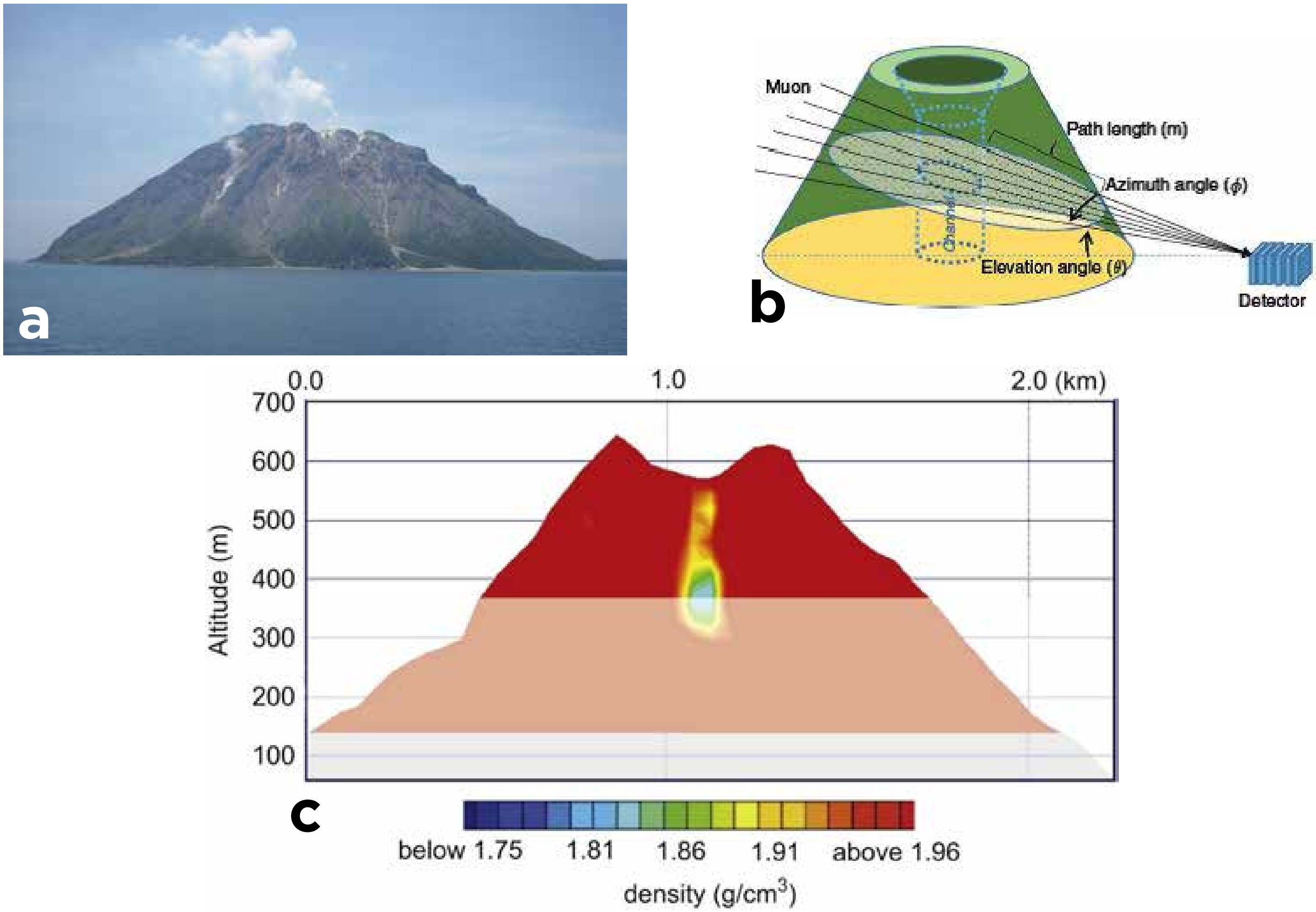

Figure 3: (**a**) Mount Iwodake is an active cone of the Satsuma-Iwojima volcano located in the southern part of Kyushu Region, Japan; (**b**) the muon detector placed at the ground surface collecting low angle muon passing through the volcano (after Tanaka et al., 2014); and (**c**) associated muon density tomography where magma is seen ~300 meters below the volcano crater (after Shinohara & Tanaka, 2012).

In addition to providing a static image of the subsurface density in three dimensions (or 3D tomography), these methods can also determine variations of density with time (4D tomography), which recently became of major importance. The injection of large volumes of fluids, mainly water and CO_2, in subsurface reservoirs is indeed increasingly performed in various applications (e.g., aquifer storage and recovery, waste water disposal, enhanced oil recovery, carbon sequestration). Determining where the location and displacements of fluids, the field-scale-induced pressure variations, and potential leakages to underground drinkable water aquifers is thus a high priority. Although the muon flux rapidly decreases with depth, preliminary analyses indicate that the muon tomography technique will have sufficient sensitivity to effectively map density variations caused by fluid displacement at depth. For example, the progressive replacement of brine by carbon dioxide (CO_2) in a 20% porous reservoir 4500 ft. (1372 m) deep should be detectable. The primary technical challenge preventing deployment of this technology in the subsurface is the lack of miniaturized muon-tracking detectors capable of fitting in standard boreholes less than 6 inches in diameter (20 cm) that will resist the harsh underground conditions (temperature, pressure, corrosion) for long periods of time (Figure 4). Due to their large size (typically 3x3x3 ft^3, 1 m^3), current muon detectors can only image the subsurface if they are placed in underground mines or tunnels. To be effectively used to create 3D images of underground CO_2 plumes or oil reservoirs, and eventually be able to monitor changes with time, muon detectors need a way to go deeper, below the potential targets, while keeping a sufficient spatial resolution (Figure 4).

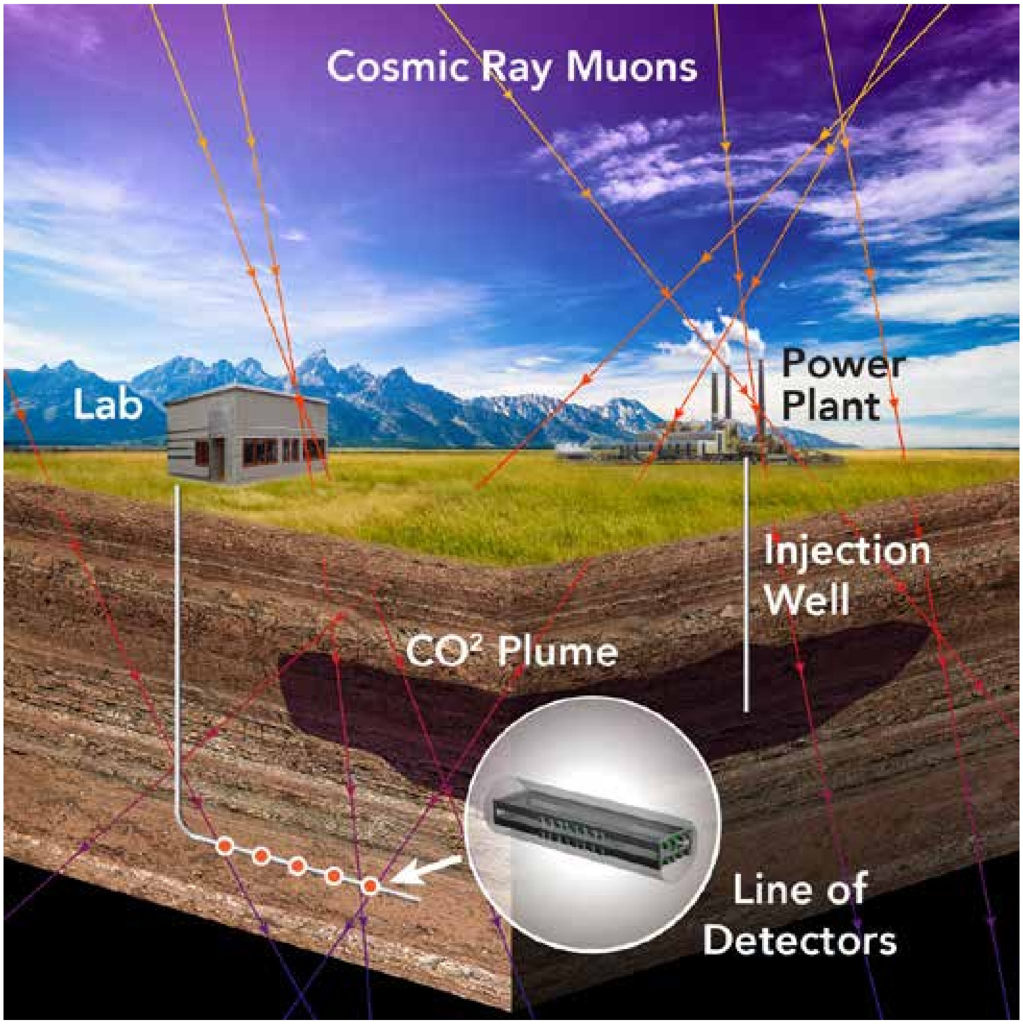

Figure 4: Conceptual representation of monitoring of a CO_2 geological storage by muon tomography. A series of PNNL borehole detectors are deployed permanently beneath the reservoir to monitor the change in density due to the replacement of brine by CO_2 in the geological formation.

Muon Detector Development

Pacific Northwest National Laboratory (PNNL) in collaboration with other U.S. National Laboratories and universities has developed a borehole muon detector (Bonneville et al., 2017) just five inches in diameter and about two feet long. This first-of-its-kind device, funded by the DOE Office of Fossil Energy as part of the Subsurface Technology and Engineering Research (SubTER), Crosscut, is a groundbreaking advancement for underground density imaging. The concept for a muon detector to be used in deep wells to monitor muon flux and the angle of deflection is based on using scintillating rods with fiber readout, pixelated silicon photomultiplier (SiPM) detection, and integrated threshold and coincidence electronics (Figure 5).

The completed prototype was deployed in PNNL's Shallow Underground Laboratory for an initial successful test in May 2016 and then in a tunnel at Los Alamos where it collected data during two months. The first results compare very well with the ones obtained by a larger detector deployed in the same tunnel (Guardincerri et al., 2017).

The market for the development of such a tool and methodology is promising since the potential subsurface applications are numerous, given reasonable construction and deployment costs. The next step to now test the detector in a borehole in real field conditions and leave it there for several months. In parallel, rapid and efficient inversion methods should be developed that will take into account not only the different muon paths, but also the data generated by other geophysical methods, such as gravity and seismic measurements.

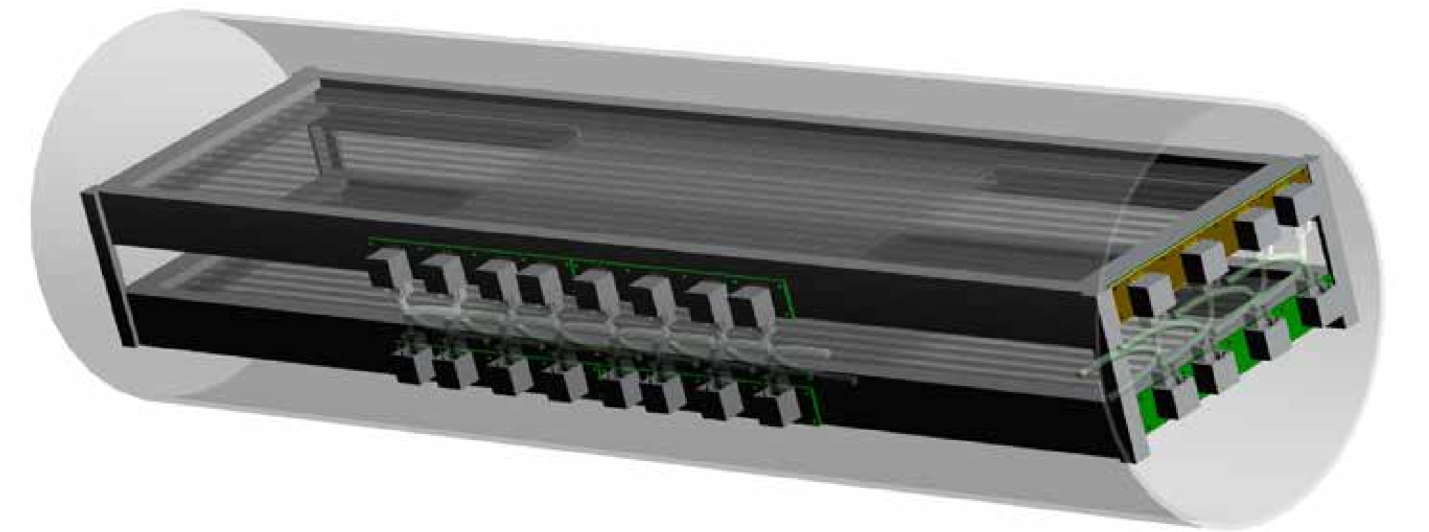

Figure 5: The PNNL Borehole Muon detector consists of 30 horizontal long scintillating rods in two layers and 60 short perpendicular rods in two layers, optical fibers, light sensors, and electronics to detect each muon that that passes through the device. Several computer simulations of muons trajectories have been performed to select the optimal geometry of the different layers. The detector counts the muons but also determine their trajectories which is required to build a 3D density image.

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DEVELOPMENT OF MUON IMAGING TECHNOLOGY FOR ARCHEOLOGICAL AND GEOPHYSICAL APPLICATIONS

(THE UNIVERSITY OF TEXAS AT AUSTIN - MAYA MUON PROJECT)

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Introduction

Muons, charged subatomic particles produced in our upper atmosphere and the most common component of cosmic rays by the time they reach the surface, are uniquely suited to near-surface imaging applications. Unlike light or x-rays, muons can penetrate tens of meters of rock or other materials. They lose energy through ionization when passing through dense material, attenuating their numbers in approximate proportion to the total mass encountered, allowing the material traversed to be determined through tomographic techniques.

Modern advances in electronic particle detection technology, pioneered at high energy particle accelerators to investigate particle interactions, provide tools to make cosmic ray tomography practical for new applications. What used to be a difficult, laborious process used only for special research applications is now viable for archeological, geophysical, and national security applications. Better knowledge of the energy spectrum of cosmic ray muons and computational techniques for calculating particle transport are providing quantitative tools for measuring the effects of different geometries and materials on the detected signals.

The earliest example of the use of cosmic rays for measuring overburden was in the 1950s, when E.P. George, an engineer, used a single channel muon spectrometer to measure the change in rate in cosmic rays for different depths underground. This allowed an independent measurement of the depth underground during the 25 year construction of the Snowy Mountain Scheme in Australia. (George, 1955).

In the 1960s, archeologists were facing a mystery in the Second Pyramid of Gaza. Only a simple chamber had been discovered in the base of this pyramid, while the nearby Great Pyramid had an elaborate chamber system running through much of the structure. Was the Second Pyramid really mostly solid, or was there a wealth of new chambers waiting to be discovered? The solution to this puzzle was proposed by particle physicist, Luis Alvarez. He realized that by detecting the cosmic ray muons penetrating the pyramid, he could map the thickness of limestone in the pyramid above the known chamber. If there were any further cavities, they would show up by reduced attenuation in the flux of muons passing through that area. The experiment was successfully carried out, with details such as the cap and external features of the pyramid being clearly seen in the data, through roughly one hundred meters of limestone. The precision was sufficient to conclude that the pyramid above the chamber did not contain any voids resembling those discovered in the Cheops and Sneferu pyramids. (Burkhard et al., 1970)

This approach was limited by the technology at the time. The detector was relatively expensive, weighed tens of tons, and had to be assembled inside the pyramid. The data had to be analyzed offline on a mainframe computer. Yet this effort was a proof of principle that provides a foundation for muon tomography today.

Keywords: Muon Tomography, Cylindrical Scintillator Strip Detector, Attenuation-Based Methods, Archeological and Geological Applications.

This approach was used again in the 1990s to image volcanoes in Japan (Nagamine et al., 1995). This time, several improvements in detector technology had begun to make this more practical. The first version used three layers of 127 cm by 127 cm plastic scintillator, and used the timing at each of four photomultipliers at the corners to locate the location of the track through the scintillating sheet. A later version adopted scintillator strip technology, which led to improved muon tracking performance.

In 2003, the Maya Muon project at the University of Texas at Austin (UT) was launched to apply recent developments in detector technology to portable systems optimized for muon imaging that could be deployed by small teams in diverse, remote applications. The UT group chose to investigate an intact Maya pyramid in Belize to demonstrate the approach and qualify detectors in a most challenging environment. The pyramid, under study by UT archaeologists, also presents important scientific opportunities that could be revealed through muon tomography.

A cylindrical detector design was chosen that could track muons from within a single mechanical structure with good efficiency over the entire open sky from which they emanate (Figure 1). Choices of detector technologies were balanced against the inherent imaging limitations arising from muon scattering in ordinary matter, the need for simple field operations, and the capability to stand the rigors of a remote jungle site with physics laboratory instrumentation including: sensitive elements to track muons, an onboard computer system, autonomous software, and low power consumption.

Prototype detectors have been tested successfully in diverse sites, including the Belize jungle, and various underground sites. They have succeeded in imaging hidden structures placed in "blind" experiments, unknown to the detector team. One detector was operated underwater to measure the muon energy spectrum at relatively low energies, a critical factor in quantifying image contrast. Some of the technical approaches and test studies are described below.

Figure 1: The late John McGill wrapping the first helical layer of scintillator strips for tracking muons on the hollow inner core of the detector.

Approach

The basic principles of the early attenuation-based methods are still being used today. A relatively constant flux of cosmic rays is generated in our upper atmosphere from collisions with high energy galactic particles. These rays, primarily composed of muons by the time they reach the surface, have a flux of approximately 1 muon per minute per square centimeter, an average energy of several GeV, with a wide distribution of energies. This distribution has a long tail reaching above 100 GeV.

Besides being available in sufficient quantities anywhere on earth free of charge, muons happen to be uniquely suited to tomographic purposes. The muon is heavy relative to an electron and similarly charged. The mass is 200 times that of an electron, which allows the muon to penetrate matter far more effectively. A muon loses energy at the approximate rate of 1 GeV per 2 meters of rock. Muons are unstable charged particles decaying to electrons and neutrinos in 2.2 microseconds, on average. For the high energies of most muons near the earth's surface, decays do not significantly deplete the muon flux. However, if muons lose much of their kinetic energy, decays and other processes do attenuate the number of muons that can be detected, providing the basic physics mechanism underpinning muon tomography.

When a muon passes through material, it primarily loses energy through ionization. Ionization is the principal mechanism by which muons are attenuated in dense matter and observed in particle detectors. Plastic scintillator strips used in particle detectors produce faint flashes of light when ionized. The 440 strips running the length of a detector in cylindrical layers each employ wavelength-shifting optical fibers to collect and transport that ionization light to a photomultiplier tubes (PMT). The PMTs convert optical signals from a scintillator strip into electrical one, which is digitized according to location of the strips (six or more for each muon track) hit by a muon. Our detectors have an onboard computer system, which reconstructs track directions and locations for a simultaneous group of hit strips that indicate a muon track. Software then records the track information in a four dimensional histogram structure, corresponding to the four parameters needed to specify a straight-line track in space. Thus, each entry in this 4D histogram gives the number of muons detected in what can be considered a bundle of ray within the tracking resolution of the detector centered on address of the histogram element; the number of entries in each histogram cell is simply related to the observed muon flux for each track bundle.

This system detects which scintillator strips are hit within a 25 ns time window, suitable for reliably identifying muon tracks and determining their trajectories with good detection efficiency (>0.5), but not their momenta. The strips are 1 cm wide and thick, and are placed in three layers around a cylindrical core. The inner and outer layers are wrapped in a helical pattern, with opposite 30 degree helices. The middle layer is axial. This pattern provides a unique "triplet" of strips hit that identifies the point on the cylinder that was hit by a muon. A reconstructable track is made of two triplets, one for the muon entry and the other for the muon exit, and these two points define a line in space. This line describes the trajectory of the muon, and can be used to infer the original trajectory. The six dimensions (two three dimensional points) over-constrain the determination of the four-parameter straight-line track, proving a powerful filter against noise hits in the scintillators.

For attenuation-based tomography, only a single detector is needed, located generally below the target to be imaged. The 4D track histogram of time-integrated track coordinates is sufficient for imaging because it represents the muon flux observed for 16 million possible track bundles, each within the tracking resolution expected for the detector. The resolution is limited by multiple scattering in the attenuating material; the design of the detectors was chosen to ensure a root-mean-square tracking error less than 20 mrad, comparable to that expected from multiple Coulomb scattering of typical muons traversing a 20 meter thick rock slab. In practice, the track resolution in each dimension is about 1/2 degree (10 mrad) in angle, about the size of the moon observed from earth and a few cm in location. For larger and smaller thickness of overburden, the change in average muon energy mostly cancels the change in deflection, causing this design to be close to optimal for a wide range of depths.

Our design also takes into account practical considerations. The detectors are relatively small and robust, allowing them to be placed manually in underground structures, for example. The diameter is just smaller than a 24 inch (61 cm) OD PVC pipe, to allow use in bore holes of modest size and underwater. The detectors are weather resistant; several of them have been coated in truck-bed liner for protection and durability. The cylindrical design provides a wide field of view, and a simple choice of vertical or horizontal orientations, with both being used regularly in our experiments. The power needed to operate a detector is under 100 watts; they have been successfully run from solar power arrays. The detectors communicate data and performance information as interrogated by a remote computer connection or insertion of a USB memory stick. Data can be stored autonomously for periods of weeks to months between interrogations.

The imaging is done with custom software developed for this application. The primary procedure used is a back-projection method, which takes the centers of the histogram cells, and projects the trajectories back onto an image surface defined in space above the detector. A 2D image histogram on this surface is filled with the sum of the hits from the 4D "track bundles" that project to it from the detector information.

This procedure is repeated for a “flat-field” run, a run with the same detector orientation, but with an unobstructed view of the open sky. These flat-field runs are usually run nearby with an exposure time equal to or greater than the image run. In cases where the target is to one side of a detector and the run is made in a difficult environment, a trick is employed to flat-field in place. The detector is rotated 180 degrees about the vertical axis, and the half of the detector that was flat-fielded in the first run now takes data, and likewise the data taking original half becomes a flat-fielding half also!

Combining data and flat-field, an attenuation map is made of the log of the ratio of the two for every "bundle of rays" described by the 4D data and corresponding flat-field histograms. By this method, detector efficiency effects from strip aliasing and manufacturing inconsistencies cancel. Conveniently, there is an approximately linear relation between muon attenuation and material depth. Furthermore, muon attenuation is also almost purely dependent on the vertical component of depth rather than the total track length, due to a fortuitous correlation between muon energies and their angles relative to the local vertical direction. (That is, to a reasonable approximation, the muon energy spectrum scales as E_\mu cos\theta, where theta is the angle of the muon from vertical.) Thus, the attenuation measured for every track bundle represented by the 4D signal and flat-field histograms provides a good measure of the vertical mass density traversed by the corresponding bundle of muons.

The location of attenuating material (or voids in surrounding material) can be determined by varying in data analysis the vertical location of the projection plane. This works as long as there is sufficient “stereo” information, which can be provided by a single data run for a small target, but is usually obtained by combining data from multiple detector locations for large targets. Structures come into “focus” when the projection plane intersects their actual location in space (Figure 2).

The projection system does not localize the attenuation of material to a point along the track, causing an out-of-focus “shadow” to appear on projections that do not intersect the object but are nearby. Other methods of 2D and 3D reconstruction have been tested, and this continues to be an active topic of research. Future advancements can use the current datasets to provide improved imaging. We expect it to be feasible to provide a self-consistent 3D unfolding of mass density from the data provided by our muon detectors.

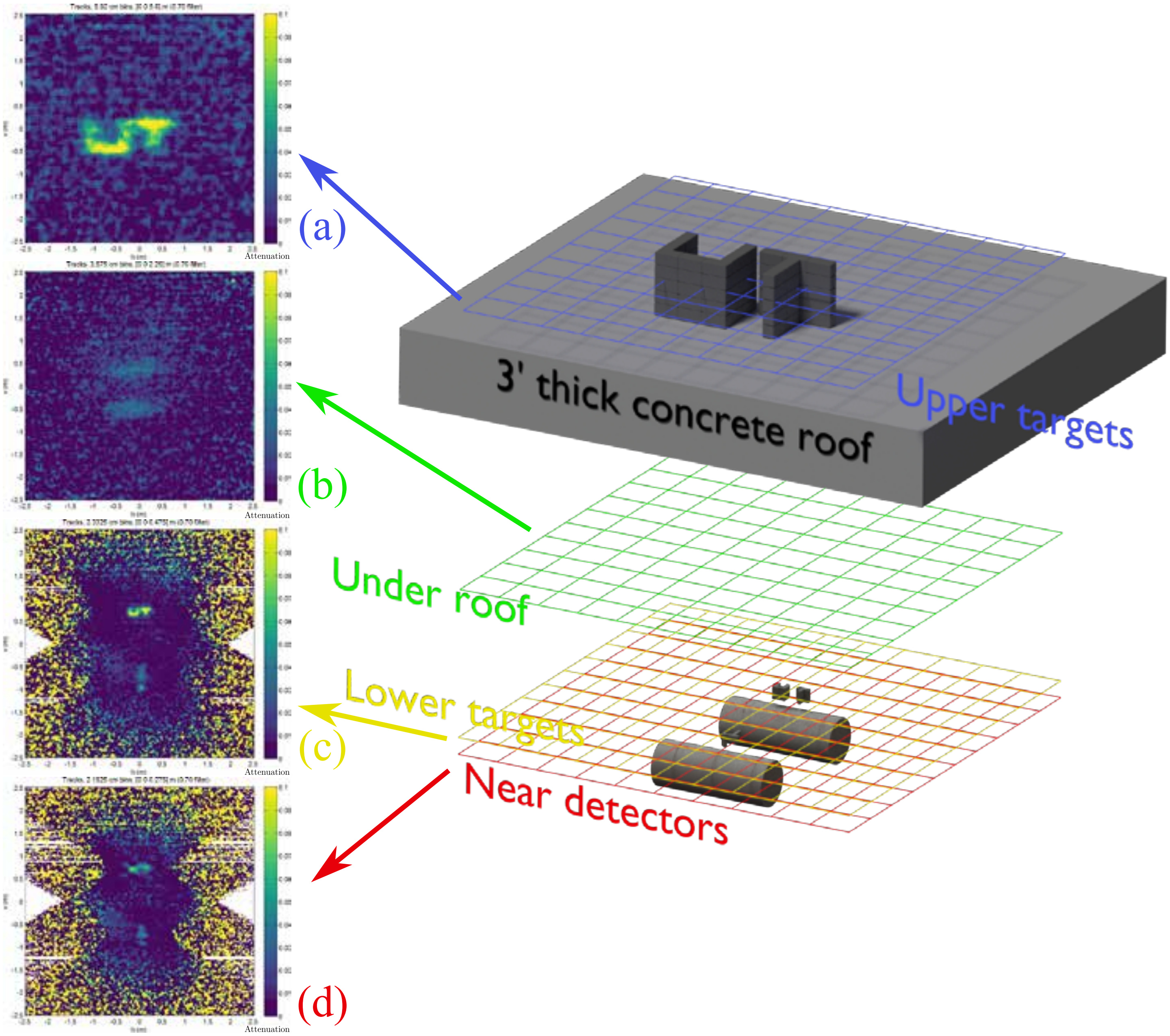

Figure 2: A data set collected with two horizontal detectors. Just above the detectors, 2x4x8 inch (5x10x20 cm) lead bricks were stacked in a couple of different orientations (visible in c). Above the roof of the lab a collection of lead-concrete bricks was stacked (visible in a). Projections between the targets show an out-of-focus "shadow" (visible in b). Color scales represent attenuation of muons relative to an open sky.

Performance

A test was performed at Sandia National Laboratories (SNL) during 2010, using a horizontal tunnel and targets placed on the surface above the tunnel. A detector was mounted on a track 2 meters below the roof of the tunnel. The top of the tunnel was roughly 0.3 m of concrete and dirt at the thinnest point. The surface was sloped gently in a North-South direction, with the thicker overburden to the North. A schematic is shown in Figure 3.

Flat-field consisted of several months of running horizontally in a nearby shed. For the data runs, the detector was moved to seventeen locations down the track it was mounted on, marked on the h axis in Figure 4. At each location, the detector was run for 48 hours.

All of the blind targets were observed over the course of the full run period. Most of the targets were initially discovered with only the first 6 hours of data taken at each location. Three of the most interesting projections are shown in Figure 4 using the full data sample. The wide stereo angles provided by the 17 positions provides excellent "focusing" power, which is clearly seen for the targets imaged at different elevations.

On the right hand side of the plots, there are two round attenuation features clearly visible, with sharpest focus in the lower 4 m projection plane, where most of the other targets are out of focus. They are marked by reduced attenuation compared to their surroundings, unlike the rest of the targets. These are ventilation shafts into the tunnel. The wall at the 0 m point and a concrete slab at the far end of the tunnel are two more features that were not part of the set of placed targets. It should be noted that the trapezoidal concrete slab was differentiated from the local soil even though it was only a few inches thick.

Fine details in the surface above the tunnel are also present; a run was made before the targets were in place, allowing two inch surface contours to be drawn from only a couple of hours of runtime at each position. This, combined with basic knowledge of the probable tunnel location, allowed the position of the runs to be calibrated on a Google Earth image for an absolute position, even before the detector was close to the concrete slab.

The different targets have identifying features that give indications of the nature of the target, size, shape, and density. The bright lead square is a lead brick stack. The two Jersey barriers have similar shapes, but one is significantly darker than the other, due to the concrete filling having a higher density than the water filling. The off axis targets have a different focal point, and they have similar overall contrast due to the attenuation only depending on the vertical depth of a target.

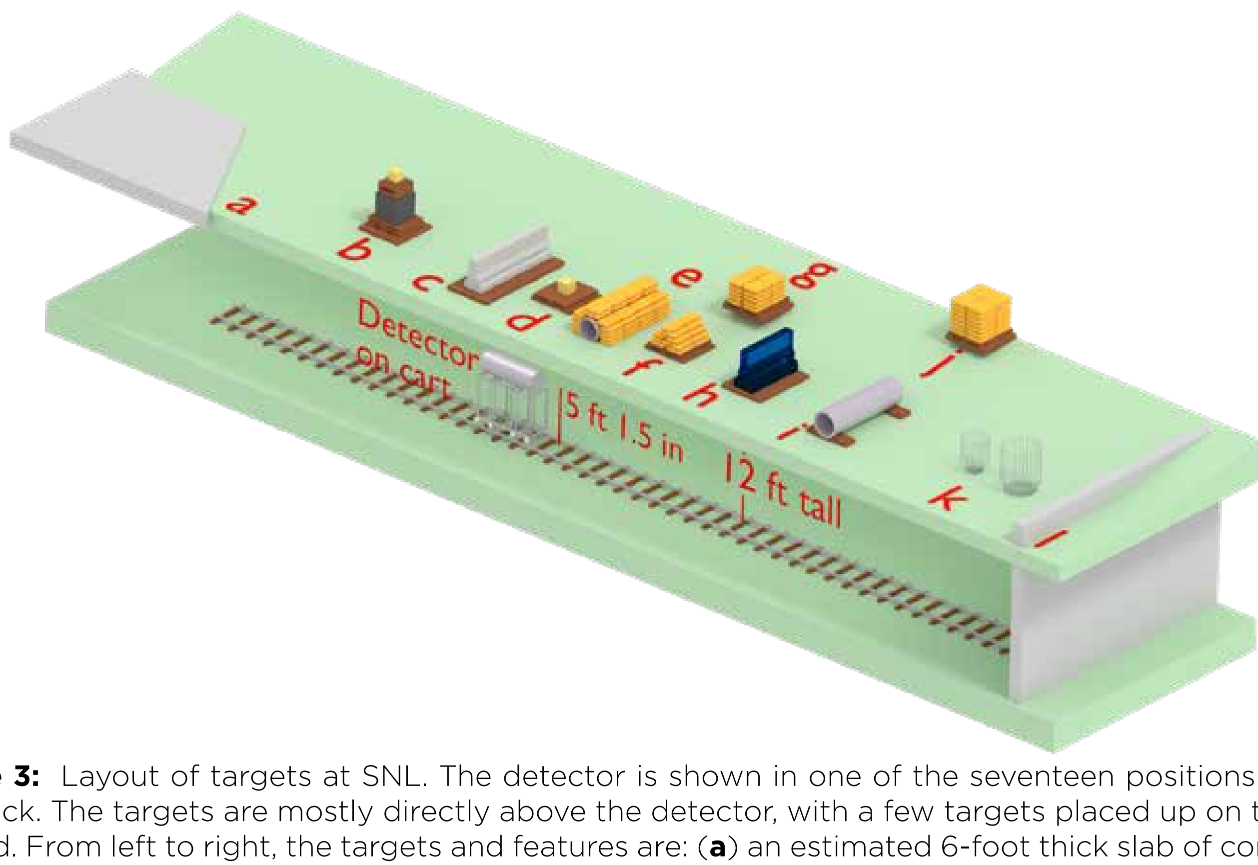

Figure 3: Layout of targets at SNL. The detector is shown in one of the seventeen positions along the track. The targets are mostly directly above the detector, with a few targets placed up on the hill instead. From left to right, the targets and features are: (**a**) an estimated 6-foot thick slab of concrete with a slanted edge; (**b**) a 3920 lb lead brick assembly on a pallet, with a sandstone block on top; (**c**) a concrete Jersey barrier 4000 lbs; (**d**) a 1 ft cube of sandstone; (**e**) 100 bags bags of sand, 50 lbs each, over a 200 lb steel culvert; (**f**) a pyramid of sand bags; (**g**) a pallet with sandbags slightly up the hill; (**h**) a 1100 lb water filled Jersey barrier; (**i**) a 24 in steel culvert, 8 ft long and 3 in thick, 2000 lbs; (**j**) a pallet with sandbags even further up the hill; (**k**) a ventilation shafts into the tunnel; and (**l**) a wall at the end of the tunnel.

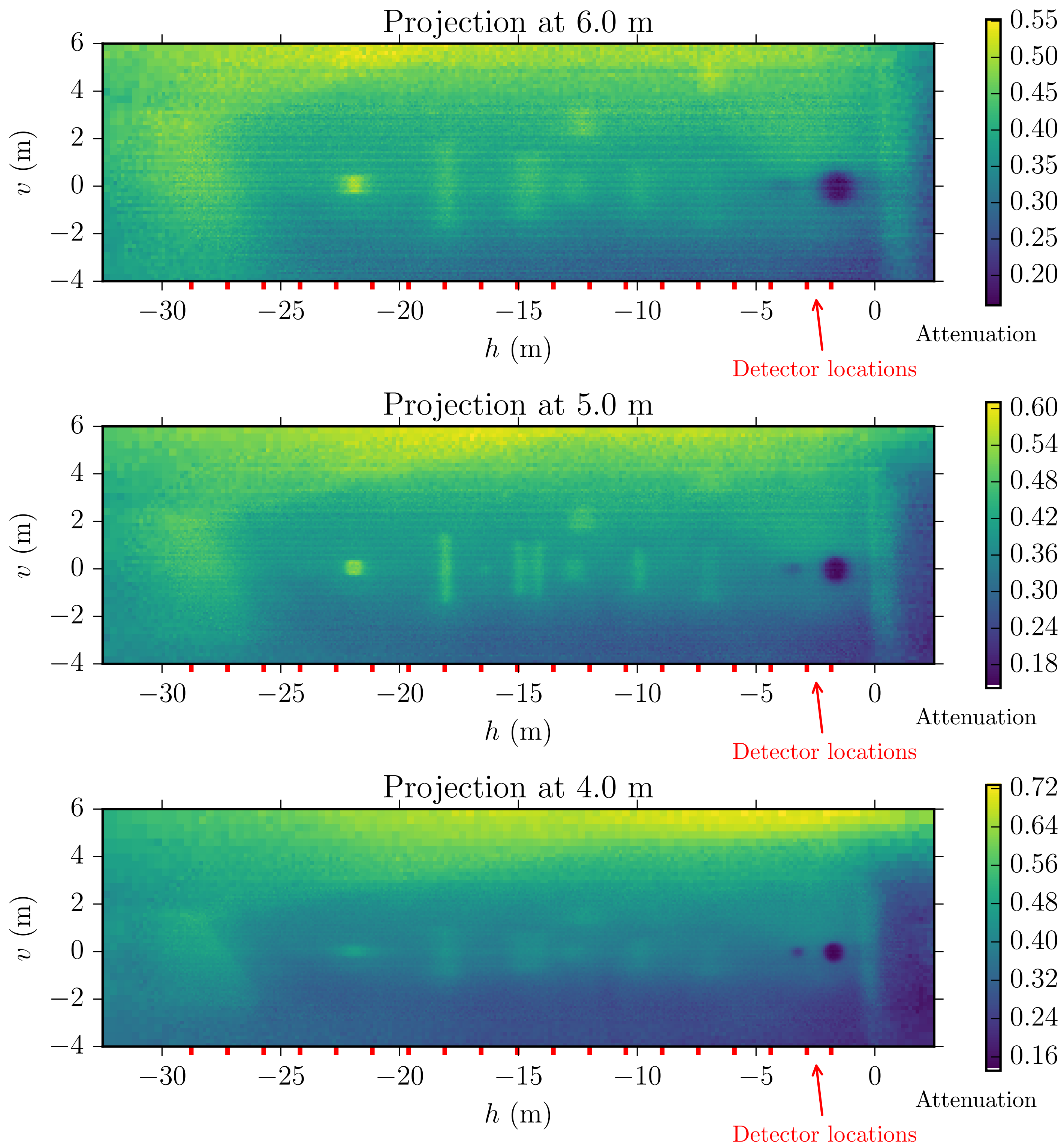

Figure 4: Projections through targets at SNL. Every object in Figure 3 is visible; with many smaller details such as the merging of the sandbags covering the culvert visible around h=-15 m. The lead block around h=-22 m has a higher attenuation than the other targets of similar size. The targets on the hill, at h=-14 m and h=-7 m are in focus in the higher projections. The listed height is distance above the detector center. Color scales represent attenuation of muons relative to an open sky.

An example of the image quality for a complex target can be seen in Figure 5, a close-up of the sandbags piled over the 24 inch culvert. The hollow interior of the culvert is clearly resolved at about 5 m from the detector using bins 10 cm in width, at an angular width of 20 mrad. The change in attenuation between the hollow portion and the walls is much larger than the statistical fluctuations.

A different technique was applied by SNL in Figure 6, using standard tomographic routines adapted for the data from our detectors. The image shows a vertical cutaway of the space above the detector, highlighting the depth information captured from the multiple positions. The structure previously seen in Figure 5 is clearly seen just before the -15 m mark. The lead cube on the left and the two hollow structures on the right are also clearly visible, as are the other structures that were directly about the detector track. The coarser binning obscures some of the smaller details, but gives even lower statistical fluctuation (noise).

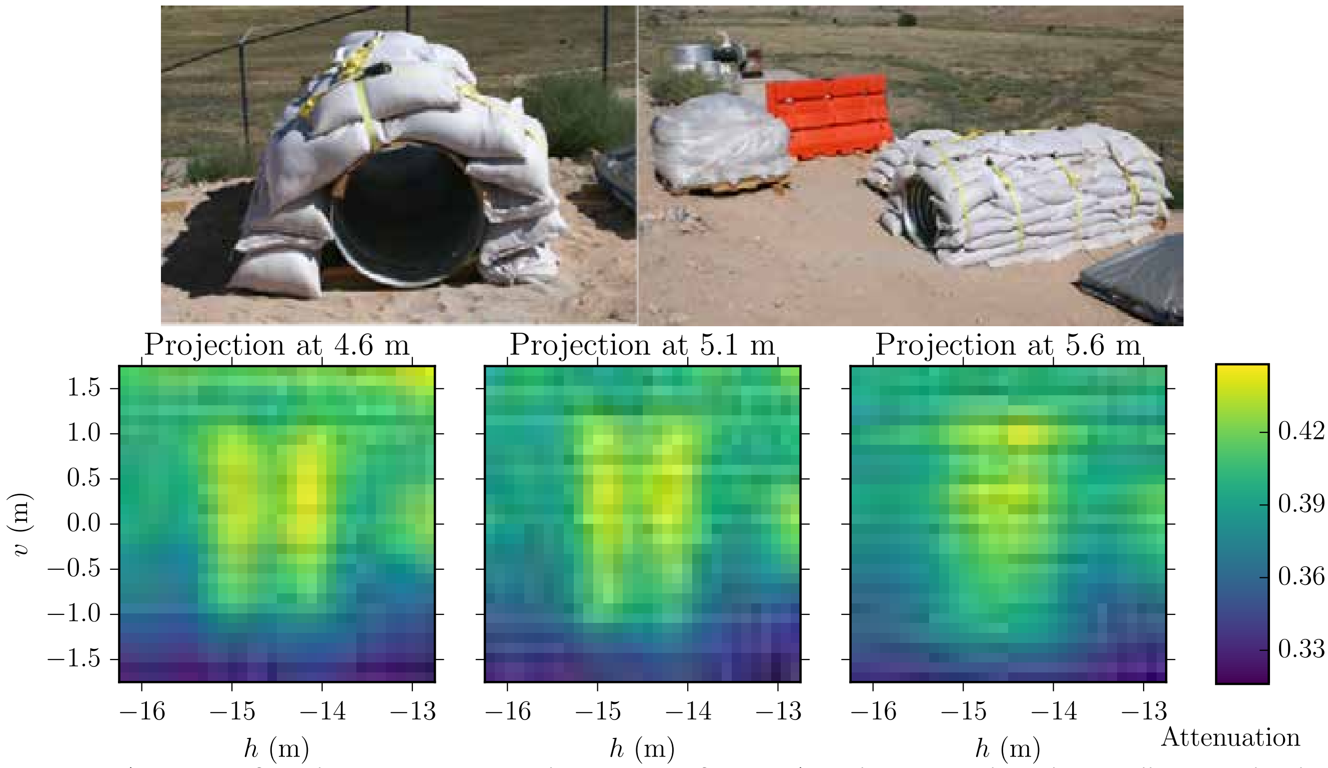

Figure 5: Closeup of arch projection and images of actual arch created with sandbags. The hollow center is clearly visible, joining together in higher projections.

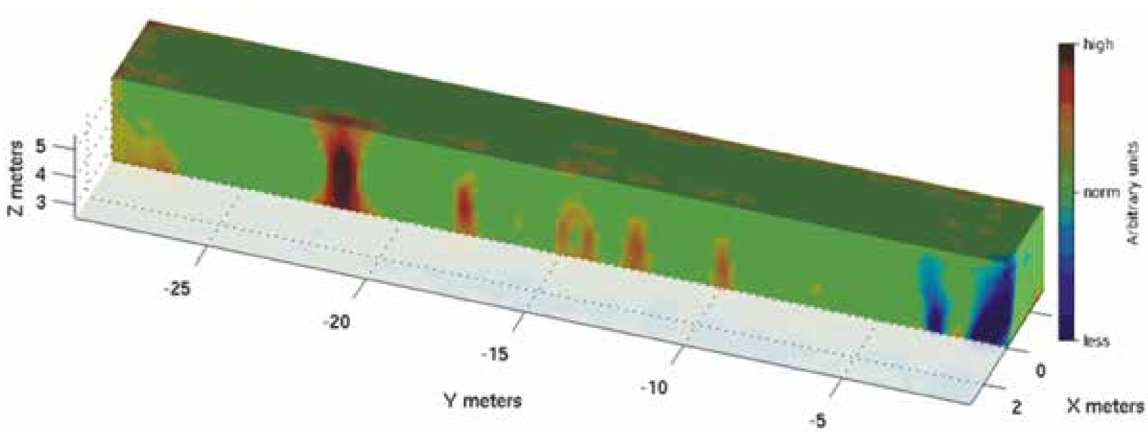

Figure 6: A standard tomographic algorithm performed by SNL. The color scale scale is a notional measure of density, with blue indicating actual voids, and red indicating higher than average density This highlights the level of detail captured in the vertical direction (but the “shadowing” is still present). Clearly visible in the vertical extent of the lead stack at -22 m and the air vents between 0 and -5 m. The culvert at -15 m shows a circular cross section in this view, which is perpendicular to its axis.

Conclusions

Their specific physical properties and abundance in natural cosmic rays make muons uniquely suited for tomography. Muon tomography with cosmic rays has existed in some form for many years, but only recently has become practical for archeological and geological applications. The necessary components for particle detection and data collection have been pioneered at high energy laboratories around the world, and are now being applied to create portable muon detectors.

A cylindrical, self contained detector can be produced with several attractive properties for cosmic ray muon imaging. The strip resolution was designed to the multiple scattering in materials. The large acceptance along with the ability to use any orientation provide a wide range of applications. Our detector design has been shown to work well in a variety of situations, such as the one demonstrated at Sandia National Labs.

The design presented here is feasible for low-cost mass production. The detectors we built can be produced for under $100,000 each; most of that cost comes from the seven 64-channel photo multiplier tubes. Developments underway with solid-state photodetectors should substantially reduce current costs and improve detector operation. The Maya Muon group is continuing to refine the design, to improve reliability and further reduce costs. Further tests are being performed around the world to evaluate the performance of the detectors.

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DRONE GEOSCIENCE

geoDRONE Report

by Ron Bell e-mail: rbell@igsdenver.com tel: 720-220-3596

- **2016: *The Year of the Drone***
- **Wohnrade Civil Engineers leading the way in UAS mapping and surveying**
- **The Tempest – a commercial grade small sUAS from UASUSA**
- **Low and ultra-low altitude UAS Magnetometry**
- **Upcoming Conferences with drone content**

2016 was a milestone year when it comes to using drones for geoscience data collection. The developments were so significant that one could argue it should be named "***The Year of the Drone***". If you have not taken notice of these little flying robots by now, you will soon.

On August 29th 2016, the Federal Aeronautical Administration (FAA) officially implemented Rule 107 effectively pushing the gate constraining the civilian use of unmanned aircraft with a maximum takeoff weight of 55 lbs. (25 kg) wide open. Within weeks, all across the United States, hundreds if not thousands of robotic birds equipped with a camera, a LiDAR unit, or an infrared sensor took flight tasked to accomplish missions directed by a combination of sophisticated autopilot software coupled to sensors intended to facilitate avoidance of other objects within the airspace. From a commercial use perspective, all of this activity is to be done under the watchful eye and guidance of a FAA certified unmanned system pilot, the so called "Pilot in Charge". By many measures, drones are being integrated into the national airspace in predictable ways by responsible people who understand the importance of following the rules governing the safe use of the national airspace. The popular press is more interested in sensationally reporting on those irresponsible individuals who unthinkingly risk harm to others while operating their aircraft. They fail to make note of the fact that, by and large, the vast majority of people engaged in using drones in their business are doing so responsibly.

Why pronounce 2016 the "***Year of the Drone***"? One can readily justify the moniker through the implementation of Rule 107. However, it is but one reason to make the proclamation, albeit an essential one. The immediate, widespread proliferation of drones is the result of the much more fundamental criteria necessary for the broad adoption of any new technology. That is, the technology must be within budgets of the consumer. Conducting basic mapping missions for environmental and engineering projects is now, for all practical purposes, affordable. Above all else, this is why 2016 was a milestone year in the application of drones to the business of geoscience.

Applying drones to geophysical data acquisition is uncommon precisely because of the cost of the highly sophisticated platforms and data acquisition systems are, for many, a barrier to entry. For the time being, the development and implementation of UAS capable of geophysical mapping is receiving the attention of a select few entrepreneurially minded geophysicists and engineers. As a result, drones that are integrated into the work flows of those conducting engineering and environmental site characterization projects most often are tasked to map the surface of the earth or observe what is placed on it rather than detect or map what occurs in the subsurface. Nevertheless, the benefits gained from drones are so numerous that within the next decade every field geoscientist and engineer will have a drone in their respective toolboxes.

Figure 1: DJI Inspire 1 used by Wohnrade Civil Engineers for site characterization surveys.

One visionary engineer that has successfully integrated drones into the workflow of her company is Mary Wohnrade, P.E., the Principal Engineer for Wohnrade Civil Engineers, Inc. (WCE) located in Broomfield, Colorado. A few months ago, I attended a Rocky Mountain UAS Professionals meetup where Mary and her colleague, Brendan Thompson, the Managing Partner at WCE spoke about how they were using drones to characterize the surface and, in some cases, execute survey grade land surveys at their project sites. I concluded from their presentation that WCE is leading the way in the implementation of drones for civil engineering projects. In her talk, Mary reported on the differences in precision and accuracy of photogrammetric survey data sets acquired over the same site but using several commercially available drones. If you wish to view the slide deck for the presentation at, you can access it at http://www.slideshare.net/UASColorado.

Figure 2: WCE Pilot in Command Brendan Thompson performing inspecting the aircraft before the mission.

As with pilot-on-board airborne geophysical surveys, many factors influence the quality of the data acquired using a drone, not the least of which is the manner in which the data are acquired, the stability of the airborne platform, and software used to process the data.

Wohnrade Civil Engineers, Inc. is an FAA Section 333 Exemption Holder, as well as an FAA Part 107 Certified Operator. For the past year and a half, the company has been performing aerial data collections using a Inspire 1 from DJI (http://www.dji.com/inspire-1) (see Figure 1) and the SwiftTrainer UAS, a fixed wing UAS developed by Black Swift Technologies Inc. (http://www.blackswifttech.com/) (see Figure 2).

In the fall of 2016, WCE participated in a "by invitation only" field trial of several off-the-shelf UAS. The objective of the trials was to assess the positional accuracy of photogrammetric data acquired using three different commercially available fixed wing small UAS. The field trials were organized by UAS Colorado and held within San Luis Valley UAS Test Site located in southern Colorado. As noted in the paragraph above, the results were reported by Mary at the local RM UAS Professional meetup.

In mid-December, Wohnrade Civil Engineers, Inc. as well as UASUSA, an unmanned aircraft systems manufacturer and service provider located in Longmont, CO received an award from UAS Colorado (http://uascolorado.com/) recognizing their excellent work using sUAS on recent missions in the San Luis Valley. UAS Colorado is a business league created to support the emerging community of UAS businesses located in Colorado and elsewhere. Through its work with local and state governments, the San Luis Valley UAS Test Site was created. This is unique facility with a wide variety of terrains and flight conditions. It is intended for individuals and companies to test unmanned aircraft of all types and sizes as well as specialized sensor systems at altitudes ranging from a few feet above the ground surface to as high as 15000 ft. (~7500 feet above ground surface). To learn more about the SLV UAS Test Site and UAS Colorado, contact Constantin Diehl (cdiehl@uascolorado.com) or Sean McClung (smcclung@uascolorado.com).

For many years, Skip Miller, the CEO and Founder UASUSA, (http://www.uasusa.com/) employed the skills and knowledge that he gained as a world class competitor in the world of RC Model aircraft combined with the engineering and manufacturing expertise of his colleagues to create a durable, small unmanned aircraft systems designed specifically for acquiring scientific data while enduring highly challenging weather conditions (i.e. a tornado). The fruit of their labors is a sUAS is called the ***Tempest.*** The unmanned aircraft is currently deployed by NASA and the Naval Research Laboratory.

The Tempest was selected by GEM Systems, Inc. (http://www.gemsys.ca/) for its Monarch fixed wing UAS magnetometry system. Capable of other payload options and missions including visible light photography, multi-spectral near infrared (NIR) imaging, and LiDAR, the ***Tempest*** is truly a commercial grade sUAS (see Figure 3).

During 2016, UASUSA expanded its operations. The company now employs 12 people to design, build, market, sell, and operate its line of robotic aircraft around the globe as well as process and interpret the high definition remotely sensed data acquired using the aircraft. The customer base of the company includes government research institutions along with companies conducting remote sensing surveys for geologic mapping, agricultural vigor assessment, mineral extraction management, and forest fire assessment.

Within the earth science and engineering industries, the primary application for small unmanned aircraft systems remains still and video photography at the project scale often for difficult to access areas and inspections of vertical structures. In addition, infrared sensors are commonly deployed to detect and map thermal emissions and vegetation under stress. There has been a somewhat excited, growing interest in using a scanning LiDAR system on a drone to capture point clouds of surface elevations in 3D. The point clouds are subsequently processed to obtain a high definition bare earth digital elevation model (DEM). For some projects, LiDAR is, in fact, preferred over the less costly high definition UAS photogrammetry due to its inherent capacity to see through the foliage. While for others, photogrammetry is preferred due to its significantly lower cost and resolution comparable to LiDAR. When scanning LiDAR systems specifically built for use with a drone cost about the same as a high resolution color camera, there will be a widespread utilization of the LiDAR for environmental and engineering sites characterization.

Figure 3: Tempest fixed-wing commercial grade UAS.

Only a couple of geophysical methods have been successfully adapted for use with small UAS: magnetometry and broadband, very low frequency electro-magnetometry (a.k.a. Radio EM). In part, this is because most of the commercially available magnetometers and EM data acquisition systems require too much power and, therefore, are too heavy for use with most electrically powered small UAS. Innovative geophysical data acquisition systems suitable for use with a sUAS will no doubt be developed and offered to the engineering and environmental industry, perhaps as early 2017.

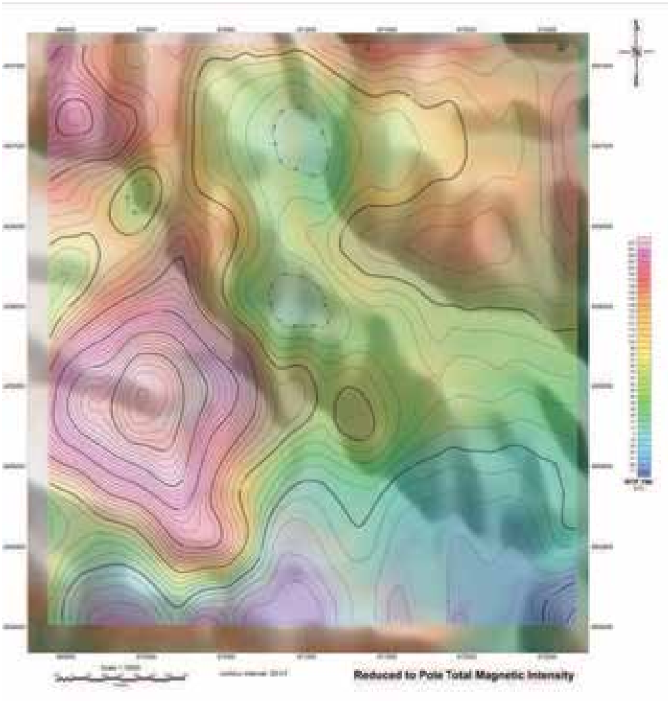

Figure 4: MGT UAS magnetometry data draped over DEM for mineral exploration.

Figure 5: S180 Mk.2 sUAS fitted with MGT magnetometer preparing to me launched via a catapult.

For now, the clear leader in the application of UAS to perform magnetic and Radio EM surveys is Dr. Johannes Stoll of Mobile Geophysical Technologies (http://www.mgt-geo.com/). Dr. Stoll began adapting a three (3) axis fluxgate magnetometer for use with a UAS in 2010. In 2016, he and his colleagues at Hanseatic Aviation Solutions (http://www.hanseatic-avs.de/) completed several commercial aeromagnetic survey using the Hanseatic S180 MK.2 pusher-style fixed wing small UAS. The objective of the surveys was to map geology for the purpose of mineral and ground water exploration. The color contour map presented in Figure 4 are Reduced-to-Pole Total Magnetic Intensity (TMI) data acquired using a fixed wing UAS and the MGT Vector magnetometer. The small UAS used for the magnetic survey is shown in Figure 5.

Dr. Stoll continued to advance the data acquisition technology in 2016 with the development of a dual sensor fluxgate magnetometer. He successfully adapted it for use with a multi-rotor UAS (a hexacopter) capable of ultra-low flights where the magnetic field sensors consistently held about 1 meter above the ground surface. The obvious application for this system is for detecting and delineating areas hosting unexploded ordnance (UXO).

Subsequently, the efficacy of this novel data acquisition system was tested over several areas known to contain buried UXO from World War I and World War II in Germany, where MGT and Hanseatic are located. The map shown in Figure 6 presents the color contours map of the TMI data for one of the test sites.

For this site, 65 magnetic anomalies were detected and determined to be due to buried ferromagnetic objects. An algorithm designed to discriminate anomalies likely due to UXO from those that are likely due to non-UXO, ferromagnetic objects was applied each of 65 anomalies resulting in the selection of 23 sites for excavation. The excavations resulted in the removal of 23 confirmed UXO. One of the UXO extracted from the site is shown to the left in Figure 6.

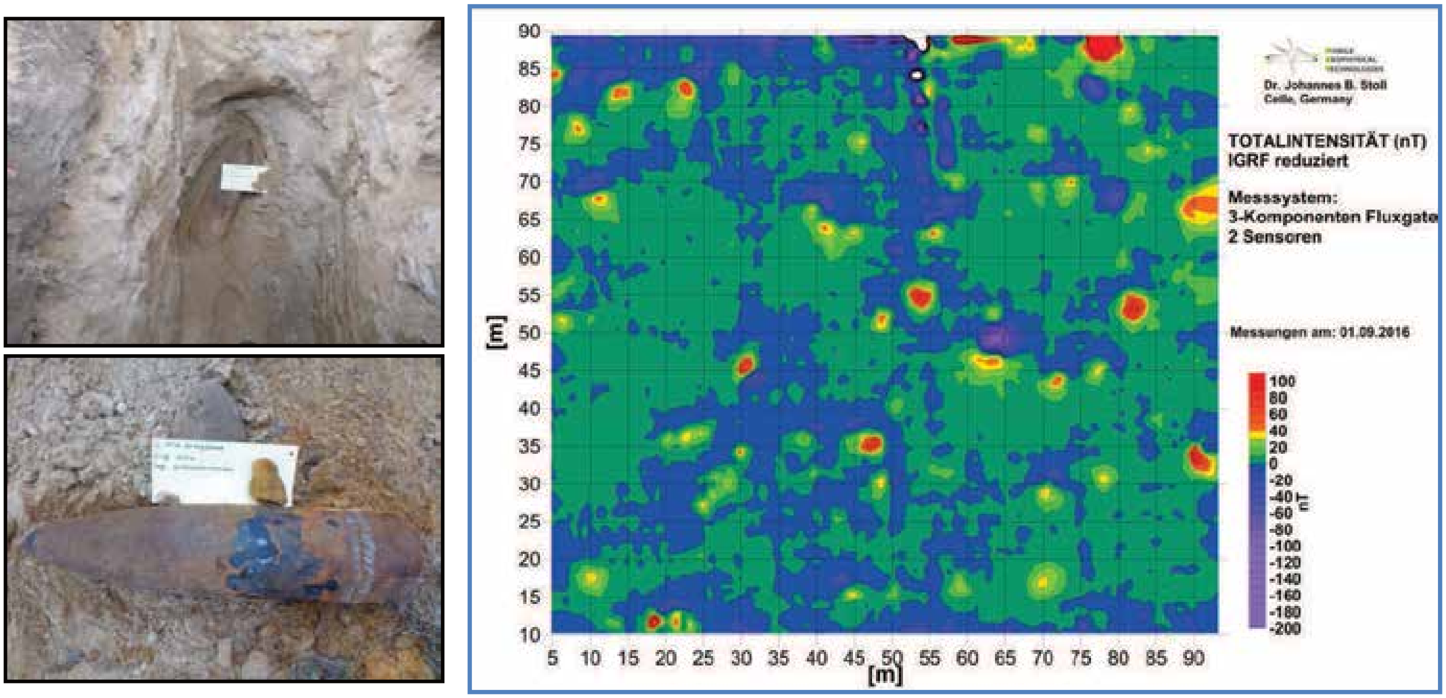

Figure 6: On left side are photographs of a 155 mm "grenade" removed from site as a result of the magnetic map (on right) created using the MGT dual sensor vector magnetometer and a UAS.

The following conferences contain some UAS content. They are worth checking out.

International LiDAR Mapping Forum Denver, CO Feb 13-15, 2017
for more info: http://www.lidarmap.org/

XPONENTIAL 2017 Dallas, TX May 8-11, 2017
Sponsored by AUVSI for more info: http://www.xponential.org/xponential2017

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*Dear Readers: Barry Allred, the editor of **FastTIMES,** and I are discussing the concept of expanding the **geoDRONE Report** into standalone regular feature article. We wish to know your thoughts about the concept before we move forward with a commitment. Specifically, is a regular report about the world of drones applied to geoscience of interest to you? Please email your thoughts and suggestions about this idea Barry (Barry.Allred@ARS.USDA.GOV.) or/and to me (rbell@igsdenver.com). Thank you in advance for your input. – Ron*

About the Author: Ron Bell is a consulting geophysicist with more than 3 decades of experience in the application of geophysical technology to the exploration for mineral, groundwater, and hydrocarbon resources as well as environmental subsurface site characterization. His company, International Geophysical Services, LLC, provides ground and airborne geophysical data acquisition and related services including the drone based data acquisition of magnetic and photogrammetry data. (www.igsdenver.com).

Topographic Mapping by Drone:

A Case Study from the Great Sand Dunes National Park

by R. Bell, Consulting Geophysicist, International Geophysical Services, LLC (rbell@igsdenver.com)

For those field geoscientists who began their careers prior to the wide spread availability of global positioning systems (GPS), it was common practice to carry a paper copy of a 7.5 minute USGS topographic map in the field for orientation purposes as well as to make notes about the location of survey traverses and/or data point measurement locations. At the time, a local coordinate grid system was often deemed adequate for most ground geophysics surveys. On the very rare occasions, a land surveyor was employed to provide precise survey control. Data point location errors were quite often a function of the map reading skills of the field staff. At the end of the day, the location of the traverse lines and data points were manually transferred to a fresh topographic map. 3D surface models were uncommon. One simply had to visualize the topographic contours in order to gain a 3D perspective.

Today, the common field practice involves the use of a handheld or mapping grade GPS either standalone or integrated with the geophysical data acquisition system to precisely locate the data in latitude and longitude coordinates. All of the data are georeferenced to a world coordinate system. An image obtained from Google Earth is employed as a base map to visually connect the data to the ground surface. A digital elevation model (DEM) data set typically at a 10 meter resolution is often downloaded from the USGS or other public domain web sites then used to render 3D surface model. Finally, the Google Earth image, elevation contours, and the location of the geophysical data are superimposed onto the 3D Surface model. Compared to what we had to do “back in the day” it is far and away easier to develop a good quality, accurate topographic-like map today.

Nevertheless, there are times when the Google Earth imagery and publicly available DEM data are simply not good enough. The resolution may be lacking or the information content conveyed in the imagery does not adequately reflect current site conditions. For these situations, it is time to send in the drone.

An unmanned aircraft systems (UAS) equipped with a color digital photographic camera of sufficient pixel resolution, light sensitivity, and adequate lens specifications for conducting a photogrammetric survey is quickly becoming the new standard in topographic mapping. As illustrated in Figure 1, UAS photogrammetry is based on the acquisition of a huge number of highly overlapping color photographs creating a data volume when processed using photogrammetry techniques will result in data products such as an ortho-rectified color photomosaic, a digital surface model, and a bare earth digital elevation model.

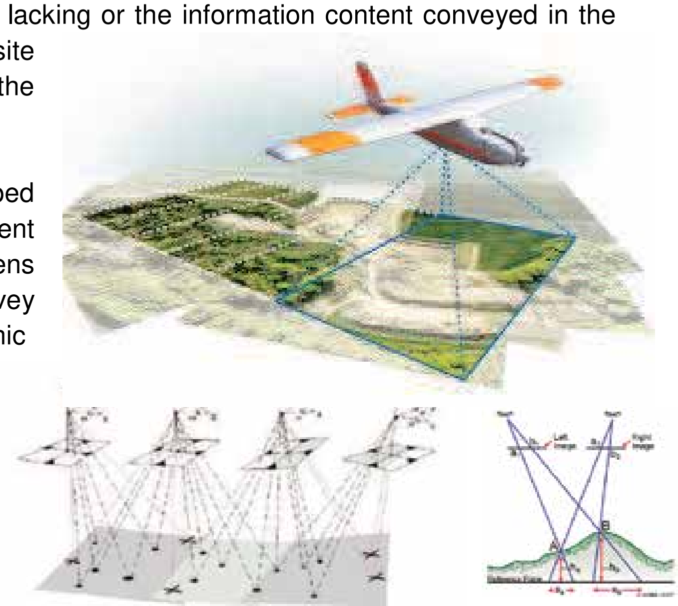

Figure 1: UAS Photogrammetry illustrated.

I recently visited with Brenden Thompson, Managing Partner of Wohnrade Civil Engineers, Inc. (WCE), a small civil engineering company that has successfully integrated UAS mapping into their workflows. In addition, they offer UAS mapping services. The company, located in Broomfield, CO, has been flying UAS Surveys commercially for 18 months, first as an FAA Exemption 333 holder, and more recently as FAA Part 107 Certified Operator. WCE uses a Swift Trainer UAS made by Black Swift Technologies and an Inspire 1 made by DJI to perform data collections for photogrammetric purposes.

WCE delivers precision mapping products of sufficient accuracy quality for use in civil engineering design projects.

The following information on topographic mapping using a UAS was provided by Brenden Thompson. I simply applied a bit of editing and reformatting to improve readability. - RB

WCE In-house Workflow

WCE has developed a unique in-house workflow that includes:

- UAS mission planning;
- UAS field data collection;
- Data processing using photogrammetry;
- Preparation of precision mapping products.

All products are generated using surveyed ground control points (GCPs), and are georeferenced in a real world coordinate system. Deliverables generally include:

- High-resolution ortho-rectified photomosaic image (2.5 to 3 cm/pixel GSD);
- Digital elevation model (DEM);
- Digital point cloud;
- 3D model;
- Digital terrain model (DTM) with 1-foot contours.

Cost Savings: UAS Technology versus Traditional Ground Survey

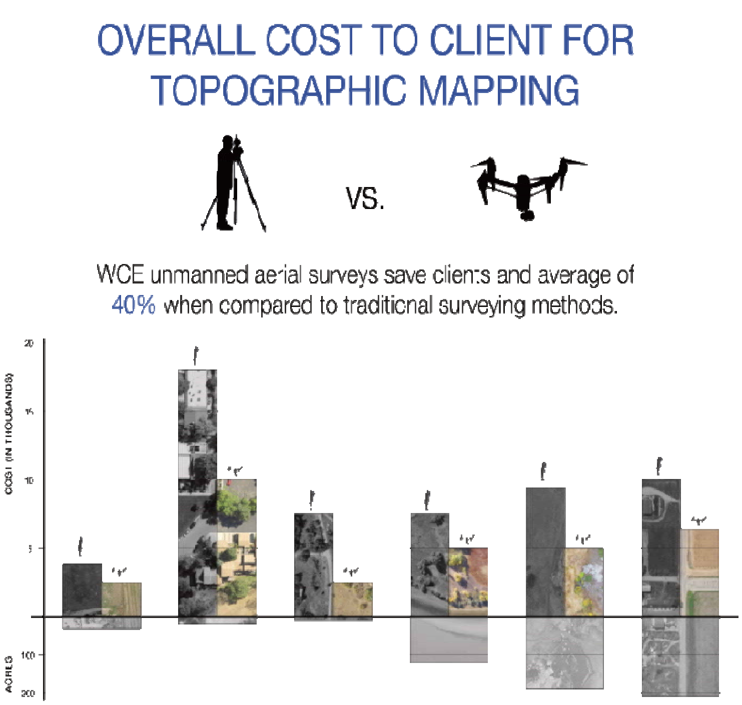

Figure 2: Comparison of ground versus UAS topographic mapping costs.

WCE has repeatedly demonstrated to their customers that UAVs are capable of generating reliable and precise ground surface models in a manner that is quite cost effective. Figure 2 presents the results of an analysis of the database for a selection of WCE UAS projects, which includes actual costs for UAS aerial mapping versus traditional ground surveying. WCE concluded that they were able to save their clients approximately 40% on average when using a UAS for topographic mapping versus ground based land mapping surveys.

The cost savings is a function of the project size, type of terrain, and time required to perform the data collection. In most cases, a UAV platform collected the data in less than an hour, as compared to traditional ground survey methods, which can require days to complete.

The 3D Point Cloud

Through the photogrammetric process a point cloud containing millions of points is generated, each point representing approximately 1 to 1.5 square inches on the ground. WCE's precision mapping products are routinely supplemented with traditional ground survey from a licensed land surveyor, to create a type of hybrid topographic map with high vertical and horizontal accuracies.

The color 3D image shown in Figure 3 represents a point cloud that was developed using photogrammetry. 145 million elevation points were required in order to provide a full and complete representation of the ground surface. Each point represents roughly 1.5 square inches on the ground.

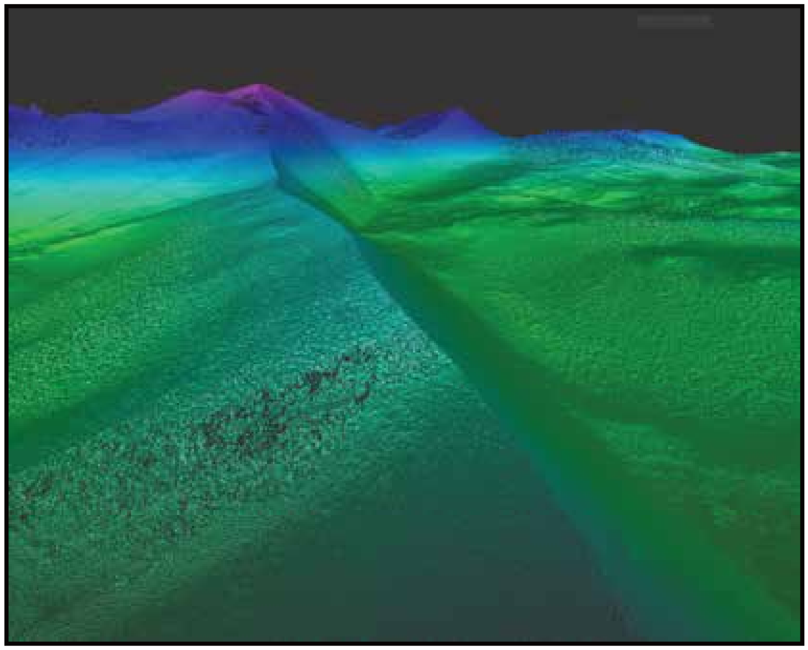

Figure 3: Rendering of 3D Point Cloud of digital elevation data obtained from a UAS photogrammetric survey.

The Great Sand Dunes Aerial Data Collection

In support of, and cooperation with, the Great Sand Dunes National Park Research Staff, Wohnrade Civil Engineers, Inc. successfully executed a UAS aerial data collection on October 19, 2016. This aerial data were later processed using photogrammetric methods to produce a geospatially accurate map for a 1-square mile area of the Great Sand Dunes National Park which is located approximately 25 miles northeast of the City of Alamosa, CO.

The milestone project was a collaborative effort by a diverse team of professionals including (Figure 4):

Figure 4: The WCE UAS Team with Jack Elston (holding the UAS) of Black Swift Technologies.

- Project Coordination by Constantin Diehl of UAS Colorado, and the Research Staff at Great Sand Dunes National Park;
- Engineering and Surveying expertise by Mary Wohnrade, P.E. of Wohnrade Civil Engineers;
- UAS Mission Planning and UAS Piloting by Brendan Thompson of Wohnrade Civil Engineers;
- UAS SwiftTrainer^{tm} Platform and Flight Management Software System developed by Jack Elston of Black Swift Technologies.

The Great Sand Dunes National Park (Figure 5) is a very unique environment presenting a number of challenges to UAS based data collection including:

- The placement and surveying of ground control points using GPS, in an area inaccessible to surface vehicles;
- Development of an effective method of anchoring the GCP targets to the ground surface in order to withstand high winds;
- Performing photogrammetric processing for a set of nearly monochromatic color photographs acquired over what turned out to be relatively homogeneous scene;
- Maintaining constant voice communications between visual observers and the Pilot in Command (PIC) during the collection. Three visual observers were required to successfully perform the collection, in addition to the Pilot in Command at the launch site;
- Variable environmental factors, most notably gusting winds and contrasting shadows;
- The north end of the Area of Interest (AOI) was 5 miles from the launch site, which was located at the Great Sand Dunes Lodge along Highway 150, outside of the boundaries National Park.

Figure 5: Great Sand Dunes National Park.

GPS Ground Control Points

A total of seven (7) surveyed ground control points (GCPs) and check points (CPs) were set by a two man crew from Wohnrade Civil Engineers on October 18, 2016 (Figure 6). It took approximately eight (8) hours to set the seven (7) GCP marker targets and collect the longitude, latitude, and elevation data for each ground GCP using a survey grade GPS. The 1-square mile AOI would usually require up to 24 GCPs. However, the AOI was inaccessible by land vehicle, which significantly reduced the number of GCPs that could be set and used for the collection.

Figure 6: UAS Photograph of UAS survey visual observer in position.

Purpose of the Study

The purpose of the Great Sand Dunes project was to acquire high fidelity aerial remote sensing data for the purpose of enhancing the current understanding of various aspects of the Great Sand Dunes National Park. This included the preparation of a baseline topographic map for monitoring change detection in the vicinity of the Star Dune. The survey flight block or Area of Interest (AOI) is a 1-square mile area centered on the Star Dune.

The primary data product is a high-resolution ortho-rectified full color photomosaic image of the AOI. The ground resolution of the image is 3 cm/pixel. This imagery revealed new information about the Great Sand Dunes previously unknown to Research Staff at the Great Sand Dunes National Park.

Aerial Data Collection

Using two (2) SwiftTrainer UAS, the 1-square mile flight block was surveyed in a total of 2 hours and 30 minutes. A total of 1,755 color photographic images were acquired and processed; 1,289 images collected with the first SwiftTrainer and 466 images were collected using the second SwiftTrainer.

One of the conditions of the Scientific Research and Collecting Permit issued by the National Park Service was that the launch and landing site had to be located outside of the boundary of the Great Sand Dunes National Park. This extended the time required for the collection considerably.

Using a single UAS would have resulted in much greater accuracy. However, during the flight operations an unfortunate incident happened to the first SwiftTrainer which resulted in the use of the backup SwiftTrainer. The camera calibration and image triggering were inconsistent between the two platforms which can be seen as interference patterns in the elevation contours shown in Figure 7.

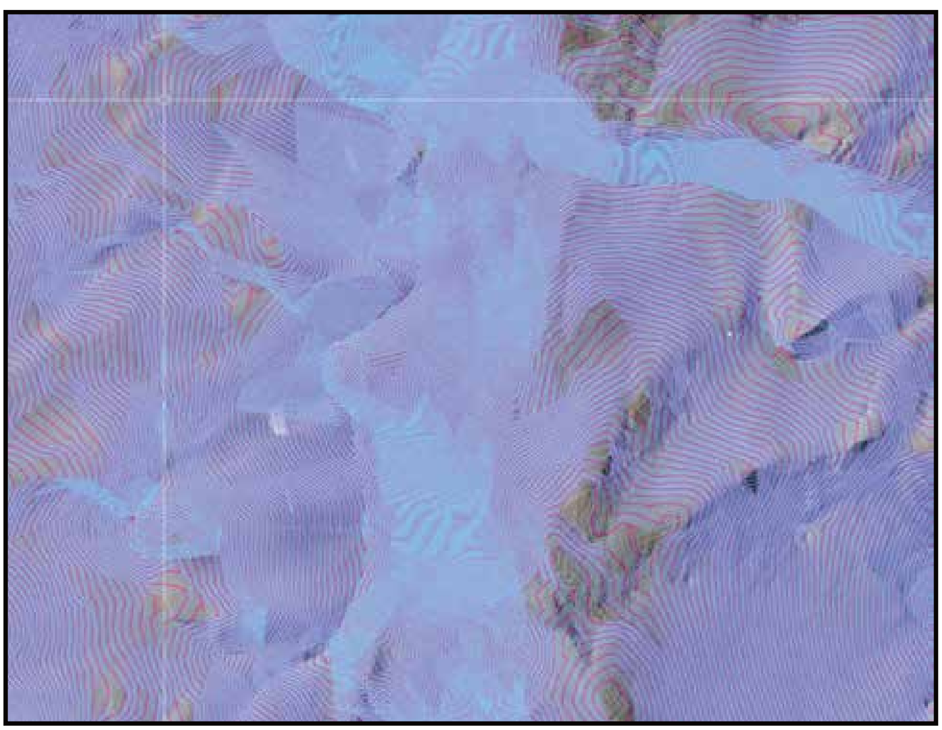

Figure 7: Contour map of elevations obtained from the UAS Photogrammetric Surveys using SwiftTrainer 1 and SwiftTrainer 2.

The SwiftTrainer UAS

The UAS team of Wohnrade Civil and BlackSwift Technologies chose the fixed-wing SwiftTrainer for the Sand Dunes project because of its ease of use, accurate ground tracks, accurate geotagging of photographic imagery, extended range of flight, and the ability to map large areas (up to 2.25 sq-mi) in a relatively short amount of time (Figure 8).

The SwiftTrainer utilizes a custom built flight control and management software that takes advantage of an onboard DEM to maintain a consistent elevation above ground surface during the flight operations and data collection process.

Figure 8: Launching the SwiftTrainer UAS.

The SwiftTrainer also offers superb data coverage with the uniform, tight spacing between images and a consistent overlap pattern, which is essential for photogrammetric processing to obtain high geospatial accuracy of the imagery and derivative data products.

Computed Image/GCPs/Manual Tie Point Positions

The image shown in Figure 9 is the offset between initial (blue dots) and computed (green dots) positions of each image acquired during the collection. In addition, it shows the offset between the initial positions (blue crosses) of the GCPs and their computed positions (green Xs) in the x-y plane. This image is provided by the ESRI data processing software.

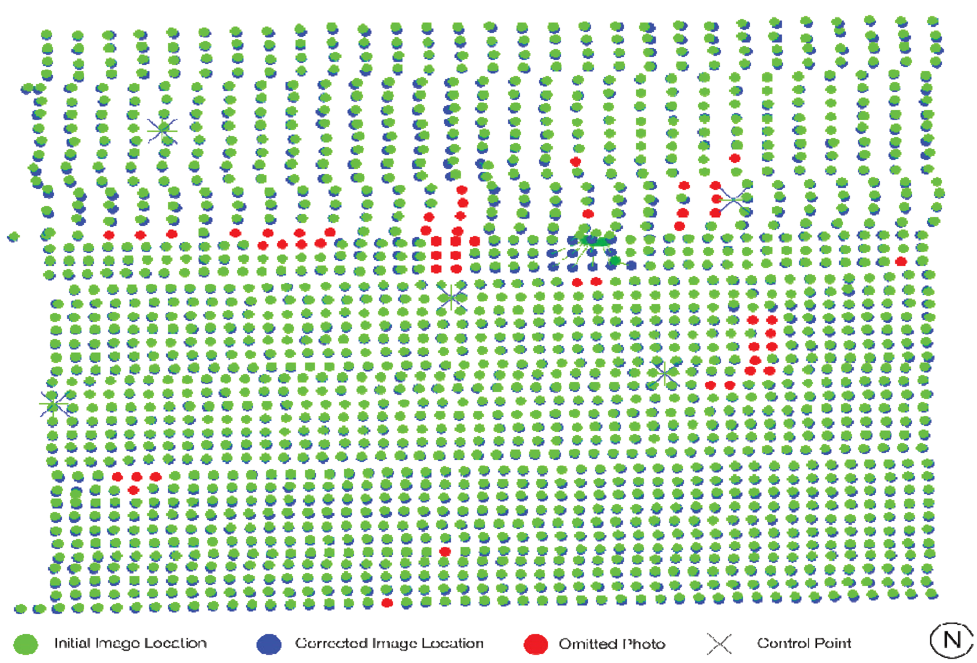

Figure 9: Data image and GCP position map.

ASPRS Horizontal Accuracy Calculations

Wohnrade Civil Engineers, Inc. calculates the RMSE accuracy for each project using methodology and equations established by the American Society for Photogrammetry and Remote Sensing (ASPRS) and published in *ASPRS Positional Accuracy Standards for Digital Geospatial Data, Edition 1, Version 1.0 - November 2014*, Photogrammetric Engineering & Remote Sensing, Vol. 81, No. 3, March 2015, pp. A1-A26.

The accuracy for the Great Sand Dunes National Park project falls short of WCE's usual high standards for several reasons and is summarized by the following RMS Errors.

RMSEx=0.22'   RMSEy=0.72'   RMSEr=0.75'

Based on Table B.3 of the ASPRS Positional Accuracy Standards (Figure 10), the Horizontal Accuracy Class for the Sand Dunes collection is 17.50 cm. When an adequate number of ground control points are used, our final deliverables usually fall within a Horizontal Accuracy Class of 10.00 cm or less.

TABLE B.3 COMMON HORIZONTAL ACCURACY CLASSES ACCORDING TO THE NEW STANDARD[6]

Horizontal Accuracy Class $RMSE_x$ and $RMSE_y$ (cm)	$RMSE_r$ (cm)	Orthoimage Mosaic Seamline Maximum Mismatch (cm)	Horizontal Accuracy at the 95% Confidence Level (cm)
0.63	0.9	1.3	1.5
1.25	1.8	2.5	3.1
2.50	3.5	5.0	6.1
5.00	7.1	10.0	12.2
7.50	10.6	15.0	18.4
10.00	14.1	20.0	24.5
12.50	17.7	25.0	30.6
15.00	21.2	30.0	36.7
17.50	24.7	35.0	42.8
20.00	28.3	40.0	49.0
22.50	31.8	45.0	55.1
25.00	35.4	50.0	61.2
27.50	38.9	55.0	67.3
30.00	42.4	60.0	73.4
45.00	63.6	90.0	110.1
60.00	84.9	120.0	146.9
75.00	106.1	150.0	183.6
100.00	141.4	200.0	244.8
150.00	212.1	300.0	367.2
200.00	282.8	400.0	489.5
250.00	353.6	500.0	611.9
300.00	424.3	600.0	734.3
500.00	707.1	1000.0	1223.9
1000.00	1414.2	2000.0	2447.7

Figure 10: ASPRS horizontal positional accuracy table.

ASPRS Vertical Accuracy Calculations

RMSEz=1.84'

Based on Table B.7 of the ASPRS Positional Accuracy Standards (Figure 11), the Vertical Accuracy Class for the Sand Dunes project is between 33.3 and 66.7 cm. Again, when an adequate number of ground control points are used, the WCE final deliverables usually fall within a Vertical Accuracy Class of between 2.5 and 10 cm.

TABLE B.7 VERTICAL ACCURACY/QUALITY EXAMPLES FOR DIGITAL ELEVATION DATA

Vertical Accuracy Class	Absolute Accuracy			Relative Accuracy (where applicable)		
	RMSEz Non-Vegetated (cm)	NVA at 95% Confidence Level (cm)	VVA at 95th Percentile (cm)	Within-Swath Hard Surface Repeatability (Max Diff) (cm)	Swath-to-Swath Non-Veg Terrain (RMSDz) (cm)	Swath-to-Swath Non-Veg Terrain (Max Diff) (cm)
1-cm	1.0	2.0	3	0.6	0.8	1.6
2.5-cm	2.5	4.9	7.5	1.5	2	4
5-cm	5.0	9.8	15	3	4	8
10-cm	10.0	19.6	30	6	8	16
15-cm	15.0	29.4	45	9	12	24
20-cm	20.0	39.2	60	12	16	32
33.3-cm	33.3	65.3	100	20	26.7	53.3
66.7-cm	66.7	130.7	200	40	53.3	106.7
100-cm	100.0	196.0	300	60	80	160
333.3-cm	333.3	653.3	1000	200	266.7	533.3

Figure 11: ASPRS vertical position accuracy table.

Final Deliverables to the Great Sand Dunes National Park Research Staff

WCE delivered the following data products to the Research Staff at the Great Sand Dunes National Park:

- High-resolution Orthomosaic Image (3 cm/pixel);
- One-foot contours in a .shp file format;
- Point cloud of the DEM in a .las file format containing over 145 million points;
- 3D Model in a .obj file format.

The following delivery formats were utilized based on the client's needs:

- AutoCAD Civil 3D .dwg file format including a surface model;
- Digital Elevation Model (DEM) in a .tif file format.

Conclusions

The UAS aerial data collection of the Star Dune at the Great Sand Dunes National Park was performed under very challenging conditions due to site access restrictions, the geologic environment, terrain, and the weather. Several site and environmental factors served to impact the geospatial accuracy of the collected data. Nevertheless, WCE learned a great deal about how to avoid and mitigate these issues for future UAS aerial data collections.

Overall, the Research Team at the Great Sand Dunes National Park is quite pleased with the results, noting that "*It is definitely the best imagery of the dunes to date!*"

The high-resolution imagery has also led to the recognition of new features at the Star Dune which has the potential for new discoveries. WCE anticipates that it will have the opportunity to perform data collections for the same AOI at the Great Sand Dunes National Park on an annual basis. As a result of this work, Wohnrade Civil Engineers has already begun developing new methods to increase vertical and horizontal accuracies in this very challenging and unique environment.

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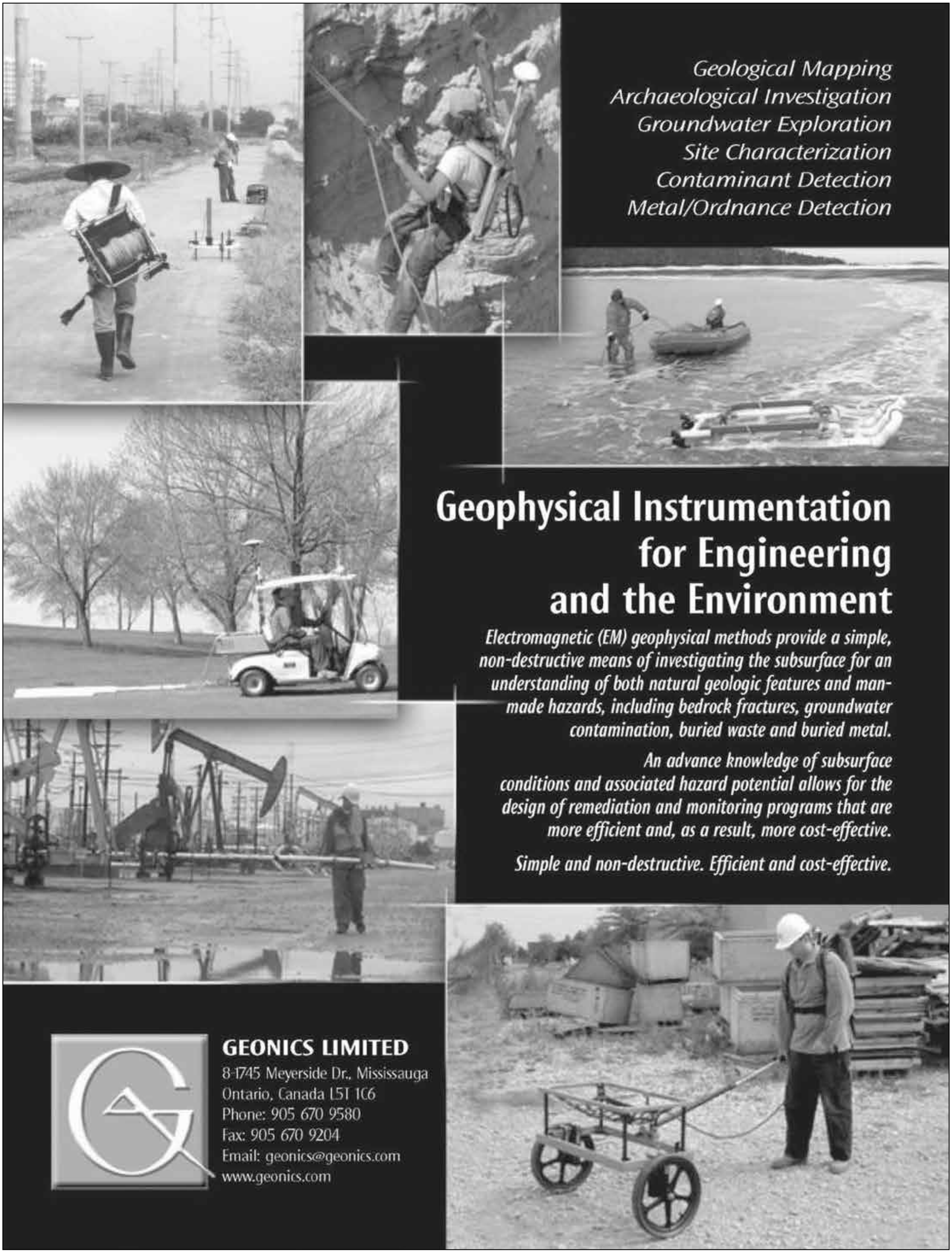
About the Author: Ron Bell is a consulting geophysicist with more than 3 decades of experience in the application of geophysical technology to the exploration for mineral, groundwater, and hydrocarbon resources as well as environmental subsurface site characterization. His company, International Geophysical Services, LLC, provides ground and airborne geophysical data acquisition and related services including the drone based data acquisition of magnetic and photogrammetry data. (www.igsdenver.com)


Geological Mapping
Archaeological Investigation
Groundwater Exploration
Site Characterization
Contaminant Detection
Metal/Ordnance Detection
Geophysical Instrumentation for Engineering and the Environment
Electromagnetic (EM) geophysical methods provide a simple, non-destructive means of investigating the subsurface for an understanding of both natural geologic features and man-made hazards, including bedrock fractures, groundwater contamination, buried waste and buried metal.
An advance knowledge of subsurface conditions and associated hazard potential allows for the design of remediation and monitoring programs that are more efficient and, as a result, more cost-effective.
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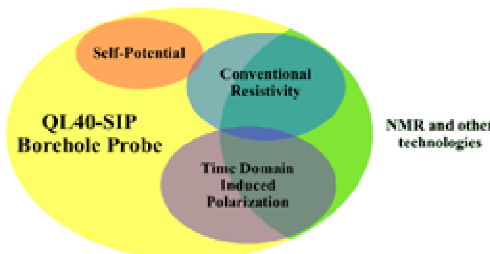
MOUNT SOPRIS INSTRUMENTS

Development of SIP Probe Announced at AGU

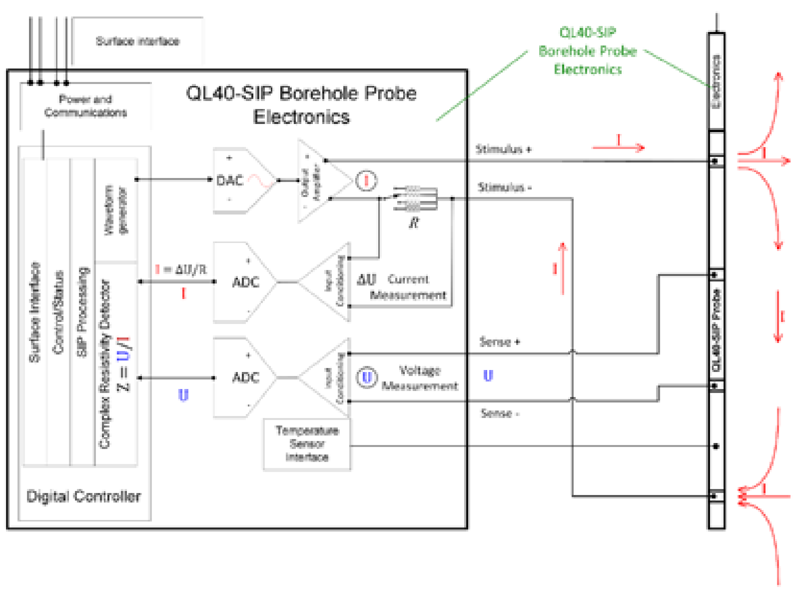
December 20, 2016

Mount Sopris announced the development of a new borehole probe based on Spectral Induced Polarization (SIP) technology at the American Geophysical Union (AGU) Fall meeting in San Francisco. The SIP probe will be directly relevant for subsurface investigations in hydrogeology, environmental, mineral exploration, and other fields, promising indirect determination of hydraulic conductivity, effective porosity, and other formation properties.



Providing a superset of measurements, the SIP probe will cost-effectively compare with nuclear magnetic resonance (NMR) logs, while also providing SP and conventional resistivity logs. It will also provide an inherently safer alternative to nuclear logging tools using radioactive material.

This project is a collaboration between Mount Sopris, Rutgers University, and Ontash & Ermac (O&E), a leading developer of spectral induced polarization (SIP) equipment for use in laboratory and surface applications. Together, this team is integrating O&E's SIP electronics into Mount Sopris' borehole logging system, followed by rigorous field validation and characterization in various borehole conditions for which comparison data is available.



The anticipated product release of commercial probe is late 2017 or early 2018. For more information, go to http://mountsopris.com/items/ql40-sip-spectral-induced-polarization/.

Exploration Instruments
Geophysical Equipment Rentals

New Pennsylvania location increases service to Eastern USA

Exploration Instruments, of Austin, Texas, has opened a new branch office in Harrisburg, Pennsylvania. The Harrisburg office is fully staffed with 4 experienced personnel and carries the complete line of instrumentation generally available from EXI. Lead Technician Jeff Sinski has spent more than 20 years in the geophysical equipment rental industry and is looking forward to continuing to provide his knowledge and expertise to the many clients he has worked with over the years.

Located at 5000 Paxton St., this EXI location occupies 3,500 sq ft of office space and warehouse in its own building with easy drive-up access and lots of parking. Ideally situated to service the Mid-Atlantic and Eastern states, customers will reduce shipping expenses by picking up instruments at the facility or availing themselves of 1 day Fedex or UPS ground service.

Equipment reservation inquiries may be made via email to service@expins.com or the main customer service phone number in Austin at 512-346-4042.

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We want to be your partner in technology. Give us a look!

PRESS RELEASE

NRG Systems to Provide Advanced Lidar Solutions to Mitigate Air Pollution Transport in the Americas

Hinesburg, VT, USA **- NRG Systems, a global leader in the distribution and service of atmospheric remote sensing solutions, has announced today the U.S. launch of advanced Lidar solutions, introducing powerful new ways to resolve the critical air quality management challenges facing North America's industrial and commercial sectors. Thanks to their ability to assess the specific nature of fugitive industrial emissions with accuracy and in real-time, Lidars are recognized as an essential tool to mitigate the negative impact of air pollution transport on our communities.**

This Lidar technology, called WINDCUBE*®,* can detect lower atmospheric wind transport conditions and industrial aerosol plumes simultaneously and in real-time, enabling the identification of the source, location, distance, altitude, and dispersion rates of potentially hazardous industrial emissions with a precision that was previously unachievable.

Whether it is used for improving the management of mineral dust transport generated by mining activities, or informing air pollution management strategies in large urban environments, WINDCUBE*®* is set to play a significant role in helping all organizations with an interest in detecting and quantifying airborne industrial aerosols to make intelligent decisions in the face of atmospheric uncertainty.

"*Efficient air quality management is one of the most important environmental challenges facing our country today. In 2015, The U.S. Environmental Protection Agency (EPA) reported that an estimated 6.6 million tons of criteria pollutants were released into the atmosphere across America. Our remote sensing solutions will concretely enable research, industrial, commercial, and public institutions to cope with air pollution hazards by visualizing their atmospheric risk,"* commented Paul Drewniak, a meteorological industry expert with over 20 years of experience, who was recently recruited to head NRG's new Lidar Meteorology Solutions business unit.

With remote sensing capabilities that range from 100m to 3km, 6km, or 10km, multiple scanning pattern choices, high resolution wind data, and aerosol structure capability, the system can capture volumetric profiles of wind speed, direction, and aerosol concentration, as well as boundary layer and cloud heights. These observations provide a detailed, 3D image of the atmosphere at high spatial and temporal resolution.

NRG Systems' meteorological products are already in use by air quality management districts, environmental firms, research institutes, and governments in more than 150 countries. "*WINDCUBE® is a commercially proven technology that offers unrivalled scanning versatility and unmatched commercial performance. Whether for fence line monitoring of refineries, petrochemical, mining, or other industrial plants, or for wind reconstruction in support of dispersion mapping and modeling, WINDCUBE® provides highly accurate, mobile, and flexible technology with unsurpassed ease-of-use and configurability*," said Drewniak.

Earlier this year, NRG Systems secured a contract with the state of New York to supply 17 WINDCUBE® 100S Lidar systems for the New York State Mesonet, an advanced weather network dedicated to improving the detection and prediction of severe weather events. "*Our immediate objective is to provide better early warning in advance of severe weather, but the benefits will go well beyond that*," explained Everette Joseph, director of the Atmospheric Sciences Research Center at the University at Albany. "*We will be able to help give guidance to a variety of interested industries, including transportation and energy. There will be significant economic benefit from having this network in New York State*."

WINDCUBE® Lidar solutions are designed and manufactured by French technology firm LEOSPHERE, and exclusively distributed in North America by NRG Systems. The technology, which is recognized as the best-in-class Lidar solution in academic communities worldwide, is an essential tool for all organizations dedicated to improving their atmospheric hazards control capabilities.

For more information, please visit www.scanninglidar.com

About NRG Systems
NRG Systems is a global leader in the distribution and service of atmospheric remote sensing products and intelligent solutions for the professional meteorology and renewable energy markets. NRG pioneered wind resource assessment more than 30 years ago, when the wind industry was just beginning. Today, the company serves multiple stages of meteorological, wind, solar, and enterprise solutions development—from academia to commercial operation. You'll find NRG products in use by air quality management districts, environmental firms, research institutes, and governments in more than 150 countries. NRG Systems. We help you visualize atmospheric risk.
www.scanninglidar.com – www.renewablenrgsystems.com

About LEOSPHERE
LEOSPHERE is a global leader in Lidar atmospheric remote observation in markets such as wind energy, weather and climate, aviation weather, air quality, and industrial risk. The company develops and manufactures new turnkey remote-sensing instruments that allow wind measurement and aerosol detection. LEOSPHERE has deployed more than 750 Lidars throughout the world in severe environments with the same concern of reliability, reduction of operational costs for clients, and dedication to atmospheric hazards control. www.leosphere.com

COMING EVENTS AND ANNOUNCEMENTS

SAGEEP 2017

30th

Registration Now Open!

Denver, Colorado
March 19-23

A very special SAGEEP has been planned for 2017. For a single registration fee, attendees will not only benefit from the oral presentations and posters typically offered, but will also have the National Ground Water Association's (NGWA) Technical Program to choose from when developing personal attendance plans! See below for what awaits the geophysical community as scientists from all over the world gather to help celebrate the 30th Anniversary - and take advantage of this unique opportunity!

Special Sessions / Oral Presentations / Posters
Exhibition and Outdoor Equipment Demonstrations
Keynote Presentation - Two Special Speakers
Short Courses on Sunday and Thursday
Pre-Conference Field Trip
Student Event
SAGEEP/NGWA Mixer

NGWA℠ The Groundwater Association

NGWA's Applications of Hydrogeophysics to Groundwater Characterization, Monitoring, and Management
Deep Groundwater Applications
NGWA Panel: Review of the Aquifer Exemption Process, History and Implementation Related to Groundwater Protection and Use

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General Chair
Dale Werkema, Ph.D.
Werkema.D@epamail.epa.gov

Technical Chair
Elliot Grunewald, Ph.D.
elliot@vista-clara.com

Symposium on the Application of Geophysics to Engineering and Environmental Problems

WWW.EEGS.ORG/SAGEEP 2017

COMING EVENTS AND ANNOUNCEMENTS

SAGEEP 2017

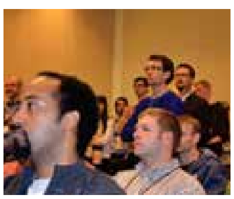
The Conference

SAGEEP is internationally recognized as the leading conference on the practical application of shallow geophysics. Since 1988, the symposium has featured over 200 oral and poster presentations, educational short courses and workshops, a commercial exhibition and field trips. In 2017, SAGEEP celebrates its 30th Anniversary **and** the co-location with NGWA's Hydrogeophysics and Deep Groundwater Conference at the Denver Marriott City Center.

About the City

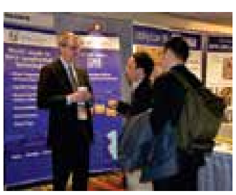
Denver, the Mile High City, a thriving cultural scene, diverse neighborhoods, and natural beauty is one of the world's most spectacular playgrounds. Located 12 miles east of the "foothills," Denver is situated at the base of the Colorado Rocky Mountains. Since its Wild West beginnings, Denver has evolved into a young, active city - stunning architecture, award-winning dining, unparalleled views year-round and 300 days of sunshine a year. The conference will be held in downtown Denver - the heart of the city.

The Technical Program



The Technical Program typically features over 200 oral and poster presentations. The list of special sessions, session topics and subtopics is found on the SAGEEP 2017 web page "Program." For additional information, contact Technical Chair Elliot Grunewald at elliot@vista-clara.com.

The Exhibits/Exhibitors Outdoor Equipment Demonstrations



In addition to 14,000 square feet of exhibition space, exhibitors will conduct equipment demonstrations. With NGWA attendees, an even wider audience of geophysics professionals interested in the latest in equipment, software and services - they will find it at SAGEEP 2017.

Sponsorships and Other Supporting Opportunities

Sponsoring an event, luncheon, or conference materials is an effective and economical way to increase visibility for your organization or services, reaching a targeted audience of geophysicists from many disciplines. Contact Micki Allen mickiallen@marac.com for more information.

WWW.EEGS.ORG/ANNUAL MEETING/SAGEEP 2017

WWW.EEGS.ORG/SAGEEP 2017/REGISTRATION

COMING EVENTS AND ANNOUNCEMENTS

SAGEEP 2017 SCHEDULE AT A GLANCE

Sunday March 19

Short Courses 8:30am-4:30pm

SC-1: Exploring Ground Penetrating Radar – Theory, Best Practices, Insights and Examples
Instructors: Kevin O'Hara and Brian Jones, GSSI

SC-2: WellCAD Geophysical Well Log Presentation & Analysis Software
Instructors: Taylor Weber and Lia Martinez, Mount Sopris Instrument Company, Inc.

SC-3: 3D Hydrogeological Modeling
Instructors: Torben Bach, MSc and Tom Pallesen, MSc; Senior Consultants, I-GIS

8:30am-5:00pm	Hidee Gold Mine Tour
5:00-7:00pm	Ice Breaker - Exhibit Hall
7:30-9:30pm	Student Event

Monday March 20

Time	Room 1	Room 2	Room 3	Room 4
8:00-10:00am	Opening Session: John Nicholl Memorial Award and Keynote Presentations Andrea Croskrey, M.S., TX Water Development Board / Kamini Singha, PhD, Colorado School of Mines			
10:00-10:20am	Coffee in Exhibit Hall			
10:20am-12:00pm	Best of Near Surface Geoscience 2016			
12:00-1:30pm	Geoscientists *Without* Borders® Luncheon /John Bradford and Mike Kalinski			
	Electromagnetic Methods	Dams and Levees	Seismic Methods	Ground Penetrating Radar
2:30-3:00pm	Coffee in Exhibit Hall			
	Theory, Modeling and Inversion	Dams and Levees (continued)	Seismic Methods (continued)	GPR (continued)
5:00-7:00pm	Poster Session I - Area Adjacent to Exhibit Hall			
	SAGEEP/NGWA Reception in Exhibit Hall			

Tuesday March 21

Time	Room 1	Room 2	Room 3	Room 4
	Electrical Methods (DC, SP & IP)	Engineering & Infrastructure	Borehole Methods	Airborne Geophysics
10:30-10:50am	Coffee in Exhibit Hall			
	Nuclear Magnetic Resonance	Infrastructure	Contamination & Threats	Airborne (continued)
11:50am-1:00pm	Workshop: Writing for Scientific Journals or Lunch on Your Own			
	NMR (continued)	Archaeology	Contamination & Threats (continued)	Airborne (continued)
	Poster Session II - Area Adjacent to Exhibit Hall			
2:20-2:50pm	Coffee in Exhibit Hall			
	NMR (continued)	Cryosphere	Contamination & Threats (continued)	Geohazards
4:30-5:30pm	Exhibitors Outdoor Equipment Demonstrations - Benedict Fountain Park (walking distance)			

Wednesday March 22

Time	Room 1	Room 2	Room 3	Room 4
	NMR (continued)	Land Reclamation	Surface and Groundwater Interactions	Geohazards (continued)
10:10-10:40am	Coffee in Exhibit Hall			
	Electrical Methods (DC, SP & IP)	Hydrocarbons	Surface and Groundwater Interactions (continued)	Water Resources
12:00-1:30pm	EEGS Annual Meeting & Luncheon			
	Humanitarian	Uncertainty & Data Fusion	Critical Zone Co-sponsored by SEG	Water Resources (continued)
3:00-3:30pm	Coffee in Exhibit Hall			
	Mining	UXO	Critical Zone (continued) Co-sponsored by SEG	Water Resources (continued)

Thursday March 23

Short Courses 8:30am-4:30pm

SC-4: Land and Marine Electrical Resistivity/IP/SP
Instructor: Jason Greenwood, Advanced Geosciences, Inc.

SC-5: Utilizing NMR for Groundwater Investigations
Instructor: Elliot Grunewald, Vista Clara, Inc.

COMING EVENTS AND ANNOUNCEMENTS

Imaging the Critical Zone

Join us at Stanford University on 24-27 July 2017.

In this workshop, we will bring together hydrogeophysicists and other critical zone scientists to explore new ways to work together, using recent advances in hydrogeophysics to address key scientific questions about the critical zone.

ABSTRACT DEADLINE: February 23, 2017
Notification of Abstract Acceptance: March 22, 2017
Final Program Published: March 22, 2017

Visit the workshop Web site <http://workshops.agu.org/hydrogeophysics/> for additional details as information becomes available.

Organizing Committee: Rosemary Knight and Kristina Keating (co-chairs), Anja Klotzsche, Kate Maher, Daniella Rempe, and Kamini Singha.

COMING EVENTS AND ANNOUNCEMENTS

Environmental
And Engineering
Geophysical Society

Dr. Dale F. Rucker, Editor
Journal of Environmental & Engineering Geophysics
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Call for Papers with a Focus on Exploring Geophysics in China - Special Issue of the Journal of Environmental & Engineering Geophysics

The Journal of Environmental & Engineering Geophysics (JEEG) announces a Call for Papers for a special issue on Geophysics in China. This issue is scheduled for publication in June 2018. The special issue co-editors are Guoqiang Xue and Jianghai Xia. Sponsorship of this issue is open.

Suggested themes are:

- Recent progress in instrument development for near surface geophysics in China
- Novel near surface geophysical systems in China
- Data acquisition, modeling, and inversion in China
- Case histories for all aspects of near surface geophysics in China

International contributions are encouraged. The special issue will accommodate at least 15 papers, but all accepted papers will be considered for publication in other JEEG issues. Papers may be submitted through the JEEG submission site, http://jeeg.allentrack.net. Indicate in the cover letter that the paper is for consideration in the Geophysics in China special issue. The deadline for submissions is March 31th, 2017.

Please be advised that while publication in JEEG is free for grayscale figures, nominal fees will be assessed for color figures. Fees for digital color figures are $100/figure USD and $550/figure for hard copy print. Please state in the cover letter that you are aware of the fees for color figures and you are willing to pay the fee (if color figures are included in the manuscript).

JEEG also offers two options for publication: a Near Surface Geophysical Letter (NSGL) and a full research article. The difference between the two is the length of the article. NSGLs are typically 1000-3000 words with up to four figures. Full articles are in excess of 3000 words and there are no limits to figures. However, a general rule of thumb is to have 1 to 2 times the number of figures per 1000 words. A 5000 word article can accommodate about 5 to 10 figures. The NSGL can also make its way through the review process faster as it takes less time to review.

Abstracts will be printed in English and Chinese. However, all work must be submitted in proper English. We encourage all non-native English speakers to seek outside writing services. If manuscripts are poorly written, there is a higher probability of rejection. Some services are listed below:

- http://www.editage.com
- http://www.internationalscienceediting.com
- http://www.journalexperts.com
- http://www.oleng.com.au
- http://www.prof-editing.com
- http://www.sciencedocs.com
- http://www.scientific-editor.com
- http://www.scitext.com
- http://www.writescienceright.com

Questions may be directed to:
Special Issue Co-Editors (for EM based papers)—Guoqiang Xue, ppxueguoqiang@163.com
Special Issue Co-Editors (for non-EM based papers)—Jianghai Xia, jxia@cug.edu.cn
Editor in Chief – Dale Rucker, druck8240@gmail.com

Environmental and Engineering Geophysical Society
1720 South Bellaire, Suite 110, Denver, CO 80222-4303
URL: www.eegs.org

Environmental and Engineering Geophysical Society	Renew or Join Online at www.EEGS.org
2017 Individual Membership Application	

Individual Membership Categories

EEGS is the premier organization for geophysics applied to engineering and environmental problems. Our multi-disciplinary blend of professionals from the private sector, academia, and government offers a unique opportunity to network with researchers, practitioners, and users of near-surface geophysical methods.

Memberships include access to the *Journal of Environmental & Engineering Geophysics (JEEG)*, proceedings archives of the Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP), and our quarterly electronic newsletter, *FastTIMES*. Members also enjoy complimentary access to SEG's technical program expanded abstracts, as well as discounted SAGEEP registration fees, books and other educational publications. EEGS offers a variety of membership categories tailored to fit your needs. Please select (circle) your membership category and indicate your willingness to support student members below:

☐ **Yes, I wish to sponsor ________ student(s) @ $20 each to be included in my membership payment.**

Individual Members

Individual members are invited to sponsor student members. Simply indicate the number of students you'd like to support (at $20 each) to encourage growth in this important segment of EEGS' membership.

Category	Electronic *JEEG* Available Online	Printed *JEEG* Mailed to You
Individual	$105	$150

Retired Members

Your opportunity to stay connected and support the only organization focusing on near surface geophysics. Retired members are invited to sponsor student members. Simply indicate the number of students you'd like to support (at $20 each) to encourage growth in this important segment of EEGS' membership.

Category	Electronic *JEEG* Available Online	Printed *JEEG* Mailed to You
Retired (*Must be Approved by EEGS Board of Directors)*	$50	$150

Introductory Members

If you have not been a member of EEGS before, we offer a reduced rate (electronic JEEG option) for new members to enjoy all the benefits of individual membership (except vote or hold office) for one year.

Category	Electronic *JEEG* Available Online	Printed *JEEG* Mailed to You
Introductory	$50	$150

Lifetime Members

Support EEGS, receive benefits on an ongoing basis and never renew again! Members of this category enjoy all the benefits of Individual membership.

Category	Electronic *JEEG* Available Online	Printed *JEEG* Mailed to You
Lifetime Member	$995	$995

Developing World Members

Those selecting this category of EEGS membership are invited to check the list of countries to determine qualification.

Category	Electronic *JEEG* Available Online	Printed *JEEG* Mailed to You
Developing World *(List of qualifying countries next page)*	$50	$150

Student Members

Students represent EEGS' future and we offer complimentary membership subsidized by Corporate Student Sponsor Members and those who sponsor students. Student members enjoy all the benefits of individual membership (except to vote or hold office). Available to all students in an accredited university up to one year post-graduation. Please submit a copy of your student ID and indicate your projected date of graduation: ___ /____ (Month/Year). Students in year two beyond graduation are offered a special rate for 1 year.

Category	Electronic *JEEG* Available Online	Printed *JEEG* Mailed to You
Student up to 1 Year Post Graduation (Grad Date: Mo/Yr.: ___/___)	$ 0	$110
Student - Year Two Post Graduation	$50	$110

Membership Renewal
Developing World Category Qualification

If you reside in one of the countries listed below, you are eligible for EEGS's Developing World membership category rate of $50.00 (or $150.00 if you would like the printed, quarterly *Journal of Environmental & Engineering Geophysics* (*JEEG*) mailed to you). To receive a printed *JEEG* as a benefit of membership, select the Developing World Printed membership category on the membership application form.

Afghanistan
Albania
Algeria
Angola
Armenia
Azerbaijan
Bangladesh
Belize
Benin
Bhutan
Bolivia
Burkina Faso
Burundi
Cambodia
Cameroon
Cape Verde
Central African Republic
Chad
China
Comoros
Congo, Dem. Rep.
Congo, Rep.
Djibouti
Ecuador
Egypt
El Salvador
Eritrea
Ethiopia
Gambia
Georgia
Ghana
Guatemala
Guinea-Bissau
GuyanaHaiti
Honduras
India
Indonesia
Iran
Iraq
Ivory Coast
Jordan
Kenya
Kiribati
Kosovo
Kyrgyz Republic
Lao PDR
Lesotho
Liberia
Madagascar
Malawi
Maldives
Mali
Marshall Islands
Mauritania
Micronesia
Moldova
Mongolia
Morocco
Mozambique
Myanmar
Nepal
Nicaragua
Niger
Nigeria
North Korea
Pakistan
Papua New Guinea
Paraguay
Philippines
Rwanda
Samoa
Sao Tome and Principe
Senegal
Sierra Leone
Solomon Islands
Somalia
Sri Lanka
Sudan
Suriname
Swaziland
Syria
Taiwan
Tajikistan
Tanzania
Thailand
Timor-Leste
Togo
Tonga
Tunisia
Turkmenistan
Uganda
Ukraine
Uzbekistan
Vanuatu
Vietnam
West Bank and Gaza
Yemen
Zambia
Zimbabwe

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Environmental and Engineering Geophysical Society

2017 EEGS Membership Application

Renew or Join Online at www.EEGS.org

CONTACT INFORMATION

Salutation | First Name | Middle Initial | Last Name

Company/Organization | Title

Street Address | City | State/Province | Zip Code | Country

Direct Phone | Mobile Phone | Fax

Email | Website

ABOUT ME: INTERESTS & EXPERTISE

In order to identify your areas of specific interests and expertise, please check all that apply:

Role	Interest or Focus	Geophysical Expertise	Professional/ Scientific Societies	Willing to Serve on a Committee?
☐ Consultant	☐ Archaeology	☐ Borehole Geophysical Logging	☐ AAPG	☐ Publications
☐ User of Geophysical Svcs.	☐ Engineering	☐ Electrical Methods	☐ AEG	☐ Web Site
☐ Student	☐ Environmental	☐ Electromagnetics	☐ ASCE	☐ Membership
☐ Geophysical Contractor	☐ Geotechnical	☐ Gravity	☐ AWWA	☐ Student
☐ Equipment Manufacturer	☐ Geo. Infrastructure	☐ Ground Penetrating Radar	☐ AGU	
☐ Software Manufacturer	☐ Groundwater	☐ Magnetics	☐ EAGE	
☐ Research/Academia	☐ Hazardous Waste	☐ Marine Geophysics	☐ EERI	
☐ Government Agency	☐ Humanitarian Geo.	☐ Remote Sensing	☐ GeoInstitute	
☐ Other	☐ Mining	☐ Seismic	☐ GSA	
	☐ Shallow Oil & Gas	☐ Other	☐ NGWA	
	☐ UXO		☐ NSG	
	☐ Aerial Geophysics		☐ SEG	
	☐ Other		☐ SSA	
			☐ SPWLA	

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 | Renew or Join Online at www.EEGS.org

FOUNDATION CONTRIBUTIONS

FOUNDERS FUND

The Founders Fund has been established to support costs associated with the establishment and maintenance of the EEGS Foundation as we solicit support from larger sponsors. These will support business office expenses, necessary travel, and similar expenses. It is expected that the operating capital for the foundation will eventually be derived from outside sources, but the Founder's Fund will provide an operation budget to "jump start" the work. Donations of $50.00 or more are greatly appreciated. For additional information about the EEGS Foundation (an IRS status 501(c)(3) tax exempt public charity), visit the website at http://www.EEGSFoundation.org.

Foundation Fund Total: $ ________________

STUDENT SUPPORT ENDOWMENT

This Endowed Fund will be used to support travel and reduced membership fees so that we can attract greater involvement from our student members. Student members are the lifeblood of our society, and our support can lead to a lifetime of involvement and leadership in the near-surface geophysics community. Donations of $50.00 or more are greatly appreciated. For additional information about the EEGS Foundation (a tax exempt public charity), visit the website at http://www.EEGSFoundation.org.

Student Support Endowment Total: $ ________________

CORPORATE CONTRIBUTIONS

The EEGS Foundation is designed to solicit support from individuals and corporate entities that are not currently corporate members (as listed above). We recognize that most of our corporate members are small businesses with limited resources, and that their contributions to professional societies are distributed among several organizations. The Corporate Founder's Fund has been developed to allow our corporate members to support the establishment of the Foundation as we solicit support from new contributors.

Corporate Contribution Total: $ ________________

Foundation Total: $ ________________

PAYMENT INFORMATION

☐ Check/Money Order ☐ VISA ☐ MasterCard

☐ AmEx ☐ Discover

Subtotals

Membership: $ ________________

Student Sponsorship: $ ________________

Foundation Contributions: $ ________________

Grand Total: $ ________________

Card Number **Exp. Date** **CVV #:**

Name on Card

Signature

Make your check or money order in US dollars payable to: EEGS. Checks from Canadian bank accounts must be drawn on banks with US affiliations (example: checks from Canadian Credit Suisse banks are payable through Credit Suisse New York, USA). Checks must be drawn on US banks.

Payments are not tax deductible as charitable contributions although they may be deductible as a business expense. Consult your tax advisor.

Return this form with payment to: EEGS, 1720 South Bellaire Street, Suite 110, Denver, CO 80222 USA

Credit card payments can be faxed to EEGS at 001.1.303.820.3844

Corporate dues payments, once paid, are non-refundable. Individual dues are non-refundable except in cases of extreme hardship and will be considered on a case-by-case basis by the EEGS Board of Directors. Requests for refunds must be submitted in writing to the EEGS business office.

QUESTIONS? CALL 001.1.303.531.7517

Environmental and Engineering Geophysical Society	Renew or Join Online at www.EEGS.org
2017 Corporate Membership Application	

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☐ **Yes, I wish to support ____ student(s) at $20 each to be included in my membership payment.**

Category	2017 Electronic JEEG	2017 Basic Rate (print JEEG)	2017 Basic + Web Ad Package
Corporate Student Sponsor *Includes one (1) individual membership, a company profile and linked logo on the EEGS Corporate Members web page, a company profile in FastTIMES and the SAGEEP program, recognition at SAGEEP, a 10% discount on advertising in JEEG and FastTIMES, a 20% discount on JEEG article color figure charges and Sponsorship of Student Memberships*	$310	$340	$840
Corporate Donor *Includes one (1) individual EEGS membership, one (1) full conference registra-tion to SAGEEP, a company profile and linked logo on the EEGS Corporate Members web page, a company profile in FastTIMES and the SAGEEP program, recognition at SAGEEP, 10% discount on SAGEEP Short Courses/Workshops for members and employees, ability to advertise job openings via an EEGS Alert or eblast, a 20% discount on JEEG article color figure charges and a 10% discount on advertising in JEEG and FastTIMES*	$660	$690	$1190
Corporate Associate *Includes two (2) individual EEGS memberships, an exhibit booth and registra-tion at SAGEEP, the ability to insert marketing materials in the SAGEEP delegate packets, a company profile and linked logo on the EEGS Corporate Members web page, a company profile in FastTIMES and the SAGEEP program, recognition at SAGEEP, a 20% discount on JEEG article color figure charges and a 10% discount on advertising in JEEG and FastTIMES*	$2410	$2440	$2940
Corporate Benefactor *Includes two (2) individual memberships to EEGS, two (2) exhibit booths and registrations at SAGEEP, the ability to insert marketing materials in the SAGEEP delegate packets, a company profile and linked logo on the EEGS Corporate Members web page, a company profile in FastTIMES and the SAGEEP program, recognition at SAGEEP, a 20% discount on JEEG article color figure charges and a 10% discount on advertising in JEEG and FastTIMES*	$4010	$4040	$4540
Website Advertising *One (1) Pop-Under, scrolling marquee style ad with tag line on Home page, logo linked to Company web site, One (1) Button sized ad, linked logo, right rail on each web page*	Purchase Separately (without membership) $600/yr. $250/yr.	$600/yr. $250/yr.	Package Rates include both website ad locations

Environmental and Engineering Geophysical Society	Renew or Join Online at www.EEGS.org
2017 Corporate Membership Application	

CONTACT INFORMATION

Salutation | First Name | Middle Initial | Last Name

Company/Organization | Title

Street Address | City | State/Province | Zip Code | Country

Direct Phone | Mobile Phone | Fax

Email | Website

ABOUT ME: INTERESTS & EXPERTISE

In order to identify your areas of specific interests and expertise, please check all that apply:

Role	Interest or Focus	Geophysical Expertise	Professional/ Scientific Societies	Willing to Serve on a Committee?
☐ Consultant	☐ Archaeology	☐ Borehole Geophysical Logging	☐ AAPG	☐ Publications
☐ User of Geophysical Svcs.	☐ Engineering	☐ Electrical Methods	☐ AEG	☐ Web Site
☐ Student	☐ Environmental	☐ Electromagnetics	☐ ASCE	☐ Membership
☐ Geophysical Contractor	☐ Geotechnical	☐ Gravity	☐ AWWA	☐ Student
☐ Equipment Manufacturer	☐ Geo. Infrastructure	☐ Ground Penetrating Radar	☐ AGU	
☐ Software Manufacturer	☐ Groundwater	☐ Magnetics	☐ EAGE	
☐ Research/Academia	☐ Hazardous Waste	☐ Marine Geophysics	☐ EERI	
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	☐ UXO		☐ NSG	
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1720 South Bellaire Street | Suite 110 | Denver, CO 80222-4303
(p) 001.1.303.531.7517 | (f) 000.1.303.820.3844 | staff@eegs.org | www.eegs.org

FOUNDATION CONTRIBUTIONS

FOUNDERS FUND

The Founders Fund has been established to support costs associated with the establishment and maintenance of the EEGS Foundation as we solicit support from larger sponsors. These will support business office expenses, necessary travel, and similar expenses. It is expected that the operating capital for the foundation will eventually be derived from outside sources, but the Founder's Fund will provide an operation budget to "jump start" the work. Donations of $50.00 or more are greatly appreciated. For additional information about the EEGS Foundation (an IRS status 501(c)(3) tax exempt public charity), visit the website at http://www.EEGSFoundation.org.

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STUDENT SUPPORT ENDOWMENT

This Endowed Fund will be used to support travel and reduced membership fees so that we can attract greater involvement from our student members. Student members are the lifeblood of our society, and our support can lead to a lifetime of involvement and leadership in the near-surface geophysics community. Donations of $50.00 or more are greatly appreciated. For additional information about the EEGS Foundation (a tax exempt public charity), visit the website at http://www.EEGSFoundation.org.

Student Support Endowment Total: $ ____________

CORPORATE CONTRIBUTIONS

The EEGS Foundation is designed to solicit support from individuals and corporate entities that are not currently corporate members (as listed above). We recognize that most of our corporate members are small businesses with limited resources, and that their contributions to professional societies are distributed among several organizations. The Corporate Founder's Fund has been developed to allow our corporate members to support the establishment of the Foundation as we solicit support from new contributors.

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Environmental and Engineering Geophysical Society

2017 Publications and Merchandise Order Form

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	0036	2014 (CD-ROM)	$75	$100
	0034	2013 (CD-ROM)	$75	$100
	0025	2008 (CD-ROM)	$75	$100
	0023	2007 (CD-ROM)	$75	$100

Member/Non-Member

	0013, 0014, 0015, 0016, 0018, and 0020	CD-ROMs for 2001, 2002, 2003, 2004, 2005 and 2006 are available upon request (call or email EEGS to check availability and place order)	$75 each	$100 each
	0012	1988-2000 (CD-ROM	$150	$225
		SUBTOTAL—PROEEDINGS ORDERED		

SAGEEP Short Course Handbooks

	0039	2013 Agricultural Geophysics: Methods Employed and Recent Applications - Barry Allred, Bruce Smith, et al.	$35	$45
	0038	2010 Processing Seismic Refraction Tomography Data (including CD-ROM) - William Doll	$35	$45
	0037	2011 Application of Time Domain Electromagnetics to Ground-water Studies – David V. Fitterman	$20	$30
	0032	2010 Application of Time Domain Electromagnetics to Ground-water Studies – David V. Fitterman	$20	$30
	0027	2010 Principles and Applications of Seismic Refraction Tomography (Printed Course Notes & CD-ROM) - William Doll	$70	$90
	0028	2009 Principles and Applications of Seismic Refraction Tomography (CD-ROM w/ PDF format Course Notes) - William Doll	$70	$90
	0007	2002 - UXO 101 - An Introduction to Unexploded Ordnance - (Dwain Butler, Roger Young, William Veith)	$15	$25
	0009	2001 - Applications of Geophysics in Geotechnical and Environmental Engineering (HANDBOOK ONLY) - John Greenhouse	$25	$35
	0004	1998 - Global Positioning System (GPS): Theory and Practice - John D. Bossler & Dorota A. Brzezinska	$10	$15
	0003	1998 - Introduction to Environmental & Engineering Geophysics - Roelof Versteeg	$10	$15
	0002	1998 - Near Surface Seismology - Don Steeples	$10	$15
	0001	1998 - Nondestructive Testing (NDT) - Larry Olson	$10	$15
	0005	1997 - An Introduction to Near-Surface and Environmental Geophysical Methods and Applications - Roelof Versteeg	$10	$15
	0006	1996 - Introduction to Geophysical Techniques and their Applications for Engineers and Project Managers - Richard Benson & Lynn Yuhr	$10	$15

Books and Miscellaneous Items

	0031	***New Pricing!!*** Advances in Near-surface Seismology and Ground Penetrating Radar—R. Miller, J.Bradford, K.Holliger Special Pricing Available for Limited Time—through March 23, 2017—end of SAGEEP 2017!	$79	$99
	0022	Application of Geophysical Methods to Engineering and Environmental Problems - Produced by SEGJ	$35	$45
	0019	Near Surface Geophysics - 2005 Dwain K. Butler, Ed.; Hardcover—Special student rate - $71.20	$89	$139
	0035	Einstein Redux: A Humorous & Refreshing New Chapter in the Einstein Saga—D.Butler	$20	$25
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	1995	To order volumes from		**2006**	JEEG 11/1 - March		**2011**	JEEG 16/4 - December
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		and to order		**2007**	JEEG 12/1 - March			JEEG 17/4 - December
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		JEEG 8/4 - December			JEEG 14/2 - June		**2015**	JEEG 20/1 - March
	2004	JEEG 9/1- March			JEEG 14/3 - September			JEEG 20/2 - June
		JEEG 9/2 - June			JEEG 14/4 - December			JEEG 20/3 - September
		JEEG 9/3 - September		**2010**	JEEG 15/1 - March			JEEG 20/4 - December
		JEEG 9/4 - December			JEEG 15/2 - June		**2016**	JEEG 21/1 - March
	2005	JEEG 10/1 - March			JEEG 15/3 - September			JEEG 21/2 - June
		JEEG 10/2 - June			JEEG 15/4 - December			JEEG 21/3 - September
		JEEG 10/3 - September		**2011**	JEEG 16/1 - March			JEEG 21/4 - December
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