LIDAR MAGAZINE

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MARCH/APRIL 2018

COMPARATIVE PLANETOLOGY

LIDAR MAGAZINE

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DEPARTMENTS

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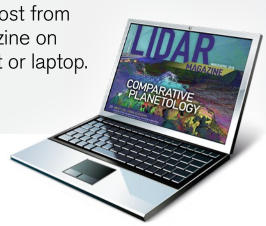

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DR. A. STEWART WALKER

Lidar in the Popular Press

I waxed lyrical in my last editorial on "LiDAR as hero" in the discovery of a "lost city" in Honduras. There have been more. The popular press, for example https://bit.ly/2EA01og, reported the use of LiDAR in the discovery of unexpectedly large areas occupied by early civilizations. "Researchers using a high-tech aerial mapping technique have found tens of thousands of previously undetected Mayan houses, buildings, defence works and pyramids in the dense jungle of Guatemala's Peten region, suggesting that millions more people lived there than previously thought," reported *The Guardian* on 3 February 2018. Thomas Garrison, assistant professor of anthropology at Ithaca College in New York, commented on his search for an ancient road, "I found it, but if I had not had the Lidar and known that that's what it was, I would have walked right over it, because of how dense the jungle is." In the BBC's reporting of the same story, https://bbc.in/2nCc3Fu, Garrison was echoed by Stephen Houston, Professor of Archaeology and Anthropology at Brown University, "I think this is one of the greatest advances in over 150 years of Maya archaeology." Houston told the BBC that, after decades of work in the archaeological field, he found the magnitude of the recent survey "breathtaking". He added, "I know it sounds hyperbolic but when I saw the [Lidar] imagery, it did bring tears to my eyes."

Only 13 days later, *The Guardian*, https://bit.ly/2C16KsU, continued, "… a high-tech laser mapping technique … is rewriting the textbooks at an unprecedented rate. Now, researchers have used the technique to reveal the full extent of an ancient city in western Mexico, about a half an hour's drive from Morelia, built by rivals to the Aztecs." LiDAR is now the established technology for this sort of archaeological discovery, where dense vegetation inhibits the value of both imagery and fieldwork. We understand this, but isn't it satisfying to see the exposure in the popular press? I don't remember this happening with the subtense bar…

In this issue also appears the report of my visit to Cepton Technologies in San José, California, to probe what makes a young company stuffed with brilliant Silicon Valley people tick. Cepton entered my world at the Commercial UAV Expo in Las Vegas last October, where the company launched its SORA 200 sensor for use on airborne UAVs. This represents a step into a new market for the company, which was founded with the intention of creating innovative products for the automotive market, which is massive compared to the ALS, TLS and MMS segments that most readers of *LIDAR Magazine* know well. It involves the use of sensors not only as essential components of autonomous vehicles but also in systems that assist drivers of the current generation of vehicles. Autonomous vehicles, of course, are in the news every day and I was pleased to receive a succinct overview of the technology, "Reinventing

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PUBLISHER Allen E. Cheves
publisher@spatialmedia.us

MANAGING EDITOR Dr. A. Stewart Walker
stewart.walker@lidarmag.com

GROUP EDITOR Marc S. Cheves, LS
marc.cheves@spatialmedia.us

CONTRIBUTING WRITERS
Marco Cecala
Dr. Srini Dharmapuri
Jeff Fagerman
Lewis Graham
Ted Knaak
Dr. David Maune
Jarlath O'Neil-Dunne
Michael Raphael
John Russo
Karen Shuckman
Ken Smerz
Paul Tice
Larry Trojak
James Wilder Young

The staff and contributing writers may be reached via the online message center at our website.

GRAPHIC DESIGN LTD Creative, LLC
WEBMASTER Joel Cheves
AUDIENCE DEVELOPMENT Edward Duff
MEDIA RELATIONS Richard Bremer

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wheels: special report—autonomous vehicles", published as part of the 3 March 2018 issue of *The Economist*. This is a compelling read with LiDAR making an appearance as early as page 3.

A deeper discussion of an application of LiDAR appears in a recent paper by Nikolaus Schmitt of Airbus, "Onboard lidar detects turbulence, volcanic ash near and far", *Photonics Spectra*, 52(2): 36-42, February 2018. This strikes a note for those of us who fly a lot but admit nervousness when anything but "light chop" is encountered. Schmitt provides an enthralling summary of LiDAR's roles on large aircraft.

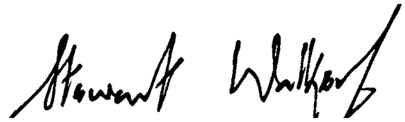
Ever since taking on the role of managing editor, I have been curious that the title of our magazine spells "LIDAR" in all caps. Meanwhile, the front page of the program of the conference with which I began this editorial reads "International LiDAR Mapping Forum". Schmitt uses "lidar". There are "Lidar" people too. What are we to make of this? The dilemma hit my desk big time when I began work on an upcoming article about ASPRS standards with Jason Stoker of USGS. Jason was adamant that we should use "lidar" or publish a disclaimer if another spelling was preferred, since "lidar" is required by the USGS style guide. Jason undergirded his belief by referring me to an article in these pages by himself and the librarian at USGS EROS, Carol Deering, "Let's Agree on the Casing of Lidar", *LIDAR Magazine*, 4(6): 48-51, September 2014. In addition to the four spellings I gave above, they also covered five others—"LiDar", "LiDaR", "liDAR", "LIDaR" and "LIdar"—and searched the literature to quantify the relative frequencies of usage ("lidar" romped home on this criterion). They made a convincing argument for "lidar", with two very persuasive strands: firstly, "lidar", like "radar", "sonar, "loran" and others, started as an acronym, then gravitated to lower case and, indeed, became a common noun as the years passed; secondly, there is historical evidence that very early writers on the subject, in the 1950s, went for lower case. I asked David Stolarz, chair of the ASPRS Standards Committee, to have a look at the issue and, if possible, make a recommendation. He agreed to take up the matter, commenting, "Perhaps we are still in the maximum flexibility stage of usage. I don't recall seeing when 'RADAR' switched to 'radar', but we are in an era in which there is de-centralized command and design of the language."

I wrote also to Dr. Stuart Granshaw, editor of *The Photogrammetric Record*, expecting that this renowned, rather British journal would take a strong view. I was not disappointed! Stuart replied:

> "*The Photogrammetric Record* has a very strong stand on 'LIDAR', 'LiDAR', 'Lidar', 'lidar'. We are very, very firmly in the 'lidar' camp. The word is obviously derived from an acronym for 'light detection and ranging'. In LiDAR, 'Li' comes from Light, 'D' from Detection, 'A' from 'And' and 'R" from 'Ranging'. Thus LiDAR is at least logical, whereas LIDAR (caps 'I') is not (what would the 'I' stand for?). 'Lidar' (with just a caps 'L') would make it a proper noun, as if there was only one lidar, which is a nonsense. However, the *Record* follows the policy that 'lidar' is a noun in its own right (thus its derivation from an acronym is now secondary). I have just looked it up in my *Shorter Oxford Dictionary* and it is, indeed, there as 'lidar' (not any of your other alternatives). This is exactly the same as the words (nouns) 'radar' and 'laser' which, although also originally acronyms, are now accepted as nouns in their own right (again my *Shorter Oxford Dictionary* has both in this form). If you write RaDAR (from radio detection and ranging) or LASER (from light amplification by stimulated emission of radiation) then also write LiDAR. But if, like the *Record* (and the *Shorter Oxford Dictionary*), you write 'radar' and 'laser', then 'lidar' is the only logical version."

This conundrum will cause insomnia only to pedants such as myself, but it would be reassuring to move forward in a consistent way. There is scope for creativity too. If the all-lower-case camp prevails, as seems likely, what would become of us: *lidar MAGAZINE*, *lidar Magazine*, *lidarMAGAZINE*, *lidarMagazine*, or something entirely different? If you have a view on this, please write in—I'll be listening! This vexing question arose during my exchange with Stuart Granshaw. I asked him whether, if we go for "lidar", it should be "Lidar" at the beginning of a sentence and the answer was, "Yes, Initial capital at the start of a sentence of course, but I would also use it in your magazine name. We are *The Photogrammetric Record*. *The Sunday Times* and *Daily Mirror* are newspapers, so surely you should use *Lidar Magazine*." Should we?

LIDAR, LiDAR, Lidar or lidar, therefore, is hale and hearty. Soon we will enjoy the SPAR 3D Expo & Conference in Anaheim, California—see you there!



A. Stewart Walker // Managing Editor

AND THE WINNERS ARE...

LIDAR LEADER AWARDS

BROUGHT TO YOU BY
ILMF & LIDAR MAGAZINE

The inaugural LIDAR Leader Awards ceremony took place at this year's International LiDAR Mapping Forum (ILMF) in Denver. ILMF—in cooperation with Spatial Media's *LIDAR Magazine*—designed the unique program to recognize excellence in three distinct categories:

- **Outstanding Personal Achievement in LIDAR**
- **Outstanding Team Achievement in LIDAR**
- **Outstanding Enterprise Achievement in LIDAR**

Lisa Murray, Group Director at Diversified Communications stated of the awards, "Heading into our sixth year of managing the International LiDAR Mapping Forum, I felt there was a need to create an awards program to recognize the amazing projects that were being presented at ILMF. Every year we learned about ground-breaking technology and innovative uses of lidar, yet there was no industry platform recognizing significant accomplishments. So the LIDAR Leader Awards were born to give the lidar community a chance to acknowledge and celebrate colleagues and achievements at their largest annual gathering in Denver. I approached Allen Cheves at *LIDAR Magazine* about partnering on this project and he enthusiastically agreed! In our first year, we received 86 nominations—more than we ever imagined—and have identified 3 winners who were announced today at the awards ceremony. We look forward to celebrating the winners and all the nominees for their excellent work and contributions."

2018 LIDAR Leader Award Recipients

(L-R): Dr. A. Stewart Walker, Managing Editor of *LIDAR Magazine*; Dr. David Maune, Associate Vice President of Dewberry; Hope Morgan, North Carolina Risk Management; Mike Tischler, Director of the National Geospatial Program; Lisa Murray, Group Director of Diversified Communications

Dr. A. Stewart Walker, Managing Editor at *LIDAR Magazine* agreed. “Throughout more than 40 years in the profession, I have continuously marveled at the technological initiatives and the people who have brought them to our geospatial world. In my various roles in ASPRS I have been in contact with numerous individuals representing organizations, both public and private, with remarkable talents for executing challenging projects. The LIDAR Leader Awards provide recognition for these individuals and organizations. Nevertheless, I was amazed at the number and quality of the nominations we received and am honored to have participated in the process. The Awards are off to a fine start and we hope they will enhance the industry in the years to come.”

Dr. A. Stewart Walker, Managing Editor of *LIDAR Magazine*

ILMF and *LIDAR Magazine* are excited to continue celebrating excellence in years to come and congratulate all of the nominees and winners for their work in advancing the industry.

Outstanding Team Achievement: North Carolina Emergency Management

The Outstanding Team Achievement in LIDAR (2-99 members) was awarded to North Carolina Emergency Management for their North Carolina Next Generation Lidar Collection team project, consisting of a five-year endeavor to collect data for the entire state. In coordination with USGS, the group started down the path of updating their legacy (lidar) data, originally flown between 2000-2005. 60 of 100 North Carolina counties were collected at 2ppsm (linear-mode) while 40 were covered via an 8 ppsm (geiger-mode) collection. While the effort was led by the office of Emergency Management and the NC D.O.T, several federal agencies and 10 different companies were ultimately involved. All data is available to the public via the program's website and has already shown significant benefits in flood zone creation for flood mapping, feature extraction for building footprints and roads in addition to regular NC D.O.T. usage for things such as planning, canopy height determination and many other creative uses.

Hope Morgan, GIS Manager at North Carolina Emergency Management said, "It is quite an honor to win the Outstanding Team Achievement in LIDAR. I was privileged to work with an amazing team of people on a coordinated effort between Federal, State, and commercial groups that allowed us to provide a great benefit to the public and the industry alike."

In addition to contractors and partners, Ms. Morgan went on to specifically thank Marc Swartz from NC D.O.T. for his work in developing an automated quality control process (for lidar data). She also thanked Gary Thompson, Watson Ross, and James Gay for their efforts with overall field and quality control. The group commended USGS for the coordination of phases 1 and 2, assistance through the BAA grant for several phases and ongoing assistance with standards and specifications.

Geiger-mode image of the *Carowinds* amusement park in Charlotte, NC.

Several of the USGS 3DEP Team members were on hand to accept the award:

Front row L to R: Allyson Jason, Kim Mantey, Vicki Lukas, Mike Tischler, Darcee Killpack, Josh Nimetz

Back row L to R: Diana Thunen, Amanda Lowe, Tim Saultz, Kari Craun, Jason Stoker, David Brostuen, Cindy Thatcher, Michael Fox

Outstanding Enterprise Achievement: **U.S. Geological Survey**

The winner of the Outstanding Enterprise Achievement Award (100+ members) was U.S. Geological Survey (USGS) for its impressive work on The U.S. Geological Survey 3D Elevation Program (3DEP). The organization developed the program, which acquires high-quality three-dimensional elevation data for the Nation and produces point clouds, bare-earth digital elevation models, and other products. Vicki Lukas, part of the 3DEP Management Team, said of the project, "USGS manages the 3D Elevation Program—3DEP—on behalf of the community to advance national lidar, from communicating documented needs to decision makers to working with a broad range of partners to acquire and deliver data nationwide."

USGS
science for a changing world

The National Map
Your Source for Topographic Information

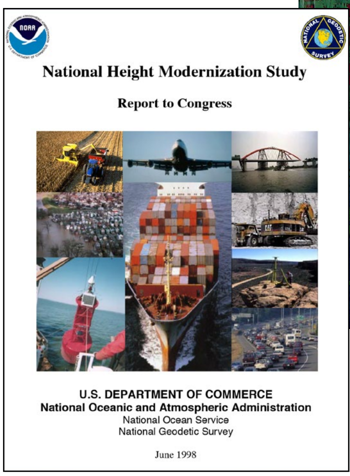
Read more about the history and future of the program on page 18 of this edition: **"3D Elevation Program: Looking Back and Forward"**

Outstanding Personal Achievement: Dr. David Maune

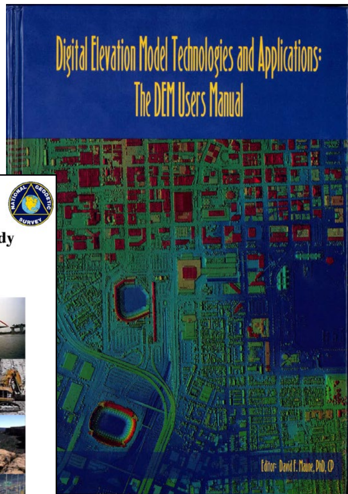
Dr. David Maune, Associate Vice President of Dewberry, was recognized for his Outstanding Personal Achievements in the industry. Maune has pioneered efforts such as authoring FEMA and NDEP documents that served as *de facto* lidar guidelines and specifications, has worked lidar portions of ASPRS Standards and USGS LIDAR base specifications, and was the editor and primary author of the 1st, 2nd and 3rd editions of the *DEM User's Manual.* Maune, who is often described as "The father of lidar," stated "I won't be satisfied until we have a seamless, high-resolution, high-accuracy 3D Nation from the tops of the mountains, to the depths of the seas, to include our inland rivers and lakes."

Dr. Maune, "The father of lidar"

Editor's Note: After receiving the award, Dr. Maune gave an outstanding acceptance address, shoehorning a chronological account of US lidar and its quality control into a few minutes. David is the author of multiple manuals, books and technical papers and numerous other authors have written about him and his multiple accomplishments. To pursue something a little different, I asked Dave to enlarge on the part of his address that had described his "lidar dreams", which you can read over the pages that follow.

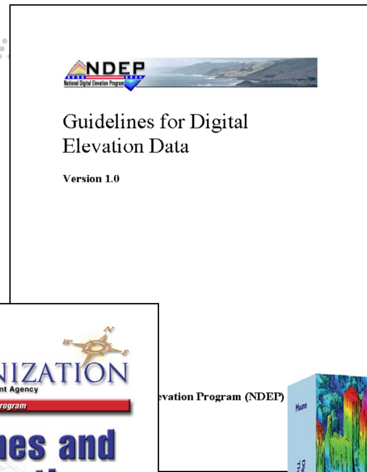


1998: NOAA *National Height Modernization Study*



2001: ASPRS 1st edition of *DEM Users Manual*

2002: FEMA *Guidelines and Specifications* for Lidar



2004: NDEP *Guidelines for Digital Elevation Data*

2007: ASPRS 2nd edition of *DEM Users Manual*

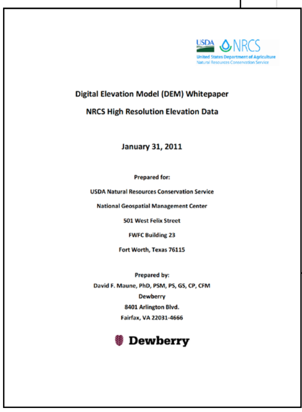
Making our Lidar Dreams Come True

Whenever I autograph a copy of one of my books, I write "May all your DEMs come true," an obvious play on words with "May all your dreams come true." After winning the 2018 LIDAR Leader Award for Outstanding Personal Achievement in lidar, sponsored by ILMF and *LIDAR Magazine*, I was asked to summarize the comments in my acceptance speech on my past and future dreams for lidar. Chronologically, my lidar dreams started in 1997, when I first evaluated lidar and IfSAR for FEMA's use in flood hazard studies.

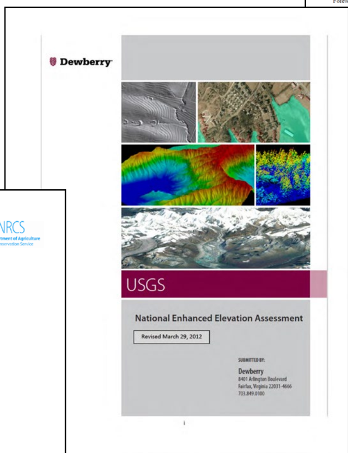
Shortly thereafter the National Geodetic Survey tasked me to prepare a study on how to modernize the National Height System in the U.S., which at that time was based on differential leveling. In NGS's *National Height Modernization Study* (1998), I proposed GPS surveys relative to CORS, plus nationwide lidar and IfSAR.

In 1998, I managed the first of Dewberry's many lidar task orders for USGS and in 2000 received USGS's

BY DR. DAVID F. **MAUNE**

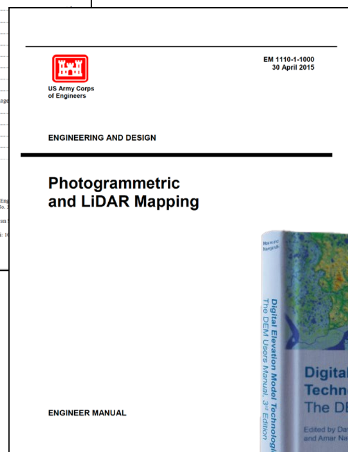


2011: NRCS DEM Whitepaper

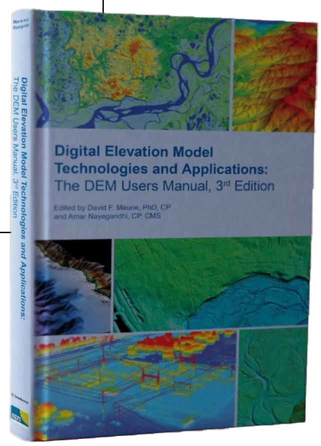


2012: USGS *National Enhanced Elevation Assessment* Report

2014: ASPRS *Positional Accuracy Standards for Digital Geospatial Data*



2015: USACE Manual on *Photogrammetric and Lidar Mapping*



2018: ASPRS 3rd edition of DEM Users Manual

Highest Quality Achievement Award for "outstanding achievements in producing lidar products of the highest quality in a timely manner."

At the ASPRS Annual Conference in 2000 in Washington, DC, I published a paper entitled, "Lidar and IFSAR: Pitfalls and Opportunities for our Future". It was so well received that ASPRS asked me to write a book on lidar and IfSAR; the *DEM Users Manual* (2001) also included sonar, photogrammetry and many other chapters.

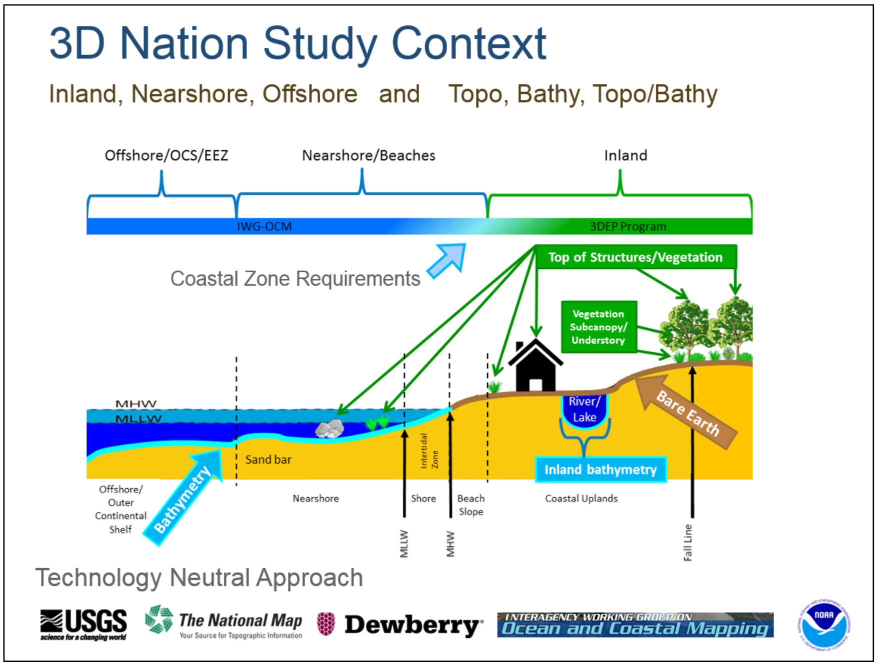
I co-authored FEMA's initial Appendix 4B lidar guidelines in 1998 and was the prime author of Appendix A to FEMA's *Guidelines and Specifications* (2002), which, with updates, served as the industry's *de facto* lidar specification until 2010, when USGS published its first draft lidar specifications. I represented FEMA on a committee of the National Digital Elevation Program and was the primary author of the *NDEP Guidelines for Digital Elevation Data* (2004).

Because so many people kept asking me for sample DEMs from lidar and other technologies, we published the 2nd edition of the *DEM Users Manual* (2007), which included a DVD with sample datasets.

I authored the *NRCS Digital Elevation Model (DEM) Whitepaper:NRCS High Resolution Elevation Data* (2011), as a USGS task order. This work was a pilot for the NEEA [NRCS is the National Resources Conservation Service of the US Department of Agriculture; NEEA is the National Enhanced Elevation Assessment].

In 2012, I authored the *National Enhanced Elevation Assessment* report, providing the blueprint for the 3D Elevation Program (3DEP). This program is enormously successful today, largely due to the extensive benefit/cost analyses that document a minimum of 5:1 lidar return on investment (ROI). I owe special thanks to all who submitted their requirements and benefits.

I worked with Qassim Abdullah, Doug Smith and Karl Heidemann in authoring the *ASPRS Positional Accuracy Standards for Digital Geospatial Data* (2014) and with Karl on three *USGS Lidar Base*



3D Nation Study of topographic and bathymetric requirements & benefits

Specifications—all providing guidance on accuracy testing of lidar data.

In 2015, Amar Nayegandhi and I authored the Engineer Manual 1110-1-1000, *Photogrammetric and LiDAR Mapping*, of the US Army Corps of Engineers.

Later in 2018, Amar and I will publish the 3rd edition of the *DEM Users Manual*, with updates to all chapters; the eBook version will have hyperlinks for all references. I owe special thanks to all the co-authors who contributed chapters or input for the 1st, 2nd and 3rd editions, which bring to fruition many of my dreams.

My earlier dreams included: (1) develop high-accuracy, affordable elevation technologies for betterment of society; (2) develop and update DEM technology standards, guidelines and specifications; and (3) implement a nationwide program, such as the 3DEP, to produce and maintain standardized high-quality DEMs used by all. These dreams are largely realized today, as documented in the *DEM Users Manual*, 3rd edition.

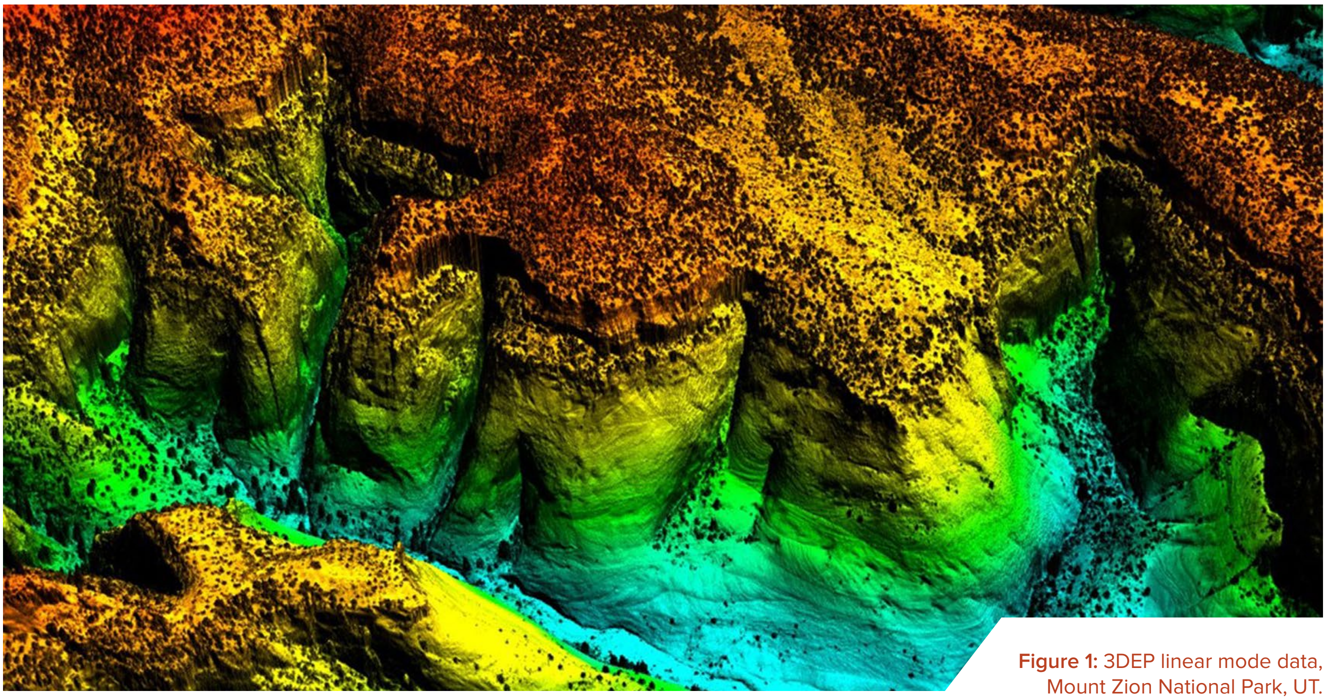
My future dreams include: (4) develop a seamless "3D Nation" from the tops of the mountains to the depths of the seas, to include inland bathymetry; (5) routinely use the latest elevation data to update the National Hydrography Dataset, flood studies, forest metrics and other datasets that require up-to-date DEMs; and (6) develop lidar applications to support fully the dozens of business uses and hundreds of mission-critical activities (MCAs) documented in the NEEA study and the 3D Nation Requirements and Benefits Study being conducted in 2018. For these future dreams to be fulfilled, it's time for me to "pass the torch" to Amar and the younger lidar professionals who will lead us into the 3D Nation of the future.

For the 3D Nation study, it is absolutely imperative that we identify DEM users who can document their MCA requirements and the dollar benefits accruing to these MCAs if they receive the topographic/bathymetric DEM Quality Levels and update frequencies required. If so, we can make all our dreams come true.

Dr. David Maune, CP, is an Associate Vice President at Dewberry Consultants LLC, headquartered in Fairfax, VA, where he is an elevation specialist and manages photogrammetric, lidar, IfSAR, and sonar projects for USGS, NOAA, FEMA, USACE, and other federal, state and county government organizations. He is an ASPRS Fellow and winner of the ASPRS Photogrammetric (Fairchild) Award. He is the editor and principal author of the 1st, 2nd and 3rd editions of *Digital Elevation Model Technologies and Applications: The DEM Users Manual*, published by ASPRS.. He authored the National Enhanced Elevation Assessment (NEEA) report that led to USGS's 3DEP. He co-authored the ASPRS Positional Accuracy Standards for Digital Geospatial Data. He is a retired Army Colonel, last serving as Commander and Director of the U.S. Army Topographic Engineering Center (TEC), now the Army Geospatial Center (AGC).

3D ELEVATION PROGRAM

Looking Back and Forward



Courtesy of Woolpert.

Figure 1: 3DEP linear mode data, Mount Zion National Park, UT.

In the early part of the decade, the idea to collect nationwide lidar sounded like an impossible dream to many, even within the U.S. Geological Survey (USGS). The cost of the data alone, estimated at $1B, seemed out of range for the USGS National Geospatial Program (NGP), which was operating at an annual budget of about $60M a year to produce national hydrography data and topographic maps as well as manage a national elevation program. Further, the sheer volume of data that would result from nationwide coverage posed an unprecedented management and delivery challenge. But, convinced by signs of the rapidly growing demand for lidar for a broad range of critical applications, and the advances being made in the industry to improve efficiency and drive down cost, USGS undertook the audacious goal of nationwide data coverage in 8 years. The team that has worked to make this dream a reality included: Larry Sugarbaker, NGP Senior Advisor (retired), whose vision and drive resulted in the National Enhanced Elevation Assessment (NEEA) and the design of the 3D Elevation Program (3DEP); Kevin Gallagher, Associate Director for Core Science Systems, who wore out his shoe leather in reaching out to Federal partners and bringing the dialog about the need for these important data to the executive level through the 3DEP Executive Forum; and the

BY VICKI **LUKAS**

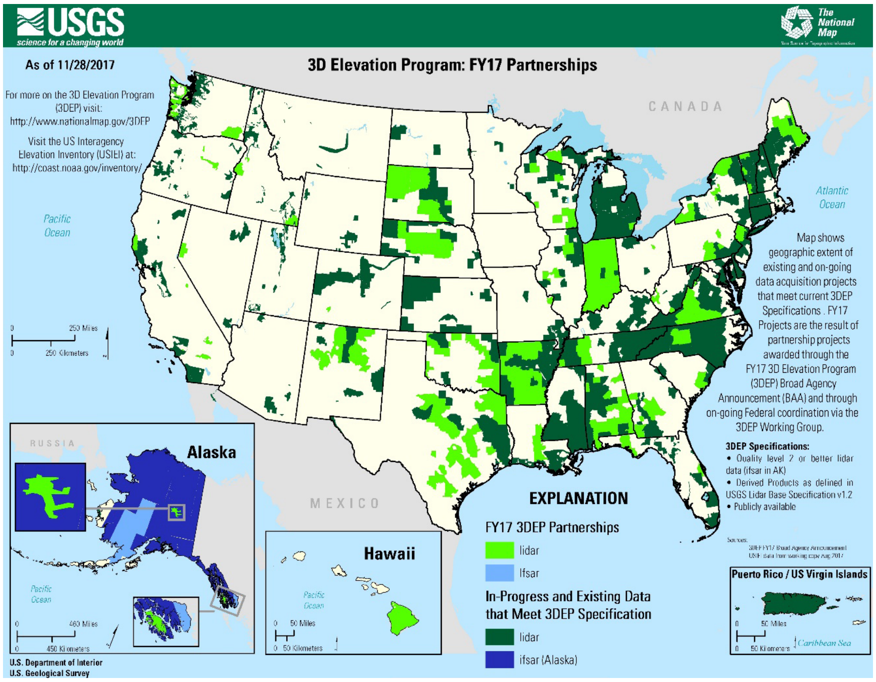


Figure 2: Status map of 3DEP coverage at the end of Fiscal Year 2017.

Table 1. Aggregate nominal pulse spacing and density.

[QL, quality level; pls/m², pulses per square meter; m, meter; ≤, less than or equal to; ≥, greater than or equal to]

Quality level	Aggregate nominal pulse spacing (m)	Aggregate nominal pulse density (pls/m²)
QL0	≤0.35	≥8.0
QL1	≤0.35	≥8.0
QL2	≤0.71	≥2.0
QL3	≤1.41	≥0.5

Table 2. Relative vertical accuracy for light detection and ranging swath data.

[QL, quality level; $RMSD_z$, root mean square difference in the z direction; m, meter; ≤, less than or equal to]

Quality level	Smooth surface repeatability, $RMSD_z$ (m)	Swath overlap difference, $RMSD_z$ (m)
QL0	≤0.03	≤0.04
QL1	≤0.06	≤0.08
QL2	≤0.06	≤0.08
QL3	≤0.12	≤0.16

many USGS employees whose dedication and excellence on a daily basis result in program development and guidance, communication, data acquisition, contracting, quality assurance and control, production, data delivery, and research. These varied roles are unified in their goal to make nationwide 3DEP data publicly available.

3DEP was born from the NEEA that documented the elevation data needs of 34 Federal agencies, 50 states, and a sampling of local, Tribal, and private organizations. 3DEP is designed based on the NEEA benefit-cost analysis to conservatively provide new benefits of $690M/year with the potential to generate $13B/year in new benefits through applications that span the breadth of the U.S. economy. The 2012 study not only underpins the goals of 3DEP, it also continues to build a strong case for lidar among decision makers, for USGS and the whole community who collectively produce and use lidar.

The 3DEP design called for quality level 2 (QL2) lidar data nationwide, with QL5 interferometric synthetic aperture radar (IfSAR) data for Alaska, where clouds and remoteness prevent statewide lidar coverage. At the time, most large area acquisitions were being collected at QL3 (see tables 1 and 2). From 2012 to 2015 both USGS and its partners worked to complete ongoing QL3 acquisitions and processing while also transitioning to QL2 in new projects. In 2015, the first new 3DEP products and services were made available, and 2016 marked the first full year of 3DEP processing at USGS. This made 2016 the first year of the 3DEP eight-year goal to complete data acquisition by 2023. An example of QL2 data is shown in **Figure 1**.

With the program design and goal established, USGS has worked to build lidar acquisition partnerships among Federal, state, local, Tribal, and other entities. USGS and NOAA are co-leads of the OMB A-16 Elevation Theme under the Federal Geographic Data Committee, and jointly lead the 3D Nation Elevation Subcommittee to coordinate topographic and bathymetric elevation data. Under the auspices of this leadership role, the 3DEP Executive

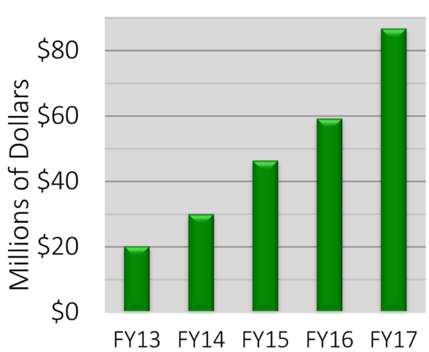


Figure 3: USGS and partner investments in 3DEP data acquisition by Fiscal Year (FY).

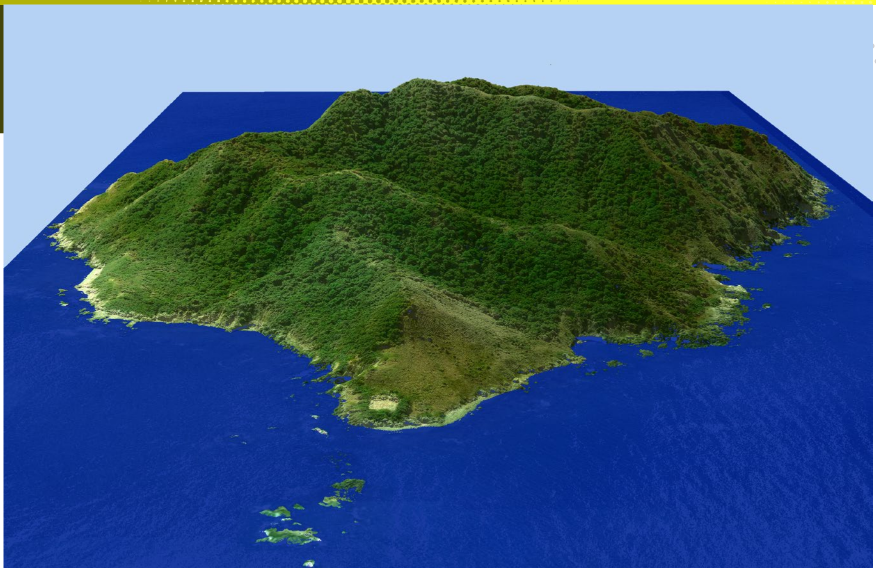


Figure 4: Lidar point cloud data fused with color imagery of Desecheo National Wildlife Refuge, Puerto Rico. Lidar was collected for all of Puerto Rico in 2016, before Hurricane Maria. These data provide a critical baseline for comparison with post-event data soon to be collected to aid in the recovery.
Created by Dr. Jason Stoker, USGS.

Forum and Working Group lead Federal coordination and the processes to engage non-Federal partners in 3DEP data acquisition and other program matters. In partnership with NOAA, the USGS 3DEP team maintains and updates the U.S. Interagency Elevation Inventory (USIEI, coast.noaa.gov/inventory) annually to document all publicly available lidar acquisition which is complete, in progress, or planned, so that all users across the community can discover these data and plan projects to avoid duplication. The 3DEP Working Group supports and populates Federal data requirements in the NOAA Seasketch tool (fedmap.seasketch.org) to stimulate and broadly promote leveraging of partnerships. The Federal requirements compiled in Seasketch are published in the annual Broad Agency Announcement (see FedBizOps at www.fbo.gov/index?s=opportunity&mode=form&id=ad1b567dec828feb3b05651fe29db766&tab=core&_cview=0 and grants.gov at www.grants.gov/web/grants/search-grants.html?keywords=G17AS00116), to solicit partnerships from all sources. Additional enhancements on which the 3DEP team is working are to establish a national multi-year plan for acquisition made up of state acquisition plans, and a national tiling scheme for planning and data delivery. These efforts will result in an orderly, systematic plan for completing 3DEP data coverage for the nation.

The success of 3DEP relies on USGS's many partners. When partnerships

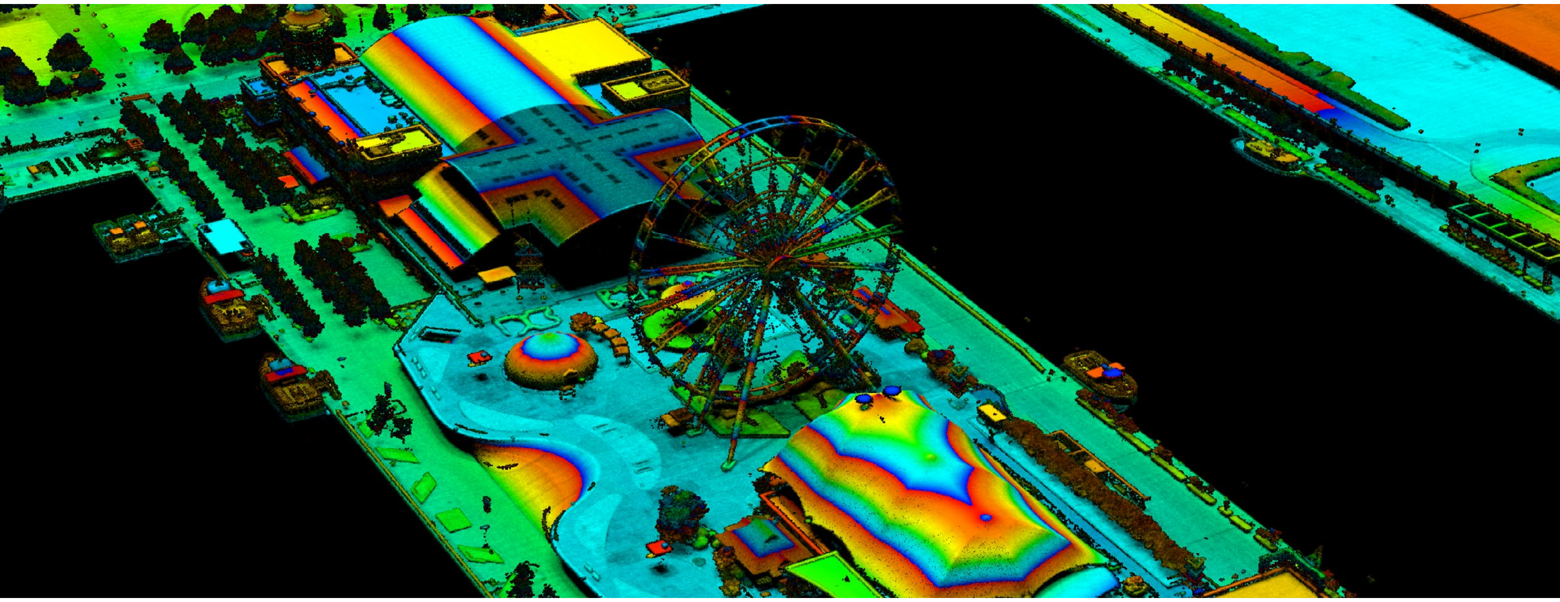


Figure 5: Sample data collected at 17,000' AGL at >20ppsm over Chicago, IL being used to assess Geiger-mode data for use in 3DEP.
Courtesy of Harris Corporation.

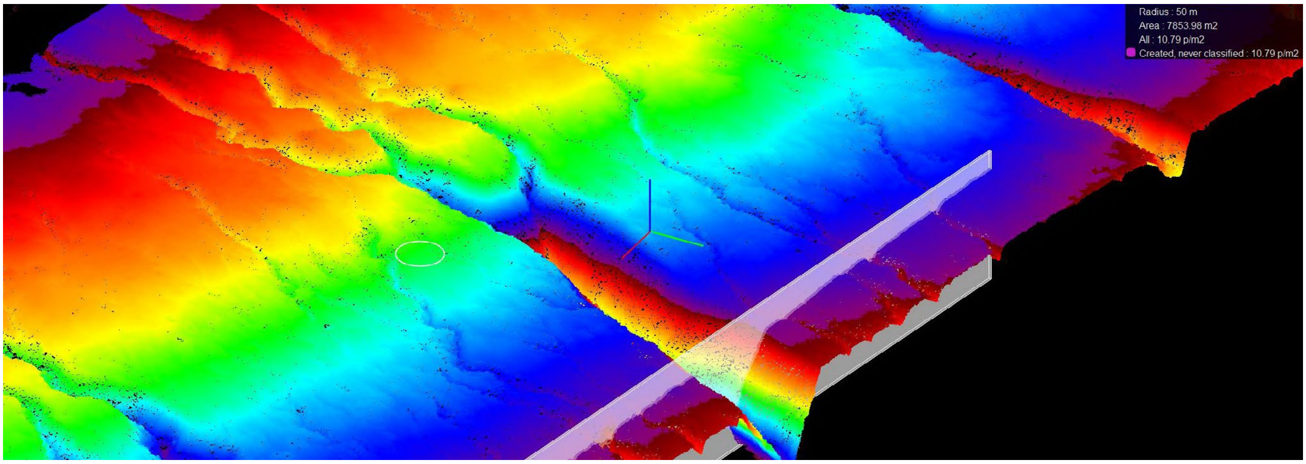


Figure 5: Sample lidar profile collected at 12,300' AGL at quality level 1 (QL1) density over a ravine on the big island of Hawaii being used to assess single-photon lidar (SPL) technology for use in 3DEP.
Courtesy of Woolpert.

have been formed and codified through agreements, data are acquired through the Geospatial Products and Services Contracts (GPSC) or cooperative agreements. USGS has processed growing data acquisition investments, for example in fiscal year 2017 nearly $87M of data acquisition was processed for a large range of Federal, state, local, Tribal, and other partners.

When the data are delivered from the private sector contractors and cooperative agreement partners, USGS performs quality control, using the USGS Lidar Base Specification (doi.org/10.3133/tm11B4) to ensure data quality and consistency. The specification is maintained by the 3DEP team and used as a standard across the industry. Version 1.3 of the specification was recently published in early March 2018.

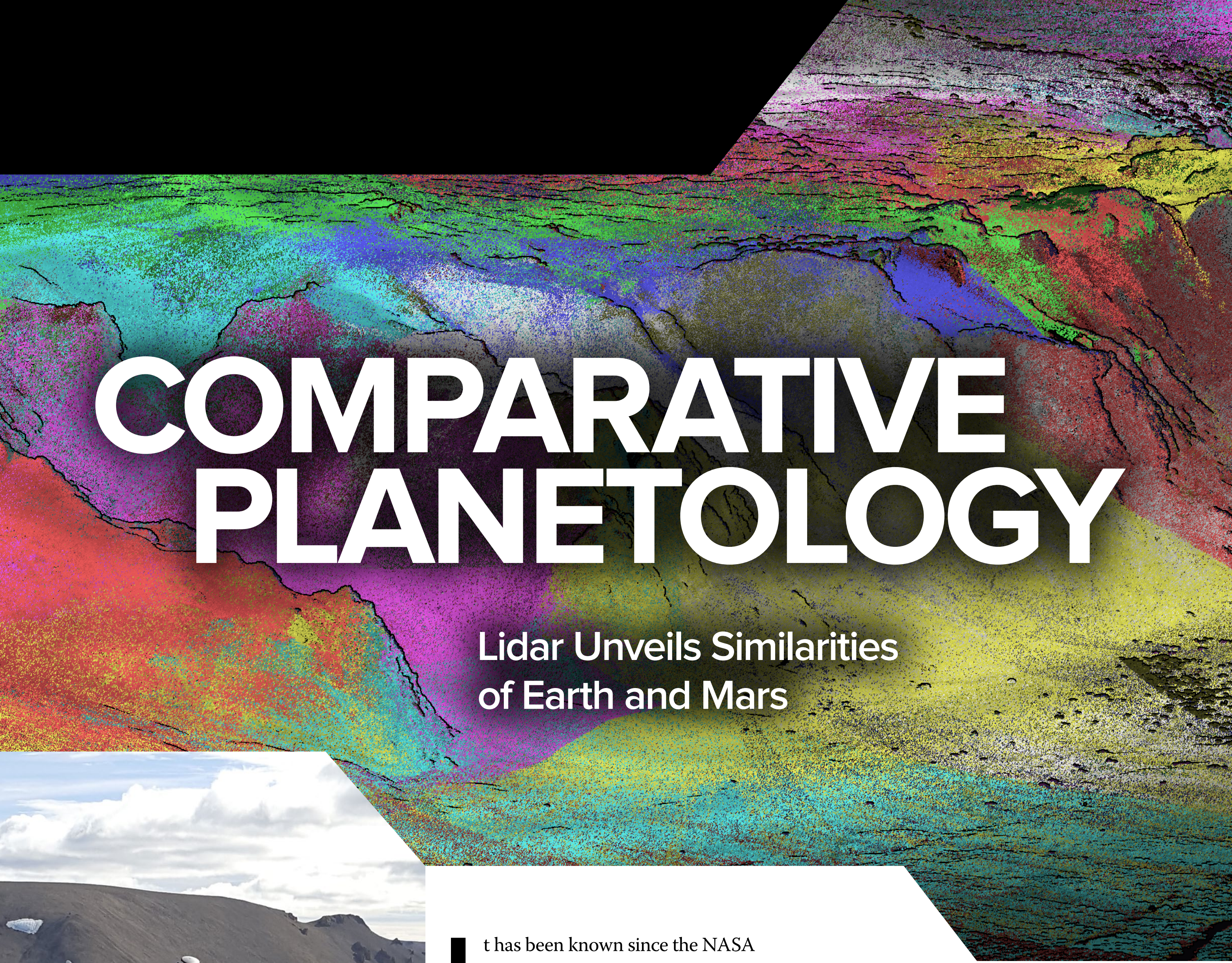
After the data pass inspection, the 3DEP team processes and publishes the data in *The National Map (*nationalmap.gov*)*, which is publicly accessible. The data that 3DEP provides support a broad range of nationally significant applications including flood risk management, infrastructure construction and management, energy development, geologic resource assessment and mapping, natural hazards assessments and mitigation, natural resource management, precision agriculture, and more.

In 2017, USGS and its partners contracted for about 12 percent of the Nation, bringing the total 3DEP-quality data available or in work to 37 percent (**Figure 2**) and investments in 3DEP have been growing each year (**Figure 3**). Prospects are strong for the upward trend to continue in FY18, though Federal budgets were not yet finalized at the time of writing. At the FY19 President's Budget level, nationwide 3DEP acquisition would be completed in 2033.

The 3DEP team continues to look forward and is moving to the cloud, assessing emerging technologies for use in the program (figs. 4, 5 and 6), and testing inland bathymetric data acquisition with a goal to extend the elevation surface under water bodies in the future. USGS is working with NOAA to develop the successor to NEEA, the 3D Nation Requirements and Benefits Study. The new study will use a technology-agnostic approach, add rivers, lakes, coasts and oceans to the equation, and once again rely on user requirements and benefits to inform program design as we begin to look at repeat coverage, when nationwide coverage is completed.

What once seemed an impossible dream to provide consistent nationwide lidar coverage is becoming more of a reality every day, thanks to a vibrant industry, ongoing advances and improvements in the technology and processes, and a growing and innovative user base. 3DEP is truly a community achievement, from the partners that fund acquisition to the private sector mapping firms that collect the data. The USGS 3D Elevation Program is honored to serve the community with USGS's elevation co-lead NOAA, to advance high quality, publicly available elevation data from the depths of the oceans to the peaks of the mountains.

Vicki Lukas is the Chief of Topographic Data Services in the National Geospatial Program of the USGS, where she oversee the 3D Elevation Program and the National Hydrography Datasets of The National Map.



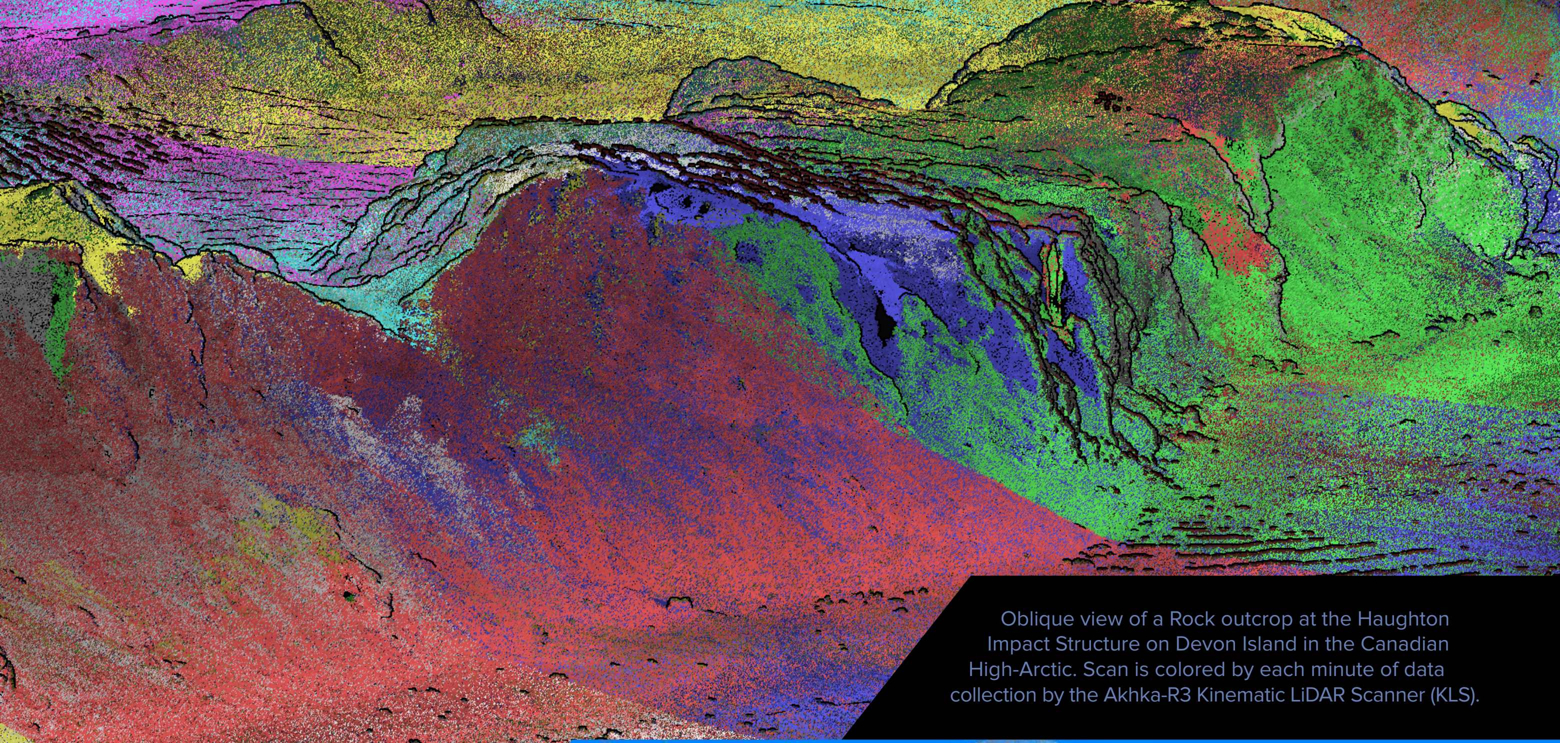
COMPARATIVE PLANETOLOGY

Lidar Unveils Similarities of Earth and Mars

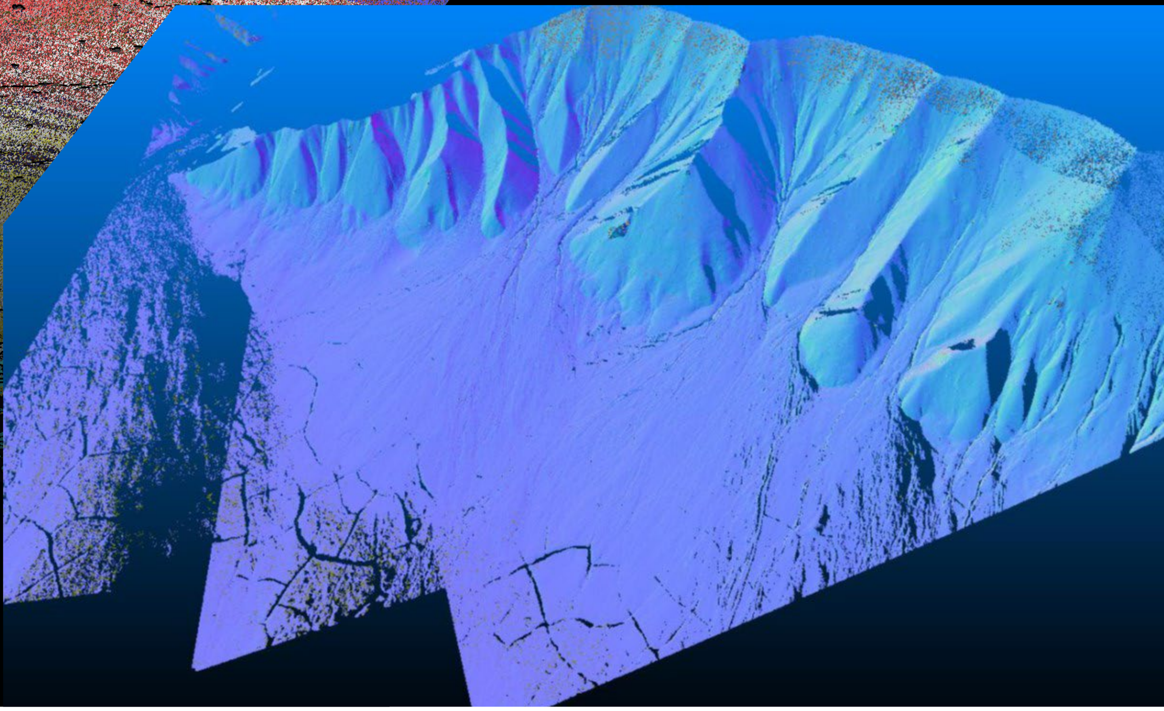
Team member (M. Zanetti) traversing with the Akhka-R3 Kinematic Lidar System (KLS) in the Haughton Impact Structure on Devon Island in the Canadian High-Arctic.

It has been known since the NASA Viking orbiters and landers of the 1970s that the surface of Mars is similar to Earth in many ways. Mars has evidence of rivers, outwash channels, and glacial features indicating an important role for water throughout its geologic history. However, Mars is not Earth. Despite geomorphologic similarity, the underlying processes that shaped Mars' landscape may be quite different between the planets. Our group specializes in Comparative Planetology, which as the name suggests, compares geologic features between the terrestrial planets (Mars, Venus, Mercury, and the Moon) to understand the fundamental processes driving their shapes and patterns. We mostly use remote-sensing datasets from satellite orbiters and robotic landers that include high-resolution imagery, topography from laser altimetry and stereo-photogrammetry, radar backscatter, and spectrometry. However, there is an essential need for ground-truthing of these datasets to understand their limitations and what they are actually telling us. Since Mars is a difficult place to visit, we study analogous features on Earth using comparable datasets. The benefit is two-fold: we can investigate the

BY MICHAEL **ZANETTI**, ANTERO **KUKKO**, CATHERINE **NEISH**, & GORDON **OSINSKI**



Oblique view of a Rock outcrop at the Haughton Impact Structure on Devon Island in the Canadian High-Arctic. Scan is colored by each minute of data collection by the Akhka-R3 Kinematic LiDAR Scanner (KLS).

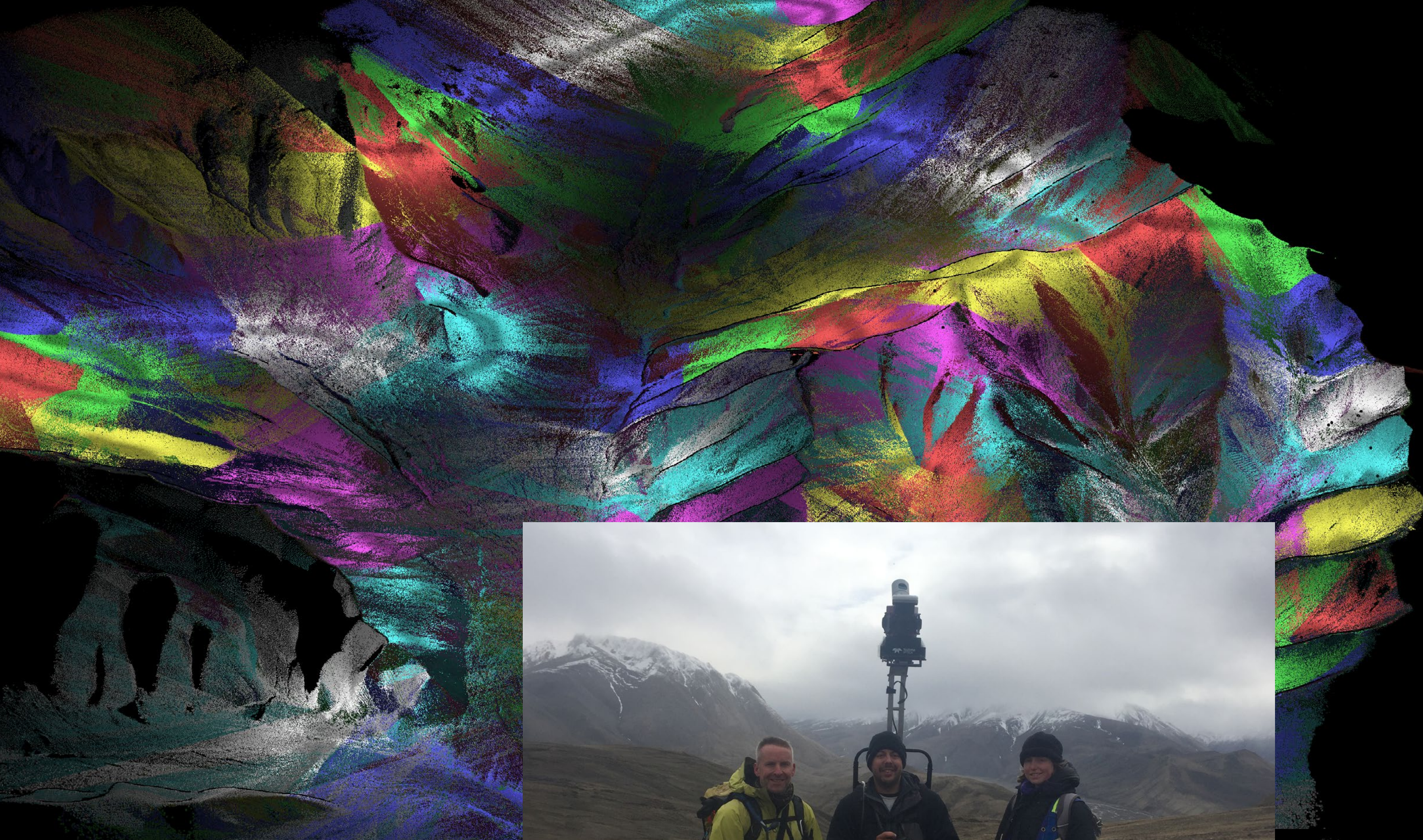


Right: Gullies cutting into hillslope in the Haughton River Valley scanned with the Teledyne Optech Polaris. Total vertical relief ~250 m.

geologic and geomorphologic processes shaping the earth in detail, helping to better understand our own planet and our own remotely-sensed data, and we can apply these Earth-based observations and measurements to infer the processes acting on the other terrestrial planets, accounting for different planetary conditions (*e.g.,* gravity and climate).

The Canadian High-Arctic shares a geomorphologic similarity with the middle and high latitudes of Mars, as both have many cold-climate landforms related to the presence of ground-ice (*e.g.,* glacier-like flows, polygonal patterned ground, debris-flow gullies). Now, using ground-based lidar scanning, and in particular ultra-high resolution mobile lidar scanning techniques, it is possible to study these systems in unprecedented detail and over areas that would have been unimaginable a decade ago.

As part of planetary analog expeditions in 2016 and 2017, researchers from the University of Western Ontario and the Finnish Geospatial Research Institute, together with industry support from Teledyne Optech, set up camps on Devon Island 75°22'26.52"N, 89°31'47.70"W and Axel Heiberg Island 79°16'11.61"N, 90°19'46.25"W to map and measure gullies and patterned ground using a suite of the latest generation tripod and mobile lidar scanning systems. Our lidar mapping has returned measurements of surface topography at

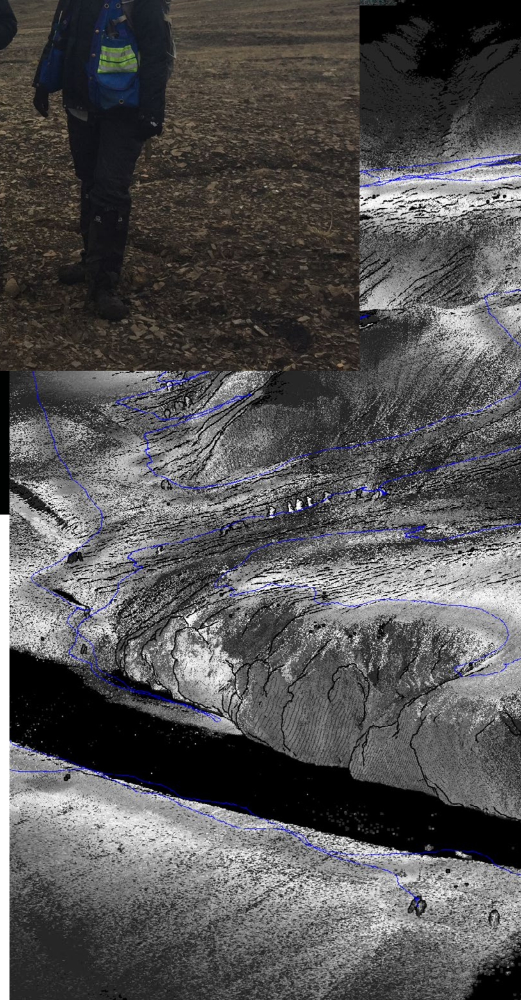


Network of erosional gullies covering ~2 acres (~2.5 billion points) in the Haughton Impact Structure mapped by hiking channels and ridge lines. Scanned with the Akhka-R3 KLS and color coded by each minute of data collection.

Axel Heiberg team members (G. Osinski, M. Zanetti, E. Harrington). A custom backpack rig was made for the Teledyne Optech Maverick mobile scanner.

unprecedented resolution (<2 cm/pixel DEM raster resolution) and is allowing us to break new ground by using mobile lidar for geomorphology research. The speed and repeatability of lidar scanning means: 1) more area is covered, which allows for study of the interplay between different morphologic features and processes, 2) less time is required, which allows researchers to do different experiments or measurements, and 3) inter-season or year-on-year change detection is possible, which allows for the determination of rates-of-change and the effects of small perturbations not captured in long-duration investigations.

The aim of the expeditions was two-fold. First, we want to advance our fundamental understanding of permafrost processes over large areas. As the Arctic climate warms, our understanding of changes within permafrost systems needs to be more complete, and the rapid data-acquisition and ever-higher point density and precision from mobile lidar systems can help monitor these changes over time. This has implications for understanding how to build better buildings and roads in the Canadian North as climate warms and ground ice melts. Understanding how these systems change over time will also address challenges with building permanent structures in permafrost terrain.

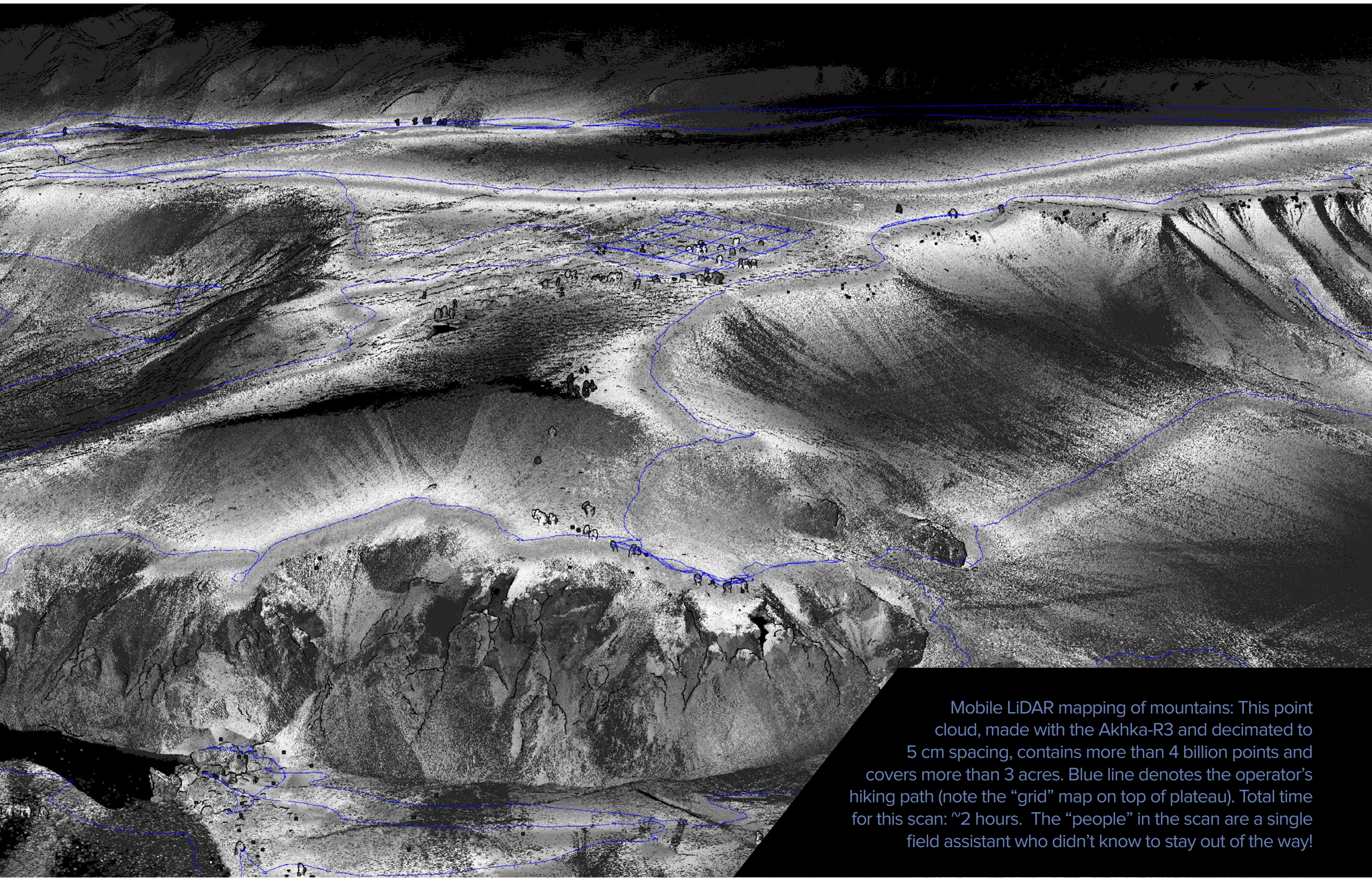


Second, we want to understand permafrost systems from a planetary perspective and examine how differences in planetary gravity, atmospheric density and composition, and even the rotational axis of Mars affect the formation of these features on Mars. Ground ice is likely to be an important resource for future manned missions to Mars, since water-ice can be used for both drinking and rocket-fuel, and comparative planetary geomorphology allows us to identify where and how accessible this water might be.

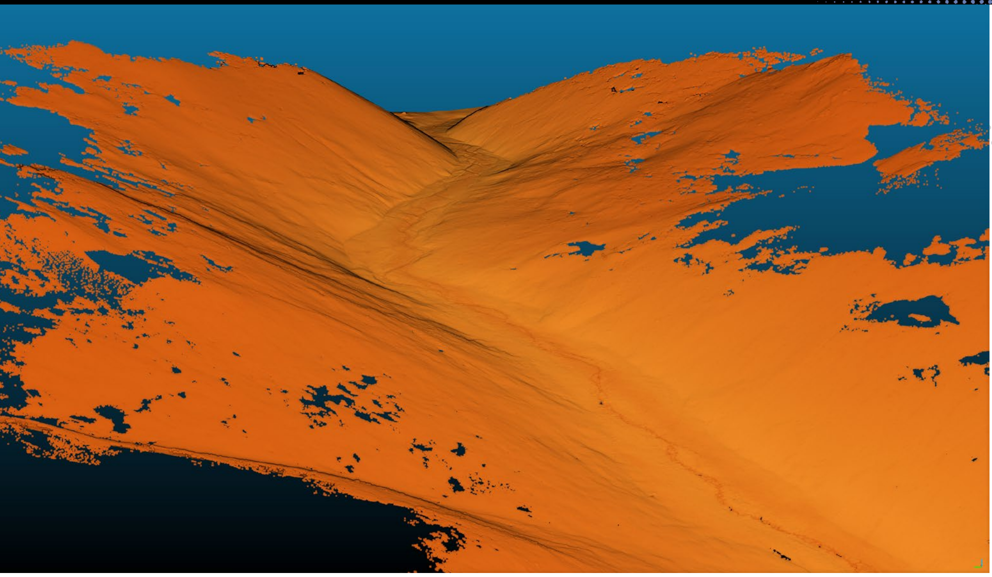
Cold-Climate Landforms on Earth and Mars: Freeze-Thaw on Earth

The daily and seasonal freezing and thawing of the ground in the Canadian High Arctic wreaks havoc on the bare rocks and soil. The volume expansion of water when it freezes in pores and cracks forces rocks to break apart and the ground to fracture. These effects are fairly commonplace in the winter in colder climates, causing potholes in roads and roof damage from backed-up gutters. But in the High Arctic, there are no trees and little vegetation to hold rocks and soil in place, thus freezing, thawing, cracking, and heaving causes much movement of the surface.

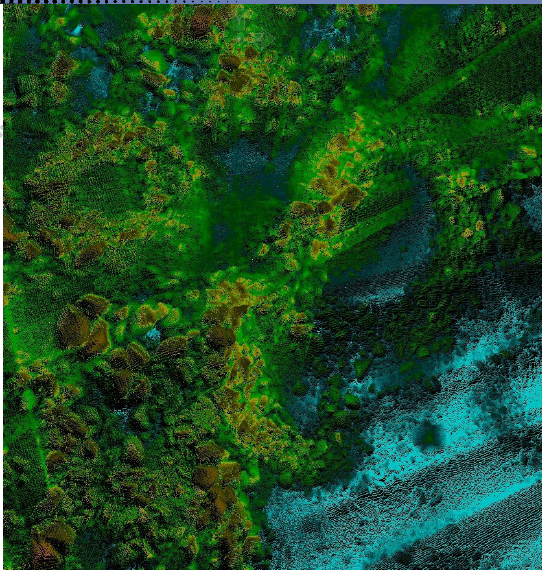
The ground of the High Arctic is permanently frozen (permafrost) below a few tens of centimeters of the surface. But within the upper zone, known as the active layer, seasonal freeze-thaw processes work in pore-spaces to sort stones and soil into patterns (imaginatively known as "patterned ground" in geomorphology parlance). When water infiltrates



Mobile LiDAR mapping of mountains: This point cloud, made with the Akhka-R3 and decimated to 5 cm spacing, contains more than 4 billion points and covers more than 3 acres. Blue line denotes the operator's hiking path (note the "grid" map on top of plateau). Total time for this scan: ~2 hours. The "people" in the scan are a single field assistant who didn't know to stay out of the way!



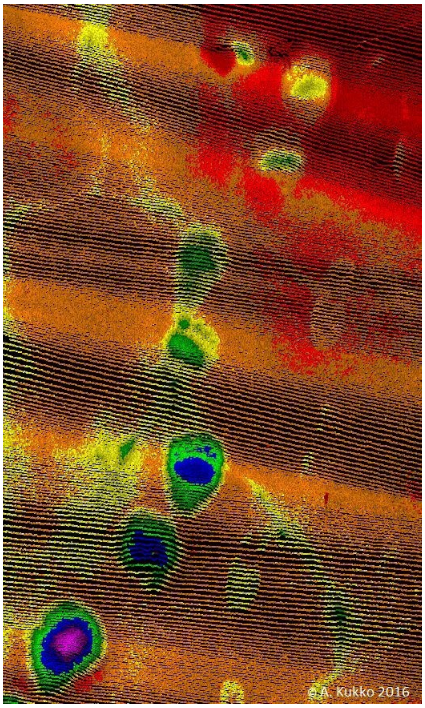
Oblique view of a "tunnel" valley, a channel originally formed beneath a glacier. The cloud is the result of a single pass walking down the centerline of the channel.



KLS scan of stone circles on Devon Island, approximately 1 m in diameter and 20-30 cm high. Stone circles, formed by frost heave and sorting, are a common type of patterned ground seen in permafrost terrains on Earth and Mars.

longer cracks, freeze-thaw processes work to propagate these cracks into fissures (ice-wedges), which then become intertwined and form polygons, creating checkerboard patterns that can cover many square kilometers. On hillslopes, thawing of snowmelt and permafrost at the margins create debris-flows and rockslides, etching into and eroding the landscapes.

These phenomena and the processes controlling them (technically known as periglacial features and processes) have been known and described since the early 1900s, with pioneering work detailing patterned ground done from the 1950s through the 1970s. At that time the characterization of these phenomena (measuring diameter, spacing, trough-depth, and other morphometric parameters) was done with painstaking and unsophisticated manual measurements. For example, year-on-year and decadal changes were measured using marked sticks shoved into the ground. The time-intensive nature of the measurements meant that only small areas could be investigated, mostly in isolation from nearby features.

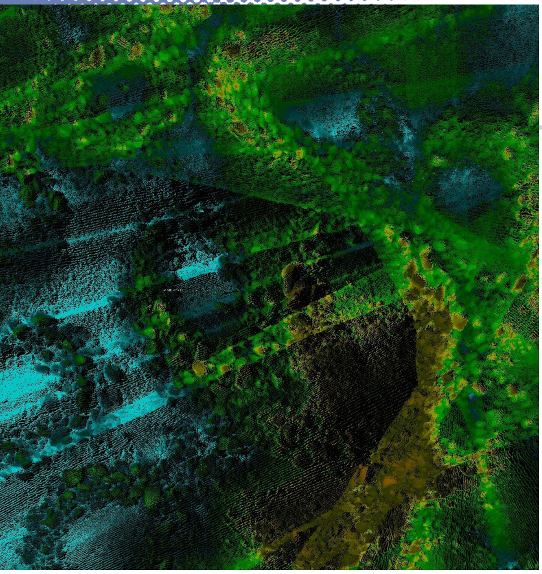


Polar bear footprints preserved in fresh mud near our Devon Island campsite. Although bear encounters are rare, all expedition members have firearms training and carry rifles on sorties. Note the operators footprints to the right of the bear tracks.

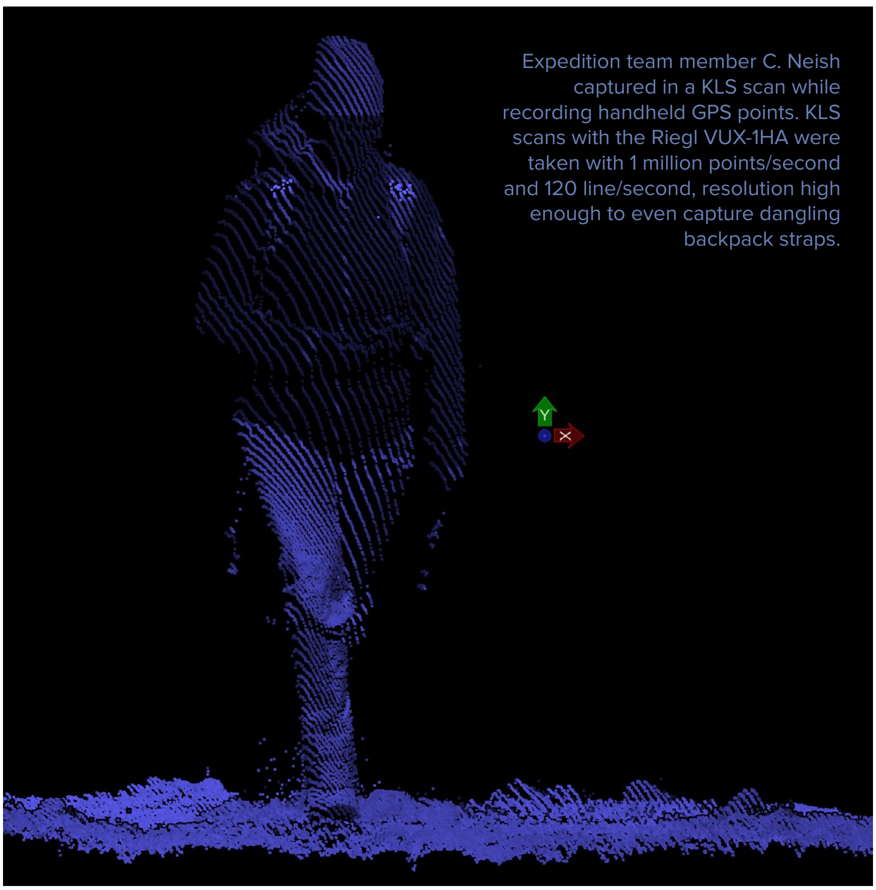
Processes Shaping the Surface of Mars

Mars is cold, but not as cold as one might expect. Although the yearly average temperature is around –55 °C (–67 °F), air and ground temperatures as high as 35° (95°F) have been measured by landed spacecraft. With these temperatures, one might expect that liquid water on the surface would be common, but it is not. The reason for this is that Mars has a very thin atmosphere, with very low atmospheric pressure (~6 mbar, ~1% of Earth's). What is exceptional about the Mars climate is that it can be close to the "triple-point" temperature/pressure of water (6.1 mbar, ~0°C), where all three phases (solid ice, liquid water, and gas vapor) can exist at the same time. For the most part, water only exists in either solid (ice) or gaseous (vapor) phases, and changes directly between these states (sublimation from a solid to liquid, deposition from a gas to a solid). Liquid water only exists in a transient state before it either freezes or boils.

The impermanence of a liquid phase of water on Mars has consequences for interpreting its surface geomorphology. Freeze-thaw processes like those in the Canadian High-Arctic might be possible during brief excursions in the planet's obliquity (see sidebar on page 32), but we don't really know if the transient water available is enough to explain the



widespread polygonal ice-wedging we see on Mars. Scientists alternatively consider the idea that sublimation and deposition of ice (with no water phase) can produce the same patterns and shapes, albeit over much longer timescales than would be possible with freeze-thaw processes. Similar to 'ice-wedging,' thermal contraction of the ground creates a crack and exposes near-surface ice, allowing for sublimation to create void spaces in the ground. These pore spaces collapse or are filled with dust and sand producing 'sublimation polygons' or 'sand-wedges.' Such phenomena are found on Earth in the Antarctic Dry-Valleys, but are rare. A sublimation-driven explanation for the morphology is mechanically very different from a freezing-water expansion mechanism. Deposition of ice from a vapor does not produce the same amount of 'wedging' force that freezing does, which would affect the morphologic characteristics of the Martian features.



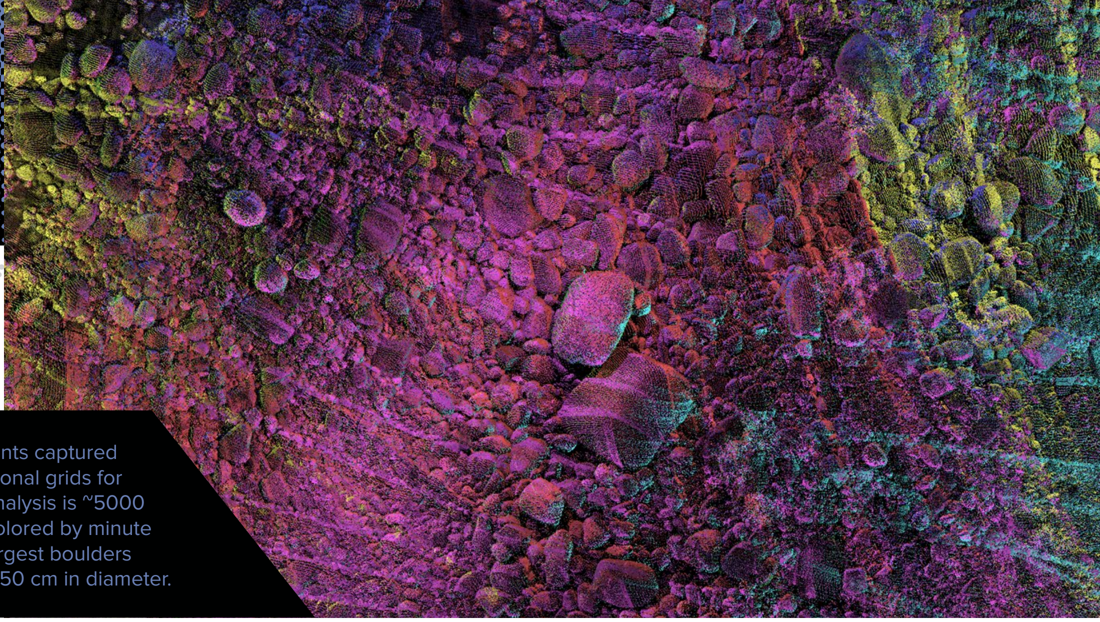
Expedition team member C. Neish captured in a KLS scan while recording handheld GPS points. KLS scans with the Riegl VUX-1HA were taken with 1 million points/second and 120 line/second, resolution high enough to even capture dangling backpack straps.

Since we know that 'ice-wedging' is the driving process in the High-Arctic, and if the morphology of Mars features are similar, our measurements may show that freezing water is necessary to explain their formation. If this is the case, then it is another important piece to understanding the very-recent geologic history of Mars.

Science Expeditions to the Canadian High-Arctic

Over the course of three expeditions in the extreme Canadian High Arctic environment on Devon Island and Axel Heiberg Island, we field tested three different lidar systems and evaluated their use for different geomorphologic measurements. Optech provided two of their newest generation scanners, a Polaris Terrestrial LiDAR scanner (TLS) and a Maverick Mobile Mapping System. Our collaborator A. Kukko at the Finnish Geospatial Research Institute provided their Akhka-R3 Kinematic LiDAR System (KLS). Each instrument produced high-quality data, yielding more than 400 Gb of mobile and TLS lidar data, but highlighted the importance of choosing the right tool for the job. To our knowledge, our expeditions are the first to use mobile lidar scanning systems to address geomorphology related questions and to be deployed in the Arctic.

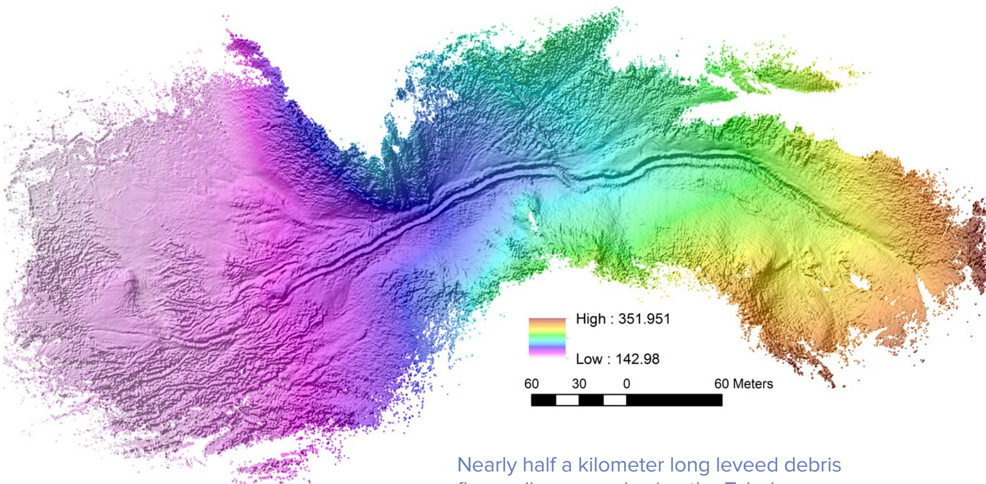
Although a major focus of the expeditions is our comparative planetology research, the lidar data we collected is being used by our team for a wide range of science investigations. Our main field projects involved surveying and mapping patterned ground, ice-wedge polygons, debris flows and channeled slopes, and sub-glacial drainage channels in order to measure various morphometric parameters—length, width, diameter, depth,



Typical density of points captured when walking orthogonal grids for surface roughness analysis is ~5000 point/m^2. KLS scan colored by minute of data collection. Largest boulders near the center are ~50 cm in diameter.

etc. These data are used in concert with ground probe data, geologic mapping, and remote-sensing datasets to interpret the underlying geologic processes acting to shape the landscape on Earth. Looking forward to future expeditions planned in 2018 and 2019 (and with other lidar data collected over the past decade), we will measure small-scale year-on-year changes to establish rates of change for these systems. To apply these data to Mars we are using the stunning 25 cm/pixel imagery and ~2 m/pixel DEMs from the High-Resolution Imaging Science Experiment (HiRISE) on the Mars Reconnaissance Orbiter (MRO) which clearly show the morphology and extent of patterned ground and hillslope channels.

The individual scanning sites are also part of an overarching project aimed at using remote predictive mapping techniques to explore the geology of the Canadian High Arctic. The prohibitive cost and logistical challenges of geologic mapping with field geologists in remote areas means that many areas have never been studied. We are using integrated remote-sensing datasets such as LANDSAT-8, ASTER, RADARSAT-2, Quickbird, etc., to identify sites of interest for ground-truth field campaigns. The characteristics of these sites in terms of composition, roughness, and topography allow for educated interpolation of geology over large regions, with particular interest in economically viable ores. The high-resolution lidar topography helps us understand and interpret the satellite radar backscattering signals because we can now accurately measure the surface roughness at length scales below the radar wavelength, and over areas on the ground large enough to cover multiple radar image pixels.



Nearly half a kilometer long leveed debris flow gully scanned using the Teledyne Optech Maverick instrument on Axel Heiberg Island. Debris flows such as this are common in middle latitudes of Mars, and our lidar measurements can help determine the evolution of these systems.

Our Field Sites

We mapped more than 50 sites of interest on Devon Island and Axel Heiberg Island. On Devon Island, the largest uninhabited island in the world, our primary field site was located within the Haughton Impact Structure, a well-preserved 39 million year old, ~23 km diameter impact crater. This site is regarded as one of the best Martian analogue sites on Earth, since it has similar rock types, a polar desert climate, and is within an impact crater (the most ubiquitous geologic structure in the Solar System). On Axel Heiberg Island we were based out of Strand Fiord, a glacier carved valley known for salt tectonics and mineral springs. The two islands offer stark contrast to one another, with Axel Heiberg dominated by mountain peaks and temperate glaciers and Devon Island dominated by desolate, bare plateaus.

To get to our respective basecamps on the islands we flew in with all of our gear on Twin Otter aircraft from Resolute Bay, a community of approximately 200 people and home to the Polar

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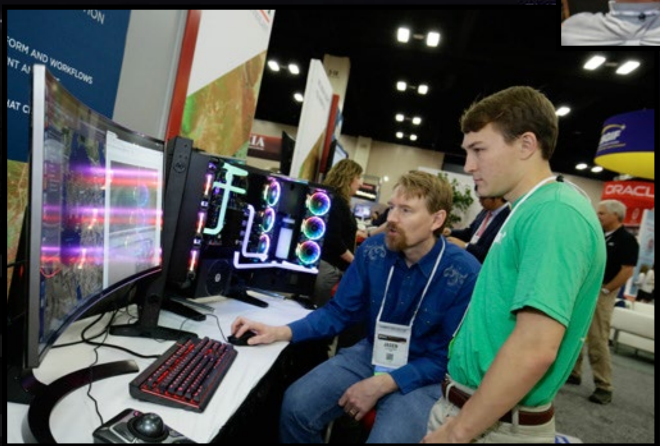

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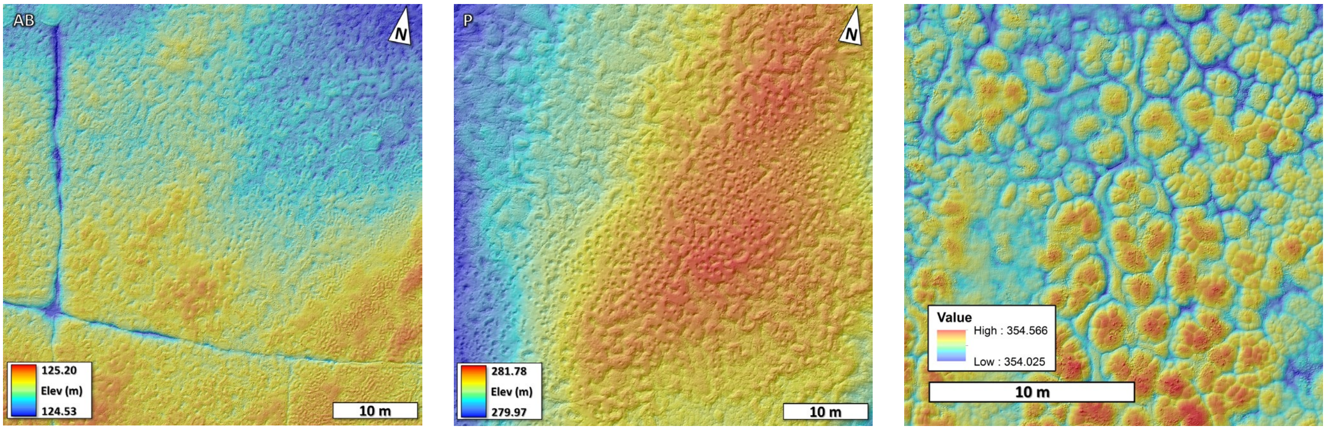
Teledyne Optech Maverick system carelessly left on the ground near our campsite on Axel Heiberg Island. Maverick scans of patterned ground and debris flow gullies were done using a custom built backpack mounting frame.

Continental Shelf Program logistics facility. We used several Kawasaki Bayou 200 ATVs on Devon and two mountain bikes equipped with fat tires on Axel Heiberg for traveling to local sites, and we also logged about six total days of helicopter time to shuttle us to more distant sites. We bunked in individual tents and shared a common "Space-dome" tent and a separate cooking tent. On these large scientific expeditions we had some amenities, including a proper touch-screen desktop computer for planning, uploading data each night, and discussion, plus a movie when the weather turned awful. The weather at this high latitude is variable, but surprisingly not as frigid as one might perceive "polar" research to be. Temperatures hovered around 1-5°C (32-41°F), with some days above 10°C (50°F). Drizzle and cloud cover were frequent, slowing data collection, but fresh snowfall was rare. The greatest benefit to Arctic research in the summer is the 24-hour sunlight, allowing for scanning at all times. If poor weather affected some part of the day we could always pick up the time later. My partner and I would often head out for several hours of scanning at midnight, since this seemed to be the time of day when the sun liked to shine.

Because we were in such remote and rugged terrain, the instruments were subjected to the cold nearly constantly. Cold-sinking the instruments overnight meant that we needed to bring them into the communal tent after breakfast to "get some heat in them". We would hook them up to direct power while we loaded our ATVs and got water for the day. This typically let us hit the ground running when we got to our first site, but on more than one occasion we lost data collection opportunities. Battery life was also an issue, requiring multiple spares and nightly charging with a portable generator.

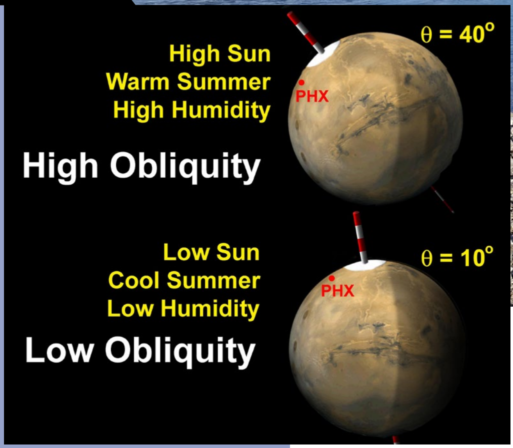


Examples of 50 m x 50 m grids used to compare surface roughness and satellite radar backscatter. The ultra-high resolution (<2 cm/pixel) DEM rasters show the variability of patterned ground and its dependence on rock types. (KLS data, note the vertical scale bars).

MARTIAN REALITY

Like a toy spinning-top, the rotational axis of a planet can be wobbly. The change of the tilt-axis angle (obliquity) and tilt-direction towards the sun (precession), known as Milankovitch cycles, play an important role in how the climate of a planet changes over time. The amount of solar radiation (sunlight) different parts of a planet receives is related to these wobbles. As a planet tilts more towards the sun, high latitudes and the poles receive more sunlight (and low latitudes and the equator less). Earth has a large moon that helps stabilize these wobbles to between 22.1° and 24.5° from vertical over some 40,000 years), but even this small 2° difference can account for ice-ages.

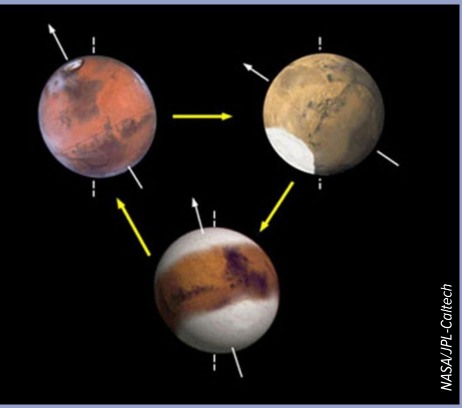
The obliquity of Mars can change by a whopping 47° over 100,000 years or so, creating massive changes to the planet's climate. When these large excursions occur, the poles of the planet receive much more sunlight, causing the ice caps to sublimate, increasing the atmospheric density. Water and carbon dioxide vapor in the atmosphere is then transported equator-ward. The water vapor is then deposited or condensed as snow, which is then mixed with dust and sand, creating thick dust-ice mantles that blanket the middle latitudes. As the obliquity of Mars returns to a more vertical orientation, the ice deposited in those middle latitude areas is then sublimated again back to the poles, leaving behind the dust and sand, creating enigmatic erosional shapes and patterns. The changes in the atmospheric pressure, local temperatures, and availability of water together make freeze-thaw processes more likely to occur, shaping the Martian landscape by processes similar to those in the Canadian High-Arctic. It is likely that many 'fresh' appearing features, such as patterned ground, ground-ice polygons, and debris-flow gullies have been formed during recent obliquity excursions. Our lidar measurements from Devon Island and Axel Heiberg are helping constrain the conditions necessary for widespread patterned ground and how it can be applied to Mars.



NASA/JPL/University of Arizona

Variations in Mars Obliquity and conditions at the Phoenix Mars Lander site (marked in red PHX).

nasa.gov/mission_pages/phoenix/images/ReplaceObliquity_002.html



NASA/JPL-Caltech

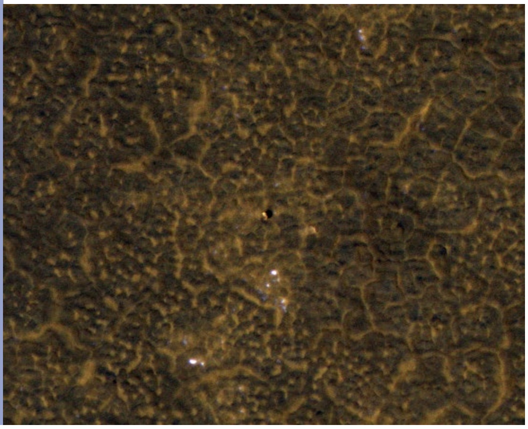
Modern-day Mars experiences cyclical changes in climate and, consequently, ice distribution. Unlike Earth, the obliquity (or tilt) of Mars changes substantially on timescales of hundreds of thousands to millions of years. At present day obliquity of about 25-degree tilt on Mars' rotational axis, ice is present in relatively modest quantities at the north and south poles (top left). This schematic shows that ice builds up near the equator at high obliquities (top right) and the poles grow larger at very low obliquities (bottom)

(References: Laskar et al., 2002; Head et al., 2003).

https://www.nasa.gov/mission_pages/msl/multimedia/pia15095.html#.WqWZVXxG1hE

Data Collection and Processing

Data collection methods varied by instrument and the features of interest. Flat ground sites, like those used for morphology of patterned ground and surface roughness analyses were most often done with the mobile systems (Optech Maverick and Akhka-R3), although some multi-look tripod scans were done in areas when the mobile systems were already deployed. To collect the mobile data we built a custom backpack mount for the Maverick instrument; the Akhka-R3 is designed to be a permanent backpack-mounted instrument. Ground scans took about 15 minutes each and were done by mapping out and flagging a



Patterned ground at the NASA Phoenix Mars Landing Site. Lander (at center) imaged by the HiRISE instrument camera with 25 cm/pixel. Image is ~138 m wide. Note the similarity of patterned ground here to our lidar measurements.

Image credit (NASA/JPL-Caltech/UofAZ_PIA15039)

The Teledyne Optech Polaris long-range TLS was ruggedness tested on Devon Island and provided data for inaccessible debris gullies and rock outcrops.

50 m x 50 m (or larger) box and traversing back and forth in a grid to saturate the point clouds and minimize shadows. It is from these scans that we achieved the 1–2 cm/pixel highest resolution DEMS. Mobile processing was done using the Distillery software for the Maverick, or by a combination of NovAtel Inertial Explorer, Riegl proprietary softwares, and TerraSolid programs (for processing operator and laser trajectories and point cloud matching for the Akhka-R3). Although some analysis for our purposes could be done directly with the point clouds, georeferenced DEMs were created from .LAS files in ESRI's ArcMap (10.4.1) for integration with other remote-sensing datasets. The major difference between the Maverick and Akhka-R3 instruments was found to be with the laser scanner (Velodyne HDL-32E vs Riegl VUX-1HA, respectively), affecting the corresponding point cloud density, scanning range (~75 m vs ~250 m resp.), and final DEM raster resolution.

For mapping grade (~20 cm/pixel) requirements the Maverick produced excellent ground data. Higher resolution (<2 cm/pixel) near-survey grade measurements were made with the Akhka-R3 (which is a similar system to the commercial ROBIN-precision system from 3D Laser Mapping).

Debris slopes and large rock outcrops were best analyzed by the tripod-mounted systems like Optech Polaris TLS, where we scanned kilometers-long plateau faces with multiple scans. As part of a multi-year study of gully erosion, many of the TLS scans taken during these expeditions were also of areas where we had existing Optech Ilris TLS scans. Polaris TLS scans were processed using ATLAScan software for point cloud merging and georeferencing, and exported to ArcMap for DEMs.

Owing to the longer range of the Riegl VUX-1HA scanner on the Akhka-R3 mobile system, we had great success mapping the same gully systems as the Polaris, with reduced shadowing. This increased coverage came at the expense of increased time and energy (from strenuous hiking) to do these scans, but did provide more uniform resolution. The mobile scanners also allowed us to cover huge areas, allowing us to effectively map entire 'mountains' and, though the course of the expeditions, scanned more than 30 hectares of the arctic. We also tested using the backpack scanners while driving on ATVs (Akhka-R3) and while biking (Maverick). The backpack scanners are top-heavy, which made for very uncomfortable scanning, but the results proved reasonable. The terrain was very rough, so the final point clouds were a bit noisier for the vehicle traverses.

Conclusion

The ultra-high resolution of the newest generation lidars is critical to advancing geomorphologic studies, and for field surveying and mapping in general. Because the technology is so new, and the data returned orders of magnitude higher in resolution than anything previous, scientists like us are just now devising ways to analyze and interpret the data and use it to its fullest potential. Our lidar work from the High-Arctic is helping us understand the interaction of ground-ice and surface topography. We can apply these lessons to Mars geomorphology research and in the search for an accessible water ice resource for future landed-human exploration.

Dr. Michael Zanetti is a post-doctoral associate at the University of Western Ontario specializing comparative planetary geomorphology and the integration of ground-based lidar with satellite remote-sensing data.

Dr. Antero Kukko works for the Finnish Geospatial Research Institute as a research manager and is an adjunct professor in the Department of Built Environment, Aalto University, Finland. His research is focused on the development and application of mobile/kinematic laser scanning.

Dr. Catherine Neish is an Assistant Professor of Earth Sciences at the University of Western Ontario. She is an expert in the use of orbital radar observations to study the geology of planetary surfaces, with a particular focus on processes related to impact cratering and volcanism.

Dr. Gordon "Oz" Osinski is an Associate Professor and the NSERC/MDA/CSA/CEMI Industrial Research Chair in Earth and Space Exploration in the Departments of Earth Sciences and Physics and Astronomy at the University of Western Ontario, Canada. He holds a PhD and BSc (Hons) in geology and has spent the past 20 years conducting fieldwork on several continents with a focus on understanding the processes that shape the surface of the Earth and other terrestrial planets.

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Cepton Technologies

The Silicon Valley Approach to Lidar Sensor Development

Cepton CEO Dr. Jun Pei outside the company's new facility in San José, December 2017.

Managing Editor Stewart Walker visited Cepton Technologies in San José, California, in December 2017, to find out why a lidar sensor supplier is located in Silicon Valley and how they bring new thinking to sensor development.

Cepton Technologies, Inc. is a fast-growing startup, founded in July 2016 to provide high-performance, high-resolution 3D lidar solutions for automotive, industrial and mapping applications. It produces four lidar sensors, the HR80T, HR80W and the brand new Vista for ground-based, primarily automotive applications, and the SORA 200 for UAV-based airborne use. Cepton stresses that its sensing principle has no rotation and thus no friction. CEO Dr Jun Pei and senior director business development, Wei Wei, met *LIDAR Magazine*'s publisher, Allen Cheves, and managing editor, Stewart Walker, during the Commercial UAV Expo in Las Vegas in October 2017 and proposed a visit to their facility in San Jose. Here is what Stewart discovered.

Cepton was founded by Jun Pei, Mark McCord and Jun Ye. There can be no doubt about the principals' intellectual acumen—all have PhDs from Stanford and Jun Pei met Mark while they were student and professor respectively. Mark

BY DR. A. STEWART **WALKER**


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-Share with anybody, maintain control, restrict access
-Take measurements
-Scalable Solutions
-Works with any PointCloud (LiDAR or image derived)

is now VP Engineering and Ye is a member of the Board. The founders provide massive expertise in optics, systems, algorithms and automotive applications. Both a serial entrepreneur and an expert in AI algorithms, Ye runs Sentieon Technologies, his third company, having successfully sold his first two, Brion Technologies (to ASML) and Founton Technologies (to Alibaba). Jun Pei consulted with Baidu in 2015 and concluded that no lidar delivered better performance than what had been available 10 years previously. Ye challenged Jun to do something different and better. He did, by forging a team handpicked for excellence. Not all are Stanford alumni, though: software VP Dongyi Liao has a PhD in nuclear engineering from MIT and worked at NVIDIA before moving to a startup then to Cepton.

At the time of my visit, Cepton was proudly awaiting the completion of its new building, less than a mile north of its first facility. The company moved in during February 2018. Triple the space of the old, the new facility will enable Cepton to run small-scale pilot manufacturing up to 10K sensors per year. Furthermore, Cepton is currently evaluating three large contract manufacturers for automotive volume production. This number sounds incredible to those of us with a background in traditional airborne lidar, where suppliers sell tens of systems annually, but doesn't sound so massive if one considers Cepton's primary market, automotive, where the units can be used in both autonomous vehicles and vehicles with drivers and advanced driver-assistance systems (ADAS). When I visited the company, headcount stood at 44, poised to expand. In the afternoon, Jun drove me to their new facility. He had planned the layout himself and the internal partitions and cubicles were awaiting assembly, all carefully thought out and incorporating expectations of dramatic growth.

During our initial conversation, Wei drew a comparison with Tesla and made an important point: success lies in speed of development and system-level innovation through making best use of mature materials and off-the-shelf (OTS) components, then adding smart packaging and control. Silicon Valley is not known for every breakthrough in fundamental sciences, but for bringing new solutions that solve meaningful, viable problems at scale. He modestly described his colleagues as hackers who bring their different culture and perspective, and apply their skills

Figure 1: Cepton Vista sensor for automotive applications.

Figure 2: Cepton SORA 200 sensor for airborne UAV applications.

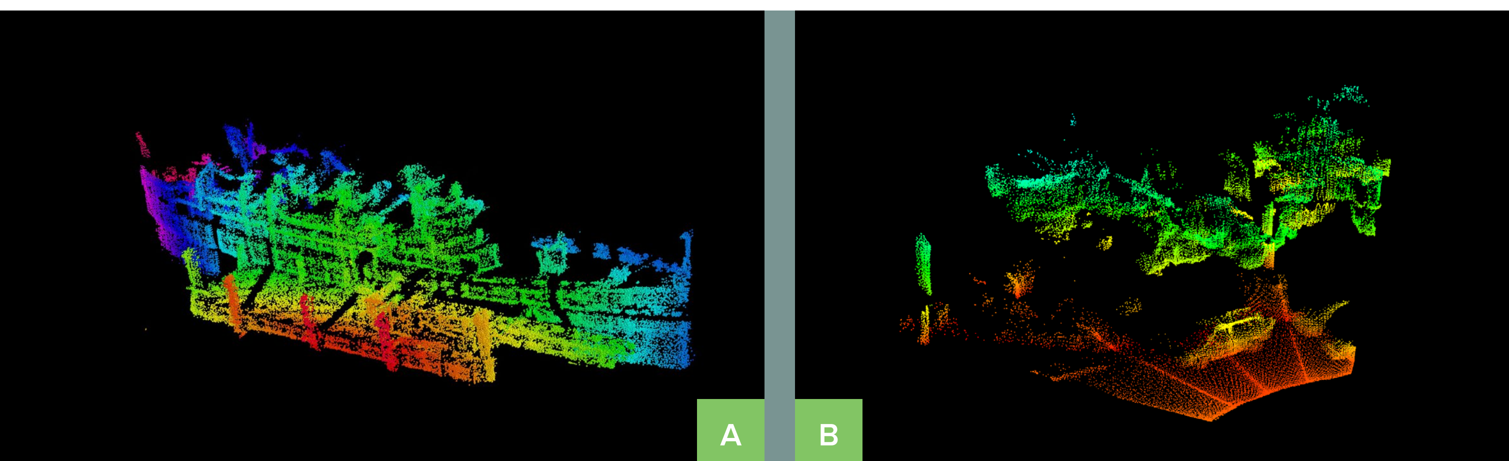
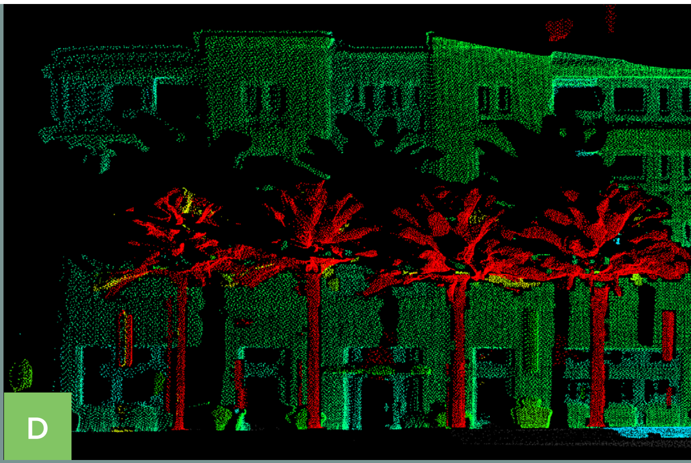


Figure 3: Examples of point clouds measured with Cepton sensors: (a) HR80T; (b) HR80W; (c) and (d) SORA 200.

to *what is available today*. They are ingenious, however, and not reluctant to tackle fresh problems. He described them as the "opposite of the Swiss watch industry", where craftspeople take a traditional approach, dedicated, persistent, creating art over generations. Striving to reveal the uniqueness of Silicon Valley as observed in both Tesla and Cepton, Wei elaborated, "We are 'hackers', trying to find out what would make the most impact and maximize the potential of every component to the limits of our knowledge, then integrate them together from different perspectives and make it happen in days, quite different from other places". Velodyne originally grew from that spirit. There were range-finders in the early days of automotive lidar and the German company Sick AG built a single-layer rotating scanner. Then Velodyne created a multi-layer rotating scanner that provided more resolution and really helped the first generation autonomous vehicles. Nevertheless, they had to work hard to remain innovative. Wei elaborated, "But now lidar is evolving, people want higher and higher resolution, resulting in camera-like images—how do you do that?" For autonomous vehicles, the consensus is that rotating lidar sensor(s) with 360-degree coverage (or field of view—FOV) is not a desirable technology. Seamless integration into the vehicle body is difficult and there are many wasted pixels. At the same time, the rotating motor is known for low reliability. All the new lidar technologies are evolving towards a confined FOV, higher resolution, no rotating motor and smaller size for deep vehicle integration. The goal for the coming mass-produced autonomous vehicles is not to have lidar as a protruding element any more. Suppliers need to move to higher resolution at lower cost—and design accordingly. Yet they cannot allow the number of laser trackers to scale directly with the required resolution.

The underlying principle of Cepton sensors is that there is a proprietary, sparse laser emission and sensing array that delivers high performance and resolution at low cost. The HR80 and Vista (**Figure 1**) models are designed for automotive and area imaging applications: the sensors output a grid of pixels, whereas the SORA 200 (**Figure 2**) model for airborne UAVs—Jun explained that "sora" is the Japanese word for sky—has two scanning lines of 300 pixels, perpendicular to the direction of flight and 18° apart. This approach facilitates a very fast frame rate beyond 200 Hz. The solution is not entirely solid-state, but the required movements are tiny and frictionless. Though there are very few lasers, dense point clouds are produced through scanning. The SORA 200 platform is very flexible and can be customized for wider FOV and higher resolution through different optics. To put this in context, Wei noted, one competitor offers 0.2° operating at 20 Hz. Cepton could have put more pixels in each line, or they could add a third line. They even thought of using only one, but decided that two would increase canopy penetration. The pulsed lasers are off-the-shelf and have a wavelength of 905 nm. Some mapping companies have requested 1550 nm, but that needs more



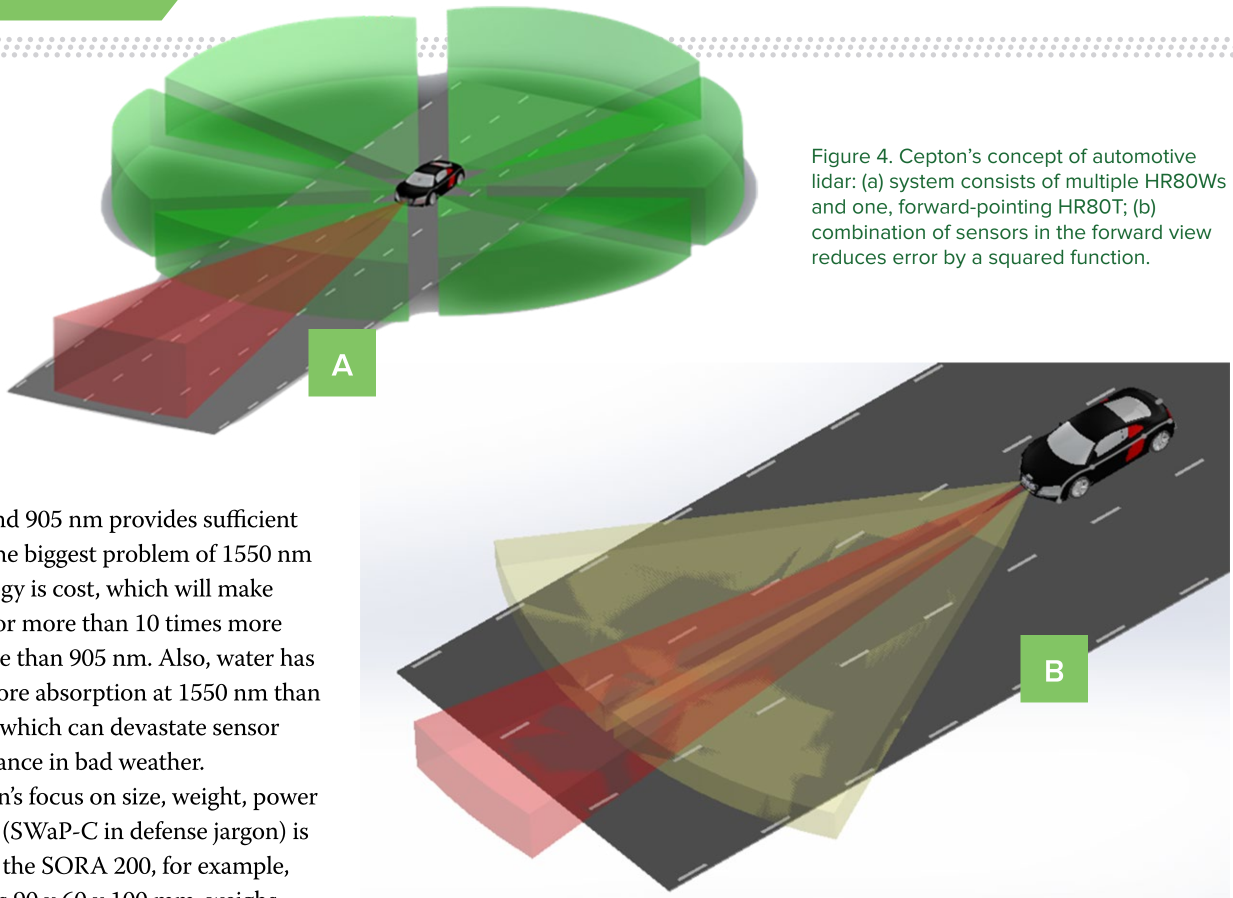


Figure 4. Cepton's concept of automotive lidar: (a) system consists of multiple HR80Ws and one, forward-pointing HR80T; (b) combination of sensors in the forward view reduces error by a squared function.

power and 905 nm provides sufficient range. The biggest problem of 1550 nm technology is cost, which will make the sensor more than 10 times more expensive than 905 nm. Also, water has much more absorption at 1550 nm than 905 nm, which can devastate sensor performance in bad weather.

Cepton's focus on size, weight, power and cost (SWaP-C in defense jargon) is obvious: the SORA 200, for example, measures 90 x 60 x 100 mm, weighs 550 g and draws 9 W. The HR80 comes in two models, the HR80T telephoto and HR80W wide angle. Examples of point clouds captured by these sensors are shown in **Figure 3**. Cepton's concept is that a car should be equipped with half a dozen HR80Ws, giving full 360° field of view, plus an HR80T looking forwards (**Figure 6a**). With both an HR80W and an HR80T looking forwards, there are more pixels in the crucial central area and the probability that an object critical to car safety is missed is minimized (**Figure 4b**; also look for Cepton on Vimeo for some informative video clips showing the system in operation). Development has been exceedingly fast: there was an alpha demo of the HR80T in November 2016, only four months after Cepton was founded; this was followed by a beta release in February 2017 and market introduction in June 2017—with worthwhile improvements between milestones. The HR80W was also released into the market in June 2017. The SORA 200 was announced at the Commercial UAS Expo in Las Vegas in October 2017. A new model, Vista, launched at NVIDIA's GTC event in March 2018, offers the same field of view as the HR80W, but with significant improvements to range, angular resolution, frequency and SWaP-C.

Cepton has worked closely with LiDAR USA to integrate the SORA 200 into UAV mapping systems and perform field tests (**Figure 5**). LiDAR USA has begun shipping these systems to its customers globally. Other customers and system integrators will work with Cepton in the UAV space. The automotive market will take two years to reach volume, but UAVs are flying today. Cepton anticipates a market for all its sensors of exceeding ten thousand units over the next two years, with significant growth thereafter. Talking to Jun and Mark in the afternoon, I asked provocatively about the manned aircraft market. Cepton admitted that this ambition would be premature for them, but from a technical point of view it's not impossible. Mark said that if enough customers ask for this product, the Cepton team will make it happen!

Wei identified an important similarity between the automotive and UAV airborne markets: both require long range and high accuracy; low cost is ideal too. Cepton is strong as far as range is concerned. Warehouse robots moving at 2 m/sec need a range of only 10-20 m: there are many low-cost technology solutions for this, making it a solved problem. UAVs will become totally

Figure 5: Cepton SORA 200 integrated on to UAV lidar system by LiDAR USA.

autonomous and perception capabilities will be necessary. Cepton can be quick to market with appropriate solutions. They are confident of their speed and expertise in the long-range, high-resolution niche. He summarized, "Cepton is working on a variety of applications where traditional lidar was too expensive but our low-cost solution becomes applicable."

Highly automated driving will be the main opportunity for lidar in the automotive market for the next three to five years. This is called Level 3—automated driving, whereby the driver's hands need not be on the steering wheel in certain scenarios: the system alerts the human driver to take over. This could become a standard offering in vehicles in 2020-23. Level 4 means hands off the steering wheel, all the time in some areas, and Level 5 means no need for a steering wheel, i.e. totally autonomous. The official explanation, for those of us less *au fait* with automotive applications, is at https://en.wikipedia.org/wiki/Autonomous_car. Current systems are not so sophisticated, of course: for example, the bleeps as a car reverses near a wall or other obstacle are often a response to simple ultrasonic measurements. Many cars have more advanced systems, with a rear-view camera and graticule superimposed on a screen to help the drive to maneuver. "Highway pilot", to drive the vehicle between freeway entrances, exits or toll booths, including lane changes, and automatic emergency braking (AEB) are the goals of car manufacturers today. This is the market that's driving Cepton and it's huge—global sales of new cars now exceed 80 million units *per annum*!

Figure 6: Rear view of Cepton HR80T, showing 100 Mbps Ethernet connection.

Cepton thinks that many UAV applications have hardly begun. Mapping is important today, but in the near future there will be autonomous delivery of goods and people and again drones will require perception capabilities. Detailed mapping, argued Wei, is challenging, but autonomous flight, even more so. The market for UAVs for deliveries will be enormous. The market for repeat mapping of construction sites using UAVs, moreover, has barely been captured. Precision agriculture is exciting too: imagery is essential for plant health, of course, but lidar can measure the physical sizes of plants and trees. These applications are not economical for manned aircraft or helicopters: UAVs are revolutionizing these markets and causing them to expand.

Wei ended the morning with some comments on the business side. Cepton already has a large number of customers in the automotive market and is proud of how far it has come in eighteen months. Prospects in the mapping market are numerous. Mobile mapping systems could be created with multiple HR80, Vista or SORA 200 sensors. MMS companies are moving away from expensive, single-line scanners, since customers want laser beams to reflect off objects at different angles, so Cepton's array approach is promising. The prices of the HR80 or SORA 200 starter kits are a few thousand dollars for one sensor and Cepton software development kit (SDK), with big reductions anticipated for volume purchases. Cepton's plan for MMS is embryonic, but it envisages a price under $20K including multiple lidar sensors and GNSS/IMU, which will be a "game changer". They want to disrupt the market. They want to pluck "low-hanging fruit". City asset management is a potential market at these lower price points. Between automotive and airborne, Cepton has no doubt that it will sell sensors in large numbers. The company has a low burn rate and foresees profitability quite soon. Wei repeated the benefits of using OTS components and avoiding exotic materials. They focus on the core—the *lidar sensor*—and don't stray into GNSS, IMU or SfM.

In the afternoon session, Jun and Mark made clear that they didn't want to share the technical details of the inside of their box, since the market is ruthlessly competitive. With the high-volume demand of automotive lidar, there are many lidar companies in the race to get into mass-production vehicles. Competitors are proud of their intellectual property and guard it assiduously. Joked Jun, "Light goes out and comes back in!" But they *do want* to be less uninformative: they have to be convincing in the market-place. Companies such as Teledyne Optech and Hexagon can describe their technology in detail because the manned aircraft market is small and their customers expect some insight.

There are around two dozen companies currently aiming at autonomous vehicles. They have an idea, make sure it works, think of a few buzz words round the technology, ask for VC money, build a prototype, ask for a second round of money—the cycle is well known and Cepton has followed it to some degree. It's a replay of history, a selection process. Stars or survivors emerge, including some superstars such as Hewlett-Packard. The Cepton principals are *old* for Silicon Valley companies. They adopt what's there. This is a more practical approach—a traditional business model: make and sell a real product at a profit. Therefore there is a rhythm in business developments. This philosophy determines the technology approach. Cepton is not developing fancy technology without revenue—this doesn't give cash flow. The goal is to bring real products to solve meaningful market problems today. The velocity of innovation can be measured by milestones in every quarter. These milestones *must* be met. Whereas an approach dependent on research grade, immature technology and/or materials may not be successful, Cepton's technology-based approach enables it to control its own destiny and be able to make an impact today. Jun mentioned the analogy of Tesla—it didn't invent the battery but innovated at packaging and system level. Cepton invests effort in system design, packaging, optics and signal processing. Packaging matters, especially for autonomous vehicles. Performance, cost and reliability are all key.

Figure 7: Cepton HR80W mounted on Clearpath Husky warehouse robot.

> "Cepton's technology-based approach enables it to control its own destiny and be able to make an impact today."

Jun thought that the UAV market is easier to enter. October 2017, the launch of the SORA 200, was only 15 months after the company was founded. Cepton's ambition is based on the business model described above. Nevertheless, the automotive market is the big one. Cepton is planning its own manufacturing for small volume and will leverage contract manufacturing for high volume production runs.

Jun identified a market gap in spatial resolution and distance. Cepton positioned itself to be top-end, >300 m range and 0.1-0.2° resolution. There are four key areas and they have made advances in all of them: optics; electronics; mechanics; signal processing (algorithms in firmware and software). They use custom optics. They invested heavily in the electronics for best signal-to-noise ratio. The mechanics are not solid-state: the micro-motion scanning array designed in-house—indeed, Cepton coined the term—has moving parts, is innovative, and is the heart and soul of the Cepton solution, according to Jun. Most mechanical systems have motors, or the entire unit spins. The result is friction, causing wear and tear on the shaft and bearings. Cepton has eliminated that. Thus these critical components have infinite life expectancies. Micro-motion, by definition, provides small movements. Mark explained, "Our sensors are not pure solid state—like voice coils in speakers: they have moving parts and they are in every car." Mark added that the technology can scale to higher resolution and longer distance in future revisions, and that the Cepton approach is simpler and less expensive than other lidar solutions: Cepton's goal is to reach DSLR weight and pricing. Jun pointed out that Cepton *excels in engineering*. "Our team has a vertically integrated skill set from optics, electronics, mechanics, to machine learning and computer vision." Jun added that Cepton has an admirable portfolio of patents, but its biggest asset is a group of people. For its size, it has a big engineering team.

The sensor does not record data but pumps out a continuous stream of measured points with coordinates, distances and intensities (**Figure 6**). Cepton has created a SDK that provides parsed and assembled point cloud data as well as diagnostic information. The SDK supports Windows, Linux, Robot Operating System, Mac OS and Native Python Bindings. If Cepton makes a firmware upgrade to the sensor, the SDK will still be compatible with user's existing software.

"Cepton has an admirable portfolio of patents, but its biggest asset is a group of people. For its size, it has a big engineering team."

Figure 8: Cepton HR80W mounted on May Mobility autonomous vehicle.

We compared the automotive and UAV lidar markets. Eighteen months ago the market in Cepton's sights was almost entirely automotive. Jun thought UAVs were toys. Wei insisted, however, that a new commercial drone market was emerging, with scope for a competitively

CEO Dr. Jun Pei relaxing with music before pursuing Cepton's next milestone.

priced sensor offering high performance. I asked why Cepton had chosen the Commercial UAS Expo event for the SORA 200 launch. Jun admitted some shyness on his company's part—they are not natural marketers. Since they had shipped only a handful of the SORA 200 units at that time, they preferred a highly technical event, where they could expect intelligent questions from visitors. When I visited, however, Cepton was in the midst of preparation for the huge Consumer Electronics Show in Las Vegas in January 2018, an entirely different prospect.

Cepton units accommodate two returns per pulse as well as intensity. More features are in the planning stage. They have deliberately designed the SORA 200 with a detection range of 200 m, for targets with 50% reflectivity, because this easily covers the 400-foot ceiling for UAVs specified in current US regulations. Indeed, the US is more generous in this respect than some other countries.

I asked about distribution. Cepton has developed a strong partner network, especially on the automotive side, including a number of start-ups. Other distributor application areas include robotics, mapping, agriculture, railways and mining. In particular, we talked about Clearpath Robotics, located in Kitchener, Ontario, Canada. It has a robotics division specializing in warehouse robots and is a reseller of sensors and components related to robotics (**Figure 7**). The global market is certainly on Cepton's radar, with plans in place for 2018.

Jun perceives the short-term prospect for autonomous cars as successful operation on defined campuses. Therefore initial sales of sensors will be small fleets of robotaxis and people movers in last-mile transportation (**Figure 8**). The lidar sensors can provide centimeter-level distance accuracy and spatial resolution, to be fused with radar and camera sensors to provide extra redundancy and reliability. For high volume production vehicles, the car companies are looking into seamless integration of lidar into the vehicle body. Behind the fascia or in the headlamps could be satisfactory positions for lidar sensors and Cepton is actively working with Tier 1 suppliers on this front.

I ended by asking Jun some questions about himself. He likes wrist watches. He built model boats and flew model planes when he was growing up. He plays the piano expertly and almost went to music academy, but preferred boats and planes for his profession, while not losing touch with music. He has a Steinway grand piano at home and an electronic upright in his office, to which he listens, as he plays, through headphones so as not to disturb colleagues as they apply their various remarkable talents to the Cepton sensors that he hopes will transform the automotive, UAVs and perhaps other lidar markets. The company's strapline, "3D lidar for smart machines" hits the spot.

Dr. A. Stewart Walker is the Managing Editor of the magazine. He holds MA, MScE and PhD degrees in geography and geomatics from the universities of Glasgow, New Brunswick and Bristol, and an MBA from Heriot-Watt. He is an ASPRS-certified photogrammetrist.

Graham, *continued from page 48*
which have not been used in the training process and see how it does. We typically express the success rate as a fraction or percentage. Thus a score of 97.5% means that our system is correctly classifying all but 2.5% of the test samples.

So what is the big deal about this? Well, if I had made a coded set of algorithms to detect a circle or a rectangle, I might do something such as code up an edge detector, look at curvature of edges, number of sides and so forth. It would be very "hard coded" to detect circles and rectangles. If I wanted to switch to detecting circles and triangles, I would have to go in and rewrite my core logic. Not so with the perceptron. I just reset the weights and train with the new set of training data. Thus as long as I have sufficient training samples, my classifier is *trainable*. This was a very novel concept for its time, becoming one of the pillars of the birth of computer implemented artificial intelligence (AI).

Unfortunately, the perceptron is binary and thus can only work with inputs that cleanly segregate into two classes. In 1969 Marvin Minsky (and Seymour Papert) pointed out that the perceptron could not solve a simple XOR classification. Minsky went on to say (without proof) that while this could potentially be solved by adding more layers to the network, it would not be possible to train. Since Minsky was such a force to be reckoned with in AI at the time, the perceptron and its variants were dead in mainstream AI research.

During this same period of time, adjusting parameters in a systematic fashion was being explored by electrical engineers in control systems design. The general technique is called *back-propagation* where the error of the output is fed in reverse order through the system using an adjustment algorithm called *gradient descent*. In 1974, Dr. Paul Werbos applied back propagation to multilayer perceptron's and the artificial neural network (ANN) was born (see **Figure 2**). ANNs were very popular in research circles in the late 1980's but the compute power for solving the weights for a large network made them impractical for real world problems.

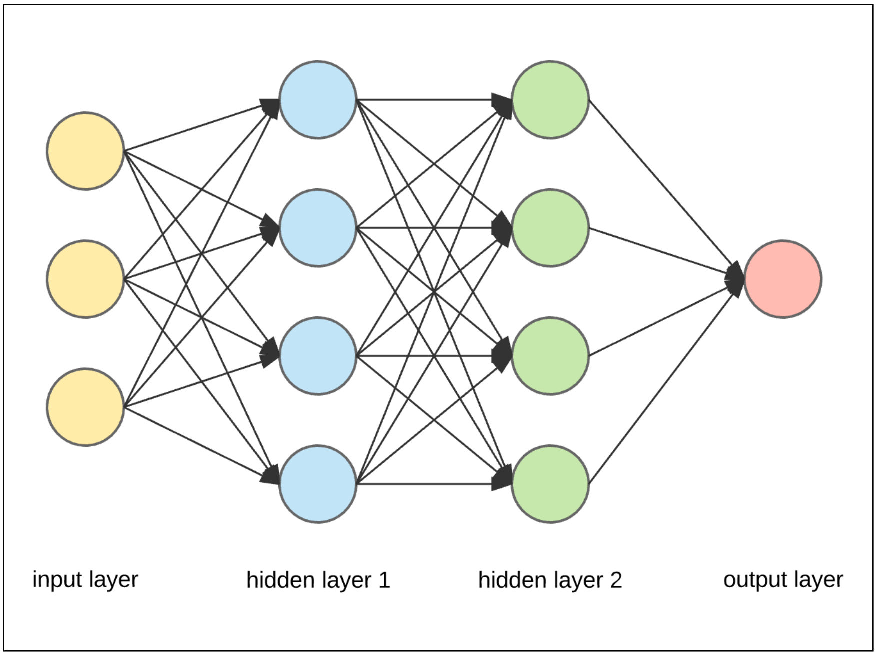


Figure 2: Multilayer Artificial Neural Network (weights not shown)

Perhaps 5 years ago, ANN once again was taken out of the closet, dusted off and programmed on new, low cost parallel processors such as Nvidia GPUs. Suddenly, programming the weights of large ANNs via backpropagation looked doable at a reasonable cost. Rapid advances were made in specific problem spaces, particularly natural language parsing. The expression *Deep Learning* that we now so often hear refers to ANNs with one or more hidden layers of neurons (hence, the *deep* part). The great thing about ANN today is that you really do not have to program anything – you can just use ready-made application programmer interfaces from a number of providers (including the aforementioned hosted system in AWS).

In next month's edition of Random Points, we'll explore the value of ANN and examine the sorts of problems to which these algorithm might be applicable. In the meantime, if you want to do experimentation on your own, I highly recommend the book "Make Your Own Neural Network" by Tariq Rashid available as a Kindle book for $3.98. In the meantime, keep those neurons firing!

Lewis Graham is the President and CTO of GeoCue Corporation. GeoCue is North America's largest supplier of LIDAR production and workflow tools and consulting services for airborne and mobile laser scanning.

LEWIS GRAHAM

I am, Therefore I Think—Part 1

We are hearing a lot about "deep learning" these days, with even Amazon Web Services offering hosted deep learning networks for rent. Recently Pix4D announced a prerelease of a deep learning classifier for point cloud data. I thought it might be fun to review deep learning and see what all this hype is about.

Way back in 1957, a new binary classifier algorithm called the *Perceptron* was invented by Dr. Frank Rosenblatt at Cornell's Aeronautical Laboratory. A binary classifier divides input into one of two categories. For example, you might have a bunch of geometric shapes feeding a binary classifier that decides if each shape most closely resembles a rectangle or a circle. The novel thing about the perceptron was that it was not a preprogrammed analytic algorithm with intrinsic knowledge of the characteristics of a rectangle or a circle. Rather it was a generic "filter" that "learned" the classes by being fed known examples and having a set of weights adjusted to move the network toward the correct response. This is shown in **Figure 1**.

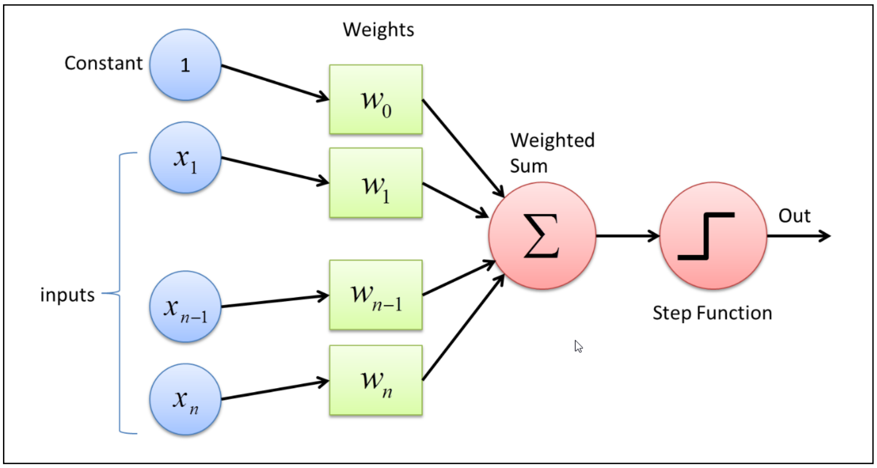


Figure 1: The Perceptron Algorithm

"The great thing about artificial neural networks (ANNs) today is that you really do not have to program anything..."

In this figure, you can imagine the inputs as being cells on a grid that feed in a 1 if the shape intersects the cell and a minus one otherwise. Each of these individual inputs (for example, if our sampling grid were 16 x 16 cells, we would have 256 individual inputs) are *conditioned* at the initial input layer. For our example, the conditioning is to make the input 1 for a covered pixel and -1 for an uncovered one. Each input is then multiplied by an adjustable weight and fed to a summer. Finally, the output of the summer is fed to a *discriminator* that outputs one of two values (say 1 or 0 which represent circle or rectangle respectively). The discriminator might be a simple threshold that says if the output of the summer exceeds 18.7, output a 1, otherwise output a 0.

A *training* set is presented to the network and the error is fed back into the system to adjust the weights. For example, if we feed the system a circle and output a zero, we have an error since we said a circle is represented by an output of 1. We feed numerous examples to the system and tweak the weights based on whether the output is correct or not. We test the efficacy of our training by feeding the system shapes

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