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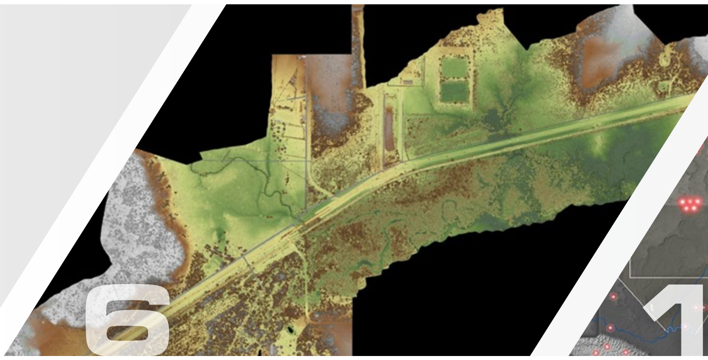
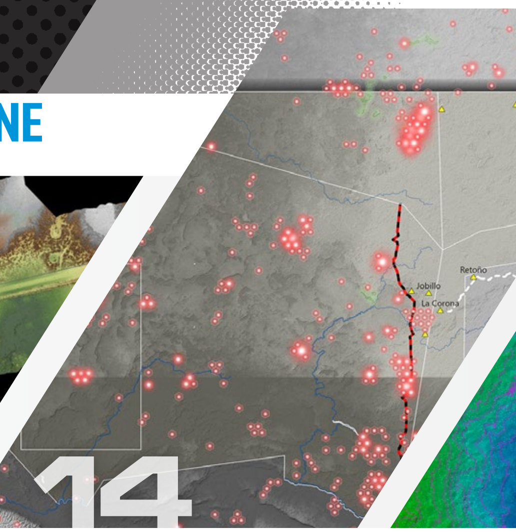
WINTER 2021

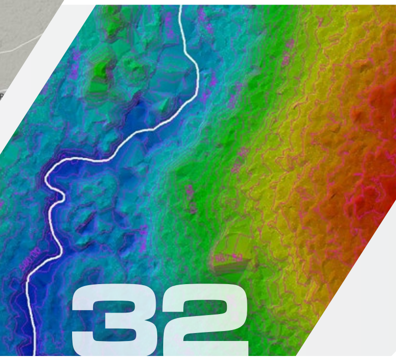
SPECIAL ISSUE

AERIAL TECH SHOWCASE

LIDAR MAGAZINE







ON THE COVER
USGS QL2 bare-earth raster DEM with color ramp for elevation, Southern Utah.
Image courtesy of The Sanborn Map Company.

IN THIS ISSUE

COLUMNS

LIDAR To Go!
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FROM THE EDITOR

DR. A. STEWART WALKER

A New Beginning?

Welcome to 2021. Last year—and, indeed, early this year—we fingered the fabric of democracy, continued to eviscerate the environment, and mismanaged the worst pandemic in 100 years. Room for improvement. Will 2021 be less bad? Of the innumerable aphorisms about new starts, I picked just one, from Seneca, "Every new beginning comes from some other beginning's end."

While our leaders ponder the great issues of state and the maintenance of our planet, those of us in the trenches have to keep renewing something rather more mundane, yet critical if we are to communicate correctly—the words we use to describe what we do. Sometimes we need an up-to-date glossary of terms. A compact one[1] has been published recently in *The Photogrammetric Record*, a UK-based, peer-reviewed journal published by the Remote Sensing and Photogrammetry Society. Compiler Stuart Granshaw is the most meticulous of editors, so this glossary, which is the fourth edition, is significant. I counted 94 instances of "lidar". Of course, it's quite useful also to those of us who dabble in photogrammetry! The references on page 147 are a fascinating collection.

This is our annual Aerial Technology Showcase issue, in which we highlight not only the legerdemain and industriousness of geospatial service providers but also the ingenuity and innovation of system suppliers. We lead with a meaty piece by Mark Meade of NV5 Geospatial (as Quantum Spatial was renamed on 10 December 2020) and Kyle King of Oklahoma Department of Transportation, presenting the vertical and horizontal accuracies achieved with three platform/sensor combinations flown over an area with numerous carefully surveyed check points. The results are amazing in both accuracy and consistency. Reflect for a moment on what lidar can do in the right hands.

We follow the lead article with three intriguing application stories. Emily Mercurio of CivicMapper and Srini Dharmapuri of Sanborn discuss lidar's contribution to stormwater management. Steve Snow of Esri describes yet another case of spectacular archaeological advances as a result of lidar data being available—this time on a Mayan site. And regular contributor Al Karlin, together with co-authors from Dewberry and Southwest Florida Water Management District, compares topobathymetric lidar with more traditional hydrographic technologies for mapping inland waterways. On the technology side, we've posted on our digital site a piece by

1 Granshaw, S.I., 2020. Photogrammetric terminology: fourth edition, *The Photogrammetric Record*, 35(170): 143-288, June 2020.

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Greg Smolka of Insight Lidar about developments in frequency-modulated, continuous wave lidar[2].

I've written often in these pages about the influx of lidar sensors to the geospatial world from the automotive world, where the principal motivation is autonomous vehicles (AVs). Maybe it's time to reflect for a moment on AVs' progress. A recent piece in the popular press suggests[3] not that the vehicles are stalling but that the path to total adoption is not as easy as we hoped. So it's timely that we publish an article by Bernd Braunecker, who headed optics development at Wild and Leica in Heerbrugg for many years, giving the measured view of a Swiss physicist, backed up by a useful overview of relevant technologies. We have noticed, nevertheless, that AV startup Nuro has been given a deployment permit by California's Department of Motor Vehicles to make deliveries by AV[4].

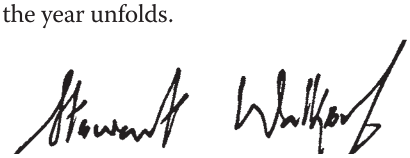
Following Evon Silvia's piece in the last issue about the ASPRS LAS Working Group[5], we bring the first of his reports on the WG's bimonthly meetings. This relates well to the article about OGC by two of the organization's big names, Scott Simmons and Stan Tillman. ASPRS owns the LAS format standard, but OGC has designated it as a Community Standard. OGC has formed a Point Cloud Domain Working Group, which should make a big difference to lidar data interoperability, especially on the dissemination side.

Many readers know that the state of Florida has been incredibly active with lidar for 20 years. The Florida Region of ASPRS runs lidar workshops every year in cooperation with the University of Florida. As a result of covid , the last one, on 22 October 2020, was virtual. We proposed to the organizers of the event that we publish those presentations for which the authors were willing to provide written articles. The result will be a special issue containing 13 articles from the meeting. Look out for it next month! The workshop was one of many first-rate virtual events during 2020—see my comments on our digital site—and we are pursuing several authors as a result.

There's a short article in *Photonics Spectra* about airborne and satellite imagery[6]. It's interesting because there's material about Hexagon's enthusiasm for hybrid sensors with lots of quotes from Ron Roth. Hexagon has made the image library in its HxGN Content Program available free of charge to government agencies and nonprofits involved in the fight against covid. The article is remarkably wide-ranging and also covers Headwall Photonics' solutions that combine hyperspectral and lidar sensors on the same platform.

Times, therefore, are somber for the planet and its citizens, yet promising and invigorating for lidar. Let's end on a lighter, rather lidar-free note. Leisure time during the holiday season presents an opportunity to view movies that we would not normally have chosen. In my home, our selections are sometimes marks of respect for stars no longer with us—wonderful choices following the passing of Diana Rigg, Sean Connery and John Le Carré last year. Do you use the *Oxford English Dictionary* (OED)? Does every editor need it? The current, second edition was published in 1989 and consists of 20 volumes totaling 21,728 pages. My neighbor, a PhD in mathematics from MIT, owns this colossus, but laments the lack of a lectern in his lounge! The second edition is being digitized and the third, due to be completed in 2037, will probably never see hardcopy. Electronic versions have been available since 1987 and the OED has been online since 2000. I took the time to view the 2019 film *The Professor and the Madman*, starring Mel Gibson and Sean Penn, based on a curious and serendipitous friendship between OED editor James Murray, a linguistic genius from Scotland without a college degree, and William Minor, a US Civil War veteran with mental health issues who submitted numerous definitions. Great stuff!

Finally, let's try to look onward and upward with the help of UAVs. We all know about drone swarms, the importance of which seems greater in defense applications than lidar data acquisition, but please glance at https://www.edinburghshogmanay.com/ to enjoy UAV formations seeing off 2020 and welcoming 2021. Ingenious and uplifting! We hope to bring you similarly inspiring stories from the lidar world as the year unfolds.



A. Stewart Walker // Managing Editor

2 https://lidarmag.com/2021/01/12/fmcw-lidar-seeks-fortune/

3 https://www.theguardian.com/technology/2021/jan/03/peak-hype-driverless-car-revolution-uber-robotaxis-autonomous-vehicle

4 https://www.cnet.com/roadshow/news/nuro-autonomous-delivery-deployment-permit-california/.

5 Silvia, E., 2020. LAS: what's on the horizon, *LIDAR Magazine*, 10(5): 12-16, October/November 2020.

6 Freebody, M., 2020. Earth imaging reveals the true state of land, sea and air, *Photonics Spectra*, 54(11): 26-33, November 2020.

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Accuracies Amaze the Experts

Tough test of lidar sensors and aerial platforms

The project area included roadway, above-ground utilities, and a rail corridor, which increased the value of the study

Technology continues to provide new and improved options for data collection in all areas of geospatial services, leading to better, more complete answers to clients' needs. These advances can be grouped into three general categories:

- Cost efficiencies, through either reduced acquisition time or the ability to move from a higher to a lower cost platform, for example lidar manufacturers have moved from 1- to 2-MHz lasers and packed impressive performance into smaller, lighter sensors, reducing project cost and impacting the selection of acquisition platforms
- Increased quality, resolution, and accuracy of the data, enabling new and innovative analytics: the performance of key sensor components has improved, as have the laser precision and detection optics, providing accuracy and detail that were unavailable several years ago
- New remote sensing capabilities, such as improvements in hyperspectral and shallow-water topobathymetric sensors that have occasioned a new, comprehensive knowledge of nearshore and riverine environments

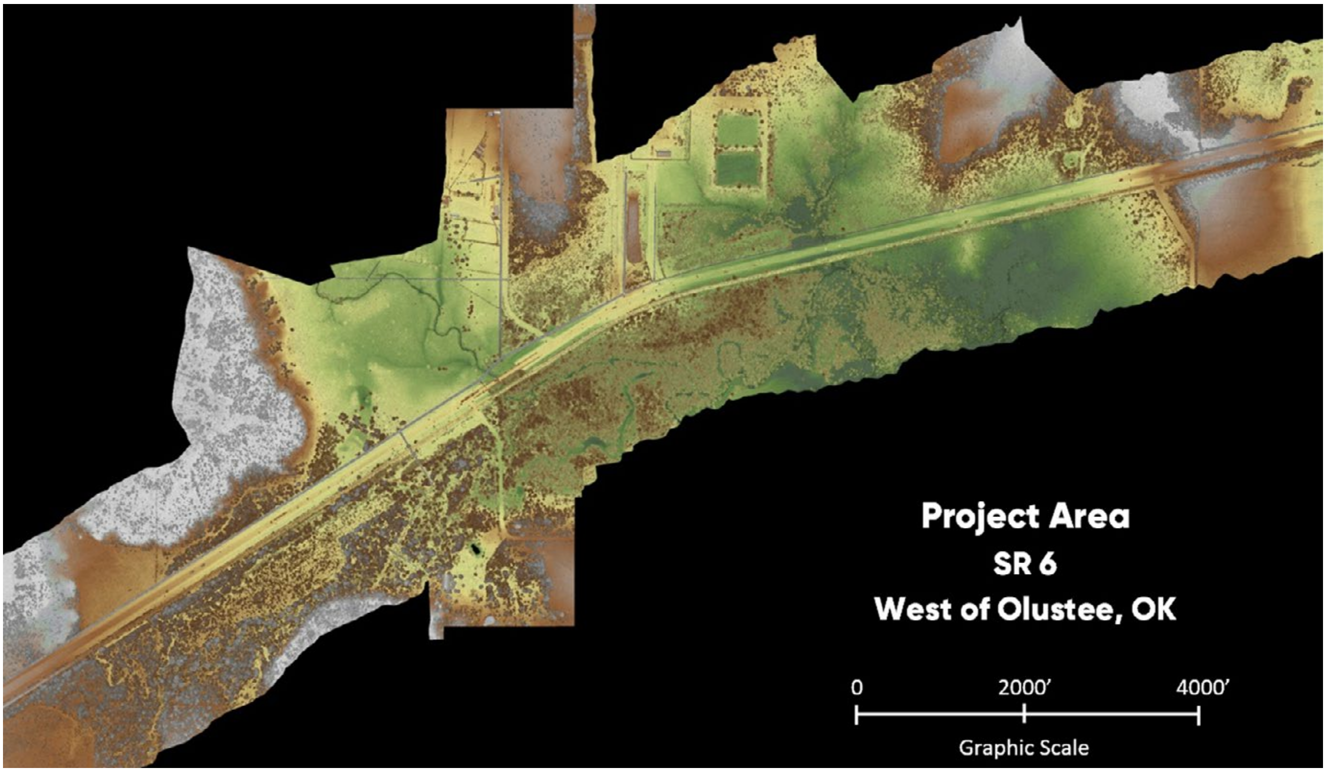
Understanding sensor performance

An acute understanding of the performance of the new sensors, in both a qualitative and a quantitative manner, is critically important to making recommendations or decisions on how to approach a project. Without sufficient awareness of sensor performance, it is impossible to make authoritative decisions that provide the perfect mix of economy, resolution, and accuracy for varied project requirements.

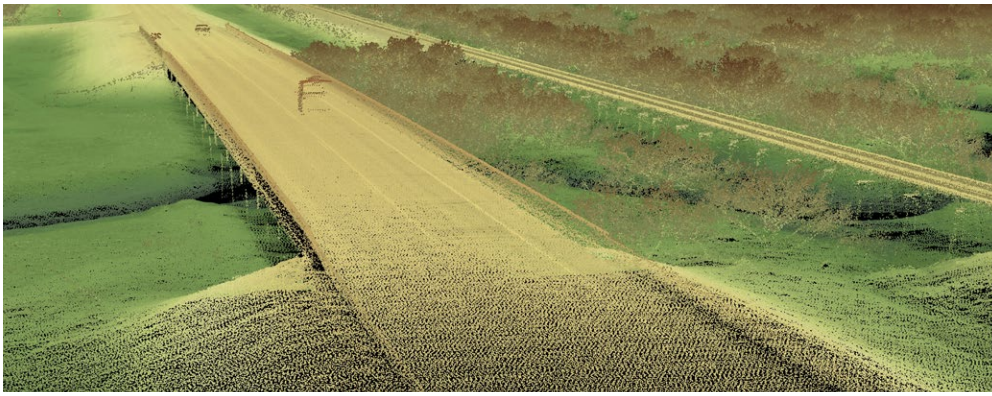
Discussions began late in 2019, therefore, between NV5 Geospatial[1] professionals, NV5 transportation and unmanned teams, and the Oklahoma

1 Formerly known as Quantum Spatial, an NV5 company.

BY MARK **MEADE** & KYLE **KING**



Project area in southwestern Oklahoma


The high-density point clouds produced in each of the flights provided fine detail for the project

Department of Transportation (ODOT), leading to groundbreaking research into lidar performance and accuracy over a two-mile stretch of rural roadway in Oklahoma.

The goals were straightforward:

- Understand the horizontal and vertical accuracy of point clouds generated from three types of lidar sensors, flown at three different altitudes
- Develop detailed statistics for lidar accuracy on hard surfaces (asphalt and concrete) and compare the results to those on soft surfaces (bare earth and varying ground cover)
- Evaluate the qualitative aspects of the point clouds in terms of applicability to multiple project types—fine feature determination of signs, rails, above-ground utilities, lane markings, guardrails etc.

The project used three sensor packages, flown independently at three different altitudes and ground speeds. These were flown on two different rotary wing platforms—a sUAS hexacopter and a helicopter.

The first package consisted of a single Riegl VUX-1 flown on the sUAS platform. The second was NV5 Geospatial's comprehensive low-altitude sensor solution (CLASS) that combines two Riegl VUX-LRs with nadir and

Platform	Sensor	Altitude (feet)	Speed (knots)	Applanix INS	Spot size (feet)	Density (ppsm)
sUAS	Riegl VUX-1	250	15	APX-20	0.12	123
Rotary	CLASS - 2 x Riegl VUX-LR	450	40	POS AV 610	0.23	80
Rotary	Riegl VQ-480i	600	45	POS AV 510	0.18	62

Table 1

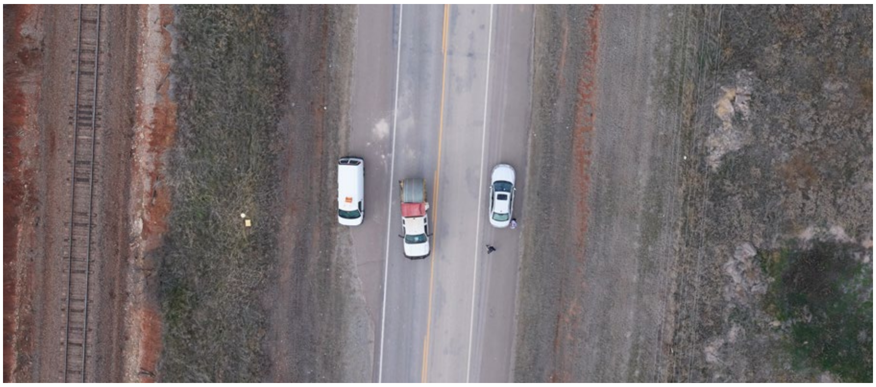
oblique imagery and a real-time weather probe. CLASS was mounted to the belly of a Bell helicopter and flown by the NV5 Geospatial team, as was the third solution, a traditional linear-mode Riegl VQ-480i sensor. **Table 1** provides a summary of the packages.

Flight parameters

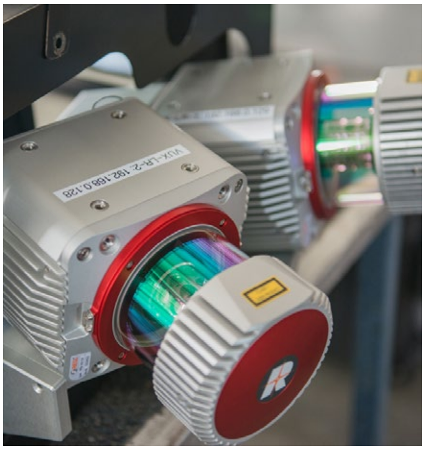
In developing the flight plans, the overarching goal was to develop point clouds with similar horizontal and vertical accuracies, allowing the point densities to vary between the sensors. These flight planning parameters were based on past experience, but lacked the detailed knowledge gained from this study. The results reported here will inform the planning of future projects.

While each of the three flights was independent of the other two in terms of planning and execution, certain factors were constant among the three, including:

- The same centrally located, high-accuracy GNSS base station was used for all trajectory post-processing, providing an ideal environment given the short baseline lengths
- The same software was used for trajectory processing and creation of the point clouds, given the line-up of all Riegl sensors and Applanix inertial navigation systems (INS)



These same vehicles are shown in the nadir RGB image captured simultaneously from the CLASS sensor solution



Two lidar sensors are integrated in the CLASS multi-sensor package, providing exceptional modeling of the bare earth and constructed environments

The point cloud provides exceptional detail of the roadway, above-ground utilities, lane markings, and adjacent railway. Note the three vehicles in the lower left of the image.

- The same high-accuracy ground targets were used in the calibration of all point clouds

Ground surveys

The tests depended significantly on the use of high-accuracy 3D calibration and blind check points on the ground, distributed throughout the project area. Quantum Spatial established the calibration points, whereas the ODOT surveying division met the demanding requirements for all the other points, using a mix of GNSS observations and differential leveling techniques to establish 419 3D locations from which to derive the research results. The points were as follows:

- 13 calibration points
- 15 hard-surface (asphalt) blind QA points
- 36 cross-section points on hard surfaces
- 344 cross-section points off pavement in varying land cover
- 24 additional blind QA points on and off hard surfaces

The number of blind points was large in order to provide a deep understanding of the performance of all platforms and sensors. The surveying methodology varied according to the type of point:

- Precision GNSS surveys with dual occupations, two independent base stations, and two very different times of the day, to ensure varying satellite constellations, were conducted for the 13 calibration and 15 hard-surface blind QA points
- Cross-sections set out throughout the project area using GNSS observations for the horizontal (XY) locations and differential leveling to establish the elevation of each of the 380 points

A GNSS occupation was located near the center of the project, providing the perfect base for post-processing the trajectories of all three flights

Precision GNSS surveys for the 24 additional blind QA points, following the standard testing procedures performed by ODOT on all aerial projects of this size.

Differential level runs between known control points and loop closures during cross-section surveys closed within 0.02 feet. The GNSS dual-occupation surveys were similarly accurate, with typical elevation differences for the dual occupations measured in the range 0.02-0.05 feet. The two elevations were averaged to give the published values.

Vertical accuracy assessment

In all, 419 blind points were established by ODOT. For the accuracy evaluation, elevations were interpolated at each of the surveyed XY locations in each of the three point clouds and compared to the field elevations. This allowed the tabulation of three differences for each blind QA location. Moreover, the elevations determined from each point cloud were then compared to those from the other two point clouds, allowing us to develop detailed accuracy statistics in six significant ways. The results were fascinating:

- The accuracies on hard surfaces (pavement) were better than expected, and very similar across all platforms
- The accuracy off pavement, in varying land cover, including bare earth, grass and tall weeds, and forested areas, met expectations but exhibited a bias (lidar points consistently higher than ground surveys), included two anomalies, and was lower than on pavement
- The point clouds were extremely consistent with each other, with no anomalies at any of the tested locations

Table 2 provides a summary of the accuracy results from the comparison of the lidar point clouds to ground surveyed check points. The two anomalies outside the paved areas were removed from these statistics.

Vertical differences between point cloud and blind QA point

The sample size was slightly smaller for the sUAS platform as the coverage was just less than that collected from the two rotary flights. This decreased coverage excluded a small number of the blind QA points.

The performance of the systems on hard surfaces was extremely impressive with a vertical root mean square error ($RMSE_{\Delta Z}$) of 0.04 feet. These results were normally distributed, as is expected on open, hard surfaces, giving a 95% confidence interval of 0.08 feet.

The two anomalies found when comparing the off-pavement points from the cross-section data with the values interpolated in the lidar point clouds were almost certainly a result of changes in the landscape itself. Almost four months passed from the airborne acquisition to the completion of the cross-sections, so there were several possible reasons for the changes. The two points varied by more than a foot in elevation when comparing cross-sections to lidar point clouds, but the lidar point clouds were very consistent with each other at these two locations: the differences ranged from 0.03 to 0.13 feet.

Elevations were determined at each of the 395 XY locations of the blind QA points in each of the independent point clouds determined from the three platforms, i.e. the calibration points and ODOT test points were not used for this evaluation. It was straightforward to compare each of the point clouds to the other two at these locations. A summary is shown in **Table 3**. The first row of

		Vertical differences (feet)			
Platform	Sample size	Average	Min	Max	RMSE
On pavement					
sUAS/VUX	46	0.00	-0.06	0.11	0.04
Rotary/CLASS	51	0.01	-0.03	0.12	0.03
Rotary/480i	51	0.02	-0.05	0.10	0.04
Off pavement					
sUAS/VUX	292	0.21	-0.08	0.57	0.19
Rotary/CLASS	344	0.18	-0.12	0.68	0.22
Rotary/480i	344	0.18	-0.11	0.57	0.21

Table 2

Differential level runs were used to establish the elevations for each of the 380 cross-section points

Five missions were required to cover the project area with a Riegl VUX-1 lidar sensor on the sUAS platform

data in the table represents the point cloud created from the CLASS sensor subtracted from the point cloud from the 480i sensor.

Point cloud to point cloud statistics

The data had very little bias, the minimum and maximum vertical differences were quite small, and the $RMSE_{\Delta Z}$ values of the datasets were extremely strong. There were no anomalies in the data in this large sample.

Finally, ODOT completed additional checks outside the scope of this research project. These tests were in line with what they typically perform for any aerial project before it is used in design engineering. They collected 24 additional points to determine the accuracy of the submitted data. These points covered the entire project area, on and off the paved surfaces. Their tests provided a mean difference of 0.10 feet and an $RMSE_{\Delta Z}$ of 0.13 feet. When the varying ground cover of these 24 points is taken into account, these results perfectly mirrored the results of the overall research.

Platform	Sample size	Vertical differences (feet)			
		Average	Min	Max	RMSE
On pavement					
480i - CLASS	51	-0.01	-0.07	0.10	0.03
sUAS - CLASS	46	-0.04	-0.07	0.06	0.04
sUAS - 480i	46	-0.04	-0.09	0.03	0.05
Off pavement					
480i - CLASS	344	0.00	-0.30	0.24	0.06
sUAS - CLASS	292	-0.04	-0.22	0.10	0.06
sUAS - 480i	292	0.00	-0.38	0.15	0.06

Table 3

Platform	Sensor	Sample size	Horizontal difference (feet)				
			Min ΔX	Max ΔX	Min ΔY	Max ΔY	CE 95
sUAS	Riegl VUX-1	9	-0.01	0.13	-0.02	0.11	0.10
Rotary	CLASS - 2 x Riegl VUX-LR	12	-0.09	0.26	-0.11	0.11	0.18
Rotary	Riegl VQ-480i	12	-0.09	0.07	-0.07	0.07	0.10

Table 4

Horizontal accuracy assessment

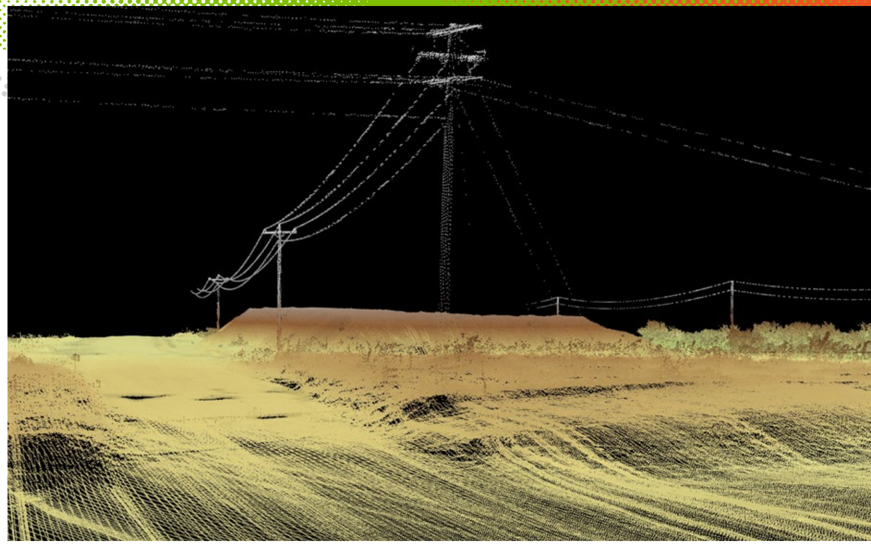
We completed a less rigorous assessment of the horizontal accuracy of the three point clouds in two different ways. The first was simply overlaying the lidar intensity images on the digital orthophotos that were produced for this mapping project. The orthophotos served as another independent source of data, with their own trajectories and calibration used in production. These images were produced at a ground sample distance (GSD) of 0.25 feet. There was perfect alignment at the pixel level, as seen in the image on the next page.

The second assessment was completed by reading the location of each of the targets in the lidar intensity images. The targets were crosses with legs 6 inches wide by 2 feet long. Precisely determining the center of the target was challenging given the resolution of the intensity images. Also note that the sample size was less than ideal for a project of this size. Even so, the results were revealing, as shown in the **Table 4**.

Estimate of horizontal accuracy from intensity images

Much like our evaluation of the vertical accuracy, the results for the horizontal accuracy exceeded expectations. The last column in **Table 4** lists the circular errors at 95% confidence, i.e. 95% of well-defined points on the ground should fall within a circle of that radius in the point cloud.

Treat these numbers with care, however, when compared to the vertical accuracy evaluation. They are directionally correct and provide confidence in the data, but are based on much less rigorous analysis. The salient point is that the data exhibits extreme accuracy and there is no statistically significant difference between any of the point clouds.



Although the main focus of this test was related to transportation, the results have broad application on many types of projects, including utilities

Perfect alignment between the lidar intensity image (left) and the digital orthophoto (right) with no detectable misalignment

Value to the professional community

The value of this study to the professional and client community is significant. As far as we know, this is the first large-scale evaluation of multiple current-generation lidar platforms. The results point to the impressive accuracy of the airborne systems flown from altitudes of 250 to 600 feet above ground. Indeed, the horizontal and vertical accuracies achieved in all three point clouds are similar to that expected from a mobile collection on the ground.

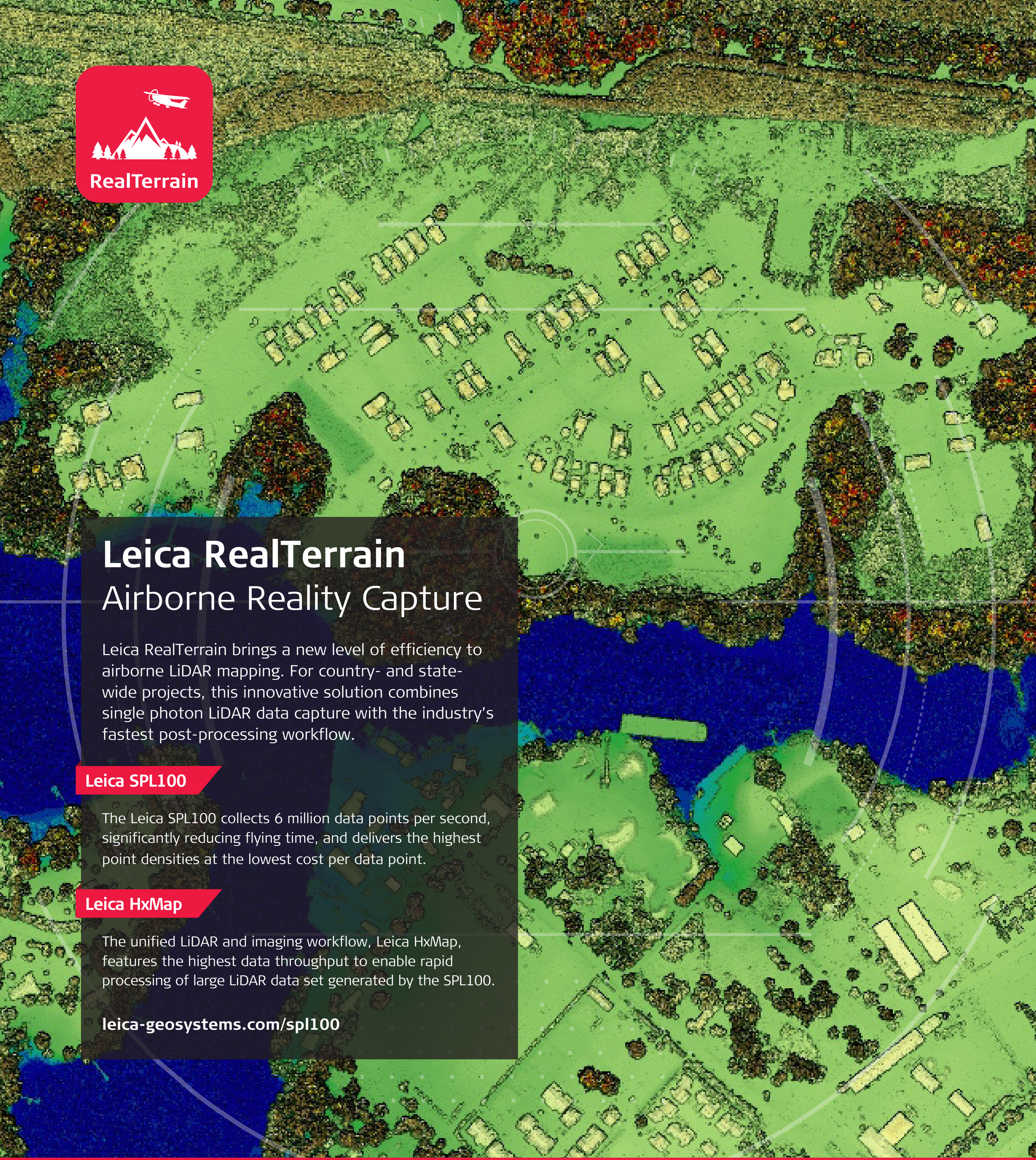
Moreover, the testing provides considerable information about the performance of the systems on paved surfaces compared to areas of varying land cover, including bare earth, tall grasses and weeds, and forested areas.

While this investigation was carried out specifically for a roadway project, the results are useful across many project types, including utility, asset inventory, airports, rail, and general engineering design.

Finally, a word of caution is needed. These results represent a single, two-mile-long project area. While the point clouds were highly accurate and perfectly consistent between the three platforms, more work is needed before drawing definitive conclusions. We plan to carry out similar projects over the coming year and share the results with the professional community.

Mark Meade, PE, PLS, CP is a senior vice president at NV5 Geospatial. He is licensed as a professional engineer and professional land surveyor and is recognized nationally as a certified photogrammetrist. He has been working in the geospatial profession for the last 26 years.

Kyle King, PLS is the chief of surveys for Oklahoma Department of Transportation. He is a professional land surveyor with over 38 years of experience with the Department. Kyle is an active member of his State's society of land surveyors and is also a member of the Transportation Research Board's Geospatial Data Acquisition Technologies Committee.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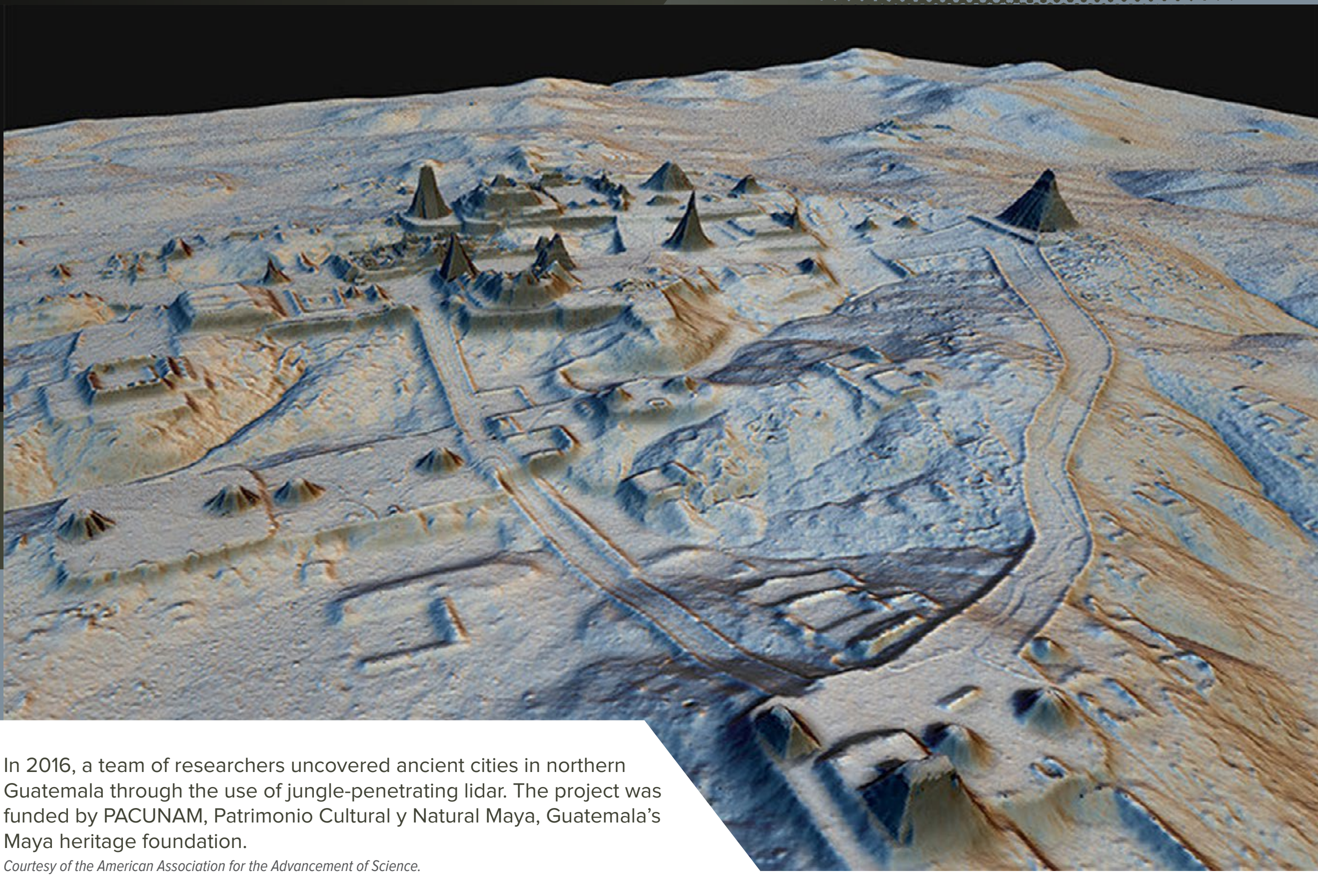


In 2016, a team of researchers uncovered ancient cities in northern Guatemala through the use of jungle-penetrating lidar. The project was funded by PACUNAM, Patrimonio Cultural y Natural Maya, Guatemala's Maya heritage foundation.
Courtesy of the American Association for the Advancement of Science.

Lidar Shows Mayan Civilization in a New Light

Archaeologists solve some mysteries of the Maya

BY STEVE **SNOW**

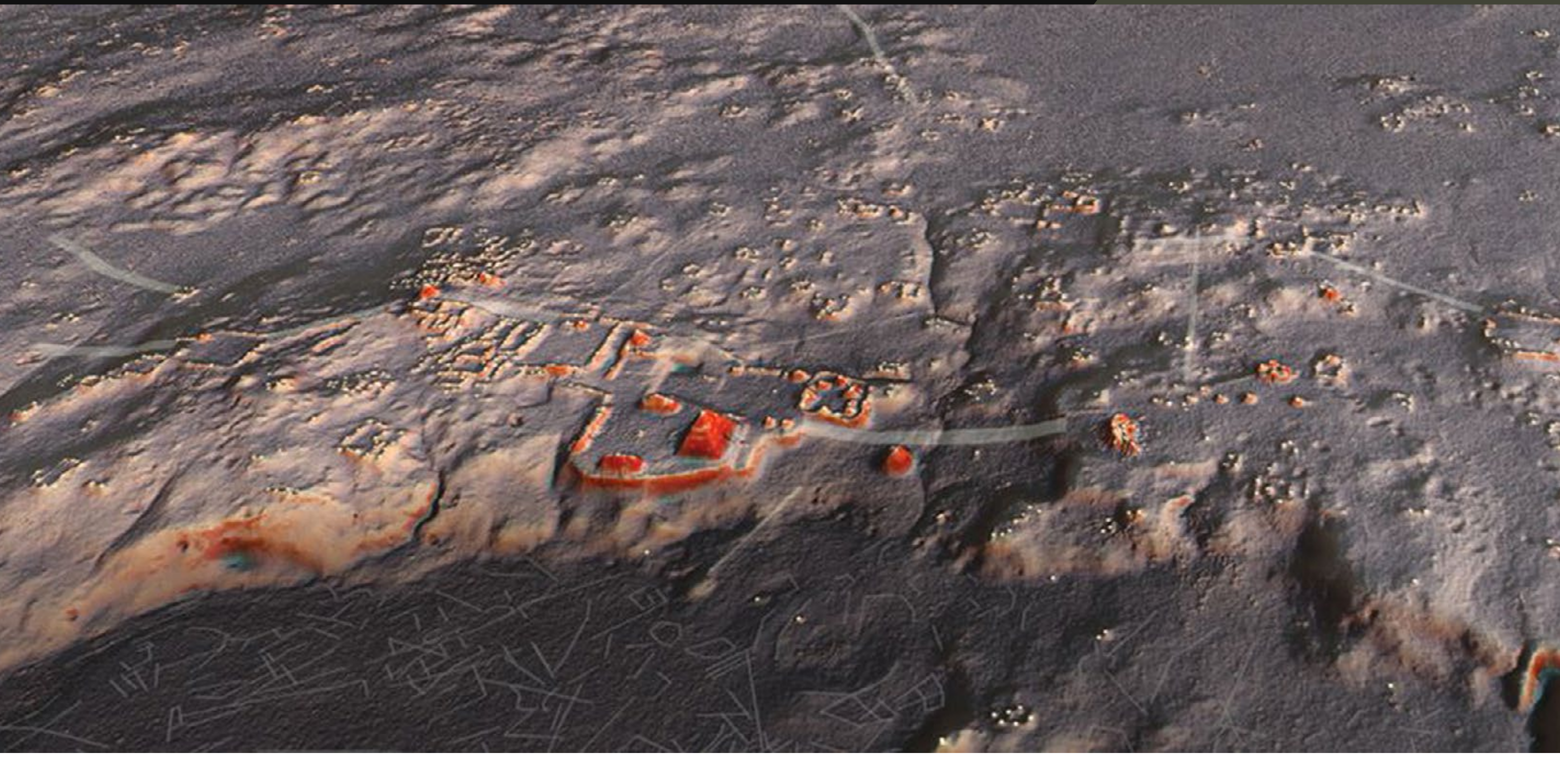
Bordered on the north and west by Mexico and on the east by Belize, the lush forests of Guatemala's Petén region have long been recognized as a treasure trove of archaeological discovery. The area is home to the Maya Biosphere Reserve, where archaeologists have spent decades studying remnants of ancient Maya civilization. A recent discovery overturned everything they thought they knew when more than 61,000 Maya structures were detected beneath a thick green veil of trees and vines.

Astonished researchers found not just a few new sites, but thousands of Maya structures revealed by lidar sensors and displayed on GIS maps. Lidar data was collected across the region in a day, and it took the team several months to produce a comprehensive 3D map that unlocked a whole new view of the area's past.

Marcello Canuto, director of the Middle American Research Institute and professor of anthropology at Tulane University, was part of the research team. He recalls his surprise when he viewed the lidar imagery of his favorite jogging path through the ancient Maya site where he conducts research.

"Part of my trail ran up, on, and along an elevated area on the site," Canuto said. "I saw the lidar, I was like, oh my God, that's a Maya road. I'd been jogging on this thing for several years and I had never recognized it."

This is a republication of an article published by Esri on 17 November 2020 at https://www.esri.com/about/newsroom/blog/lidar-images-reveal-mayan-civilization/. *LIDAR Magazine* is grateful to author Steve Snow.



A different view of the terrain shown in the previous illustration.

A new way to look at an ancient civilization

Viewing the lidar data, Canuto and his colleagues were confronted with a vast amount of raw architectural and settlement data and a host of compelling implications about the nature of Maya civilization. The lidar data, rich with thousands of newly discovered temples, homes, roads and more, clearly demonstrated a capacity to accommodate millions of people. Previous research had suggested much lower numbers. The revised estimation of local Maya population size in ancient times also shifted other assumptions about a tropical society with relatively small political centers.

"What does the old model imply? It implies nonurban. It implies low population. It implies a low degree of sociopolitical complexity and integration," Canuto said. "Now we can say, that's implausible, given the data of millions of Maya in this area."

Among many other revelations from lidar data, the team was surprised by the scale of modification to the landscape for advanced farming, a complex system of raised roads and causeways enabling travel between urban centers, reservoirs, irrigation, and terracing indicative of a civilization accustomed to adapting to extremes of a tropical climate.

"We're able to find the big sites, and then all the settlements," Canuto said. "All the smaller houses, all the construction to create a society and an infrastructure that was built to improve their lives, to render the landscape more productive or less dangerous. That's the part that is incredibly exciting for me."

Learning more from lidar

Lidar can be used to generate precise, 3D information about the surface characteristics of the terrain and the vegetation that covers it. GIS maps of lidar collected in the Petén region led to the discovery of thousands of new features at an unprecedented pace. However, the speed with which lidar scans an archaeological site is only one of the ways it revolutionizes the field. Lidar also provides a comprehensive representation of infrastructure, both small and large—an especially useful insight for areas with heavy plant cover.

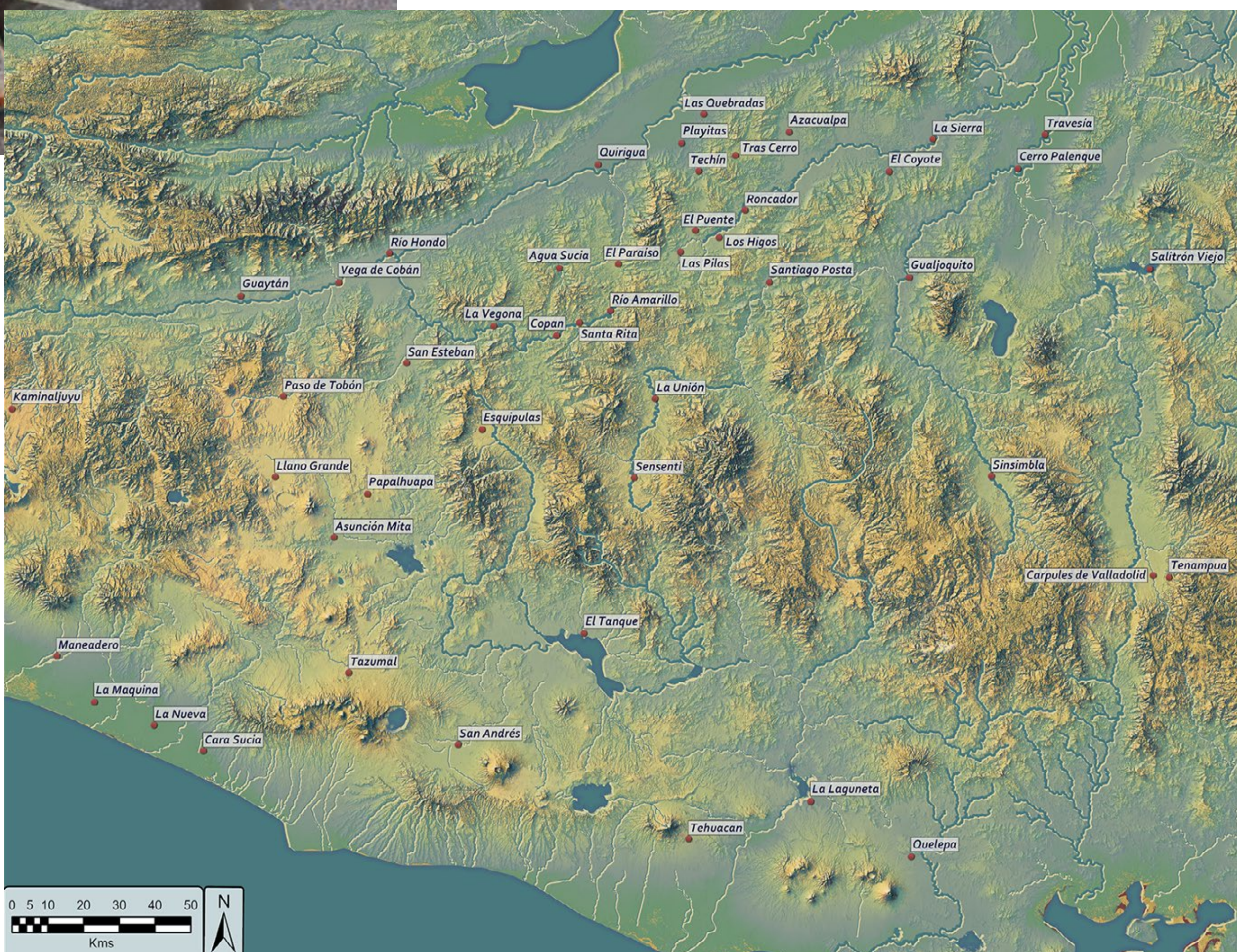
"There's a real blind spot in the jungle," said Canuto. "If I walk in front of a big temple that's 20 meters high, I'll see it… but what you can't figure are monumental things over a prolonged space or distance, like a road."

Lidar data collected in Petén may also help researchers understand and preserve Guatemalan heritage beyond the scope of archaeological research. While the technology was gathering details of ancient built structures, it was also amassing a vast store of data on the natural environment.

"We're using five percent of all the lidar data. The other 95 percent is all the vegetation," Canuto said. "As archaeologists, we rarely look at the rest of that data. But there's an amazing amount of information about the landscape that can also be used. Lidar captures a digital census of forest volume and forest type."

Even within the scope of archaeology, lidar data can be helpful beyond its initial use. The same year Canuto and his colleagues were learning the true depths of Maya development in Guatemala, archaeologist Takeshi Inomata from the University of Arizona was investigating a site in Mexico using lidar data freely available online.

"Takeshi is excavating in Veracruz and Tabasco in Mexico at this massive site that was hiding in plain sight," Canuto said. "It was so big and earthen in nature, that it just looked like a big mound. It's of such massive size that an archaeologist



Marcello Canuto created this map to display the spread of found Mayan sites.

would never say, 'That's a building.' But when you see the lidar, it's obvious."

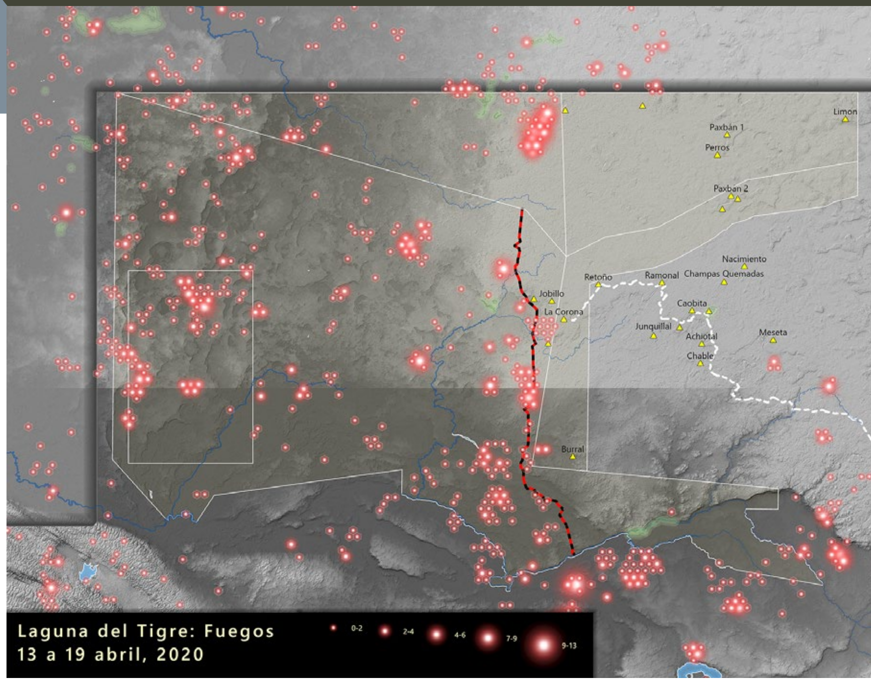
Shedding light on the distant past

Traditional archaeological study relies entirely on what researchers can see and find, with an ongoing goal of mapping an accurate landscape-scale view of every structure.

Until recent years, the process of locating and investigating sites for archaeological research had changed little. Most projects began with either a ground-level physical survey, in which researchers would flag any features or objects that indicated further investigation; or with a visual bird's-eye survey, by plane or drone. Neither approach was capable of penetrating the dense forest canopies typical of Mayan settlements.

Lidar had been used by archeologists since the 1970s to map European castles and structures, but always in open areas and fields. It wasn't until 2009 that lidar advanced enough to prove useful in jungle and forest settings. The landmark 2009 Caracol survey in Belize successfully penetrated heavy tree cover, revealing dozens of previously unknown structures and causeways and thousands of agricultural terraces in a fraction of the time a manual survey would have taken.

The success of Caracol inspired researchers at the Foundation for Maya Cultural and Natural Heritage (PACUNAM), a Guatemalan organization focused on protecting the country's natural and cultural heritage, to oversee the breakthrough lidar research in Petén. PACUNAM worked with the National Center for Airborne Laser Mapping at the University of Houston (NCALM) and NCALM aircraft carried cutting-edge lidar mapping equipment to create a comprehensive three-dimensional landscape of the Maya Biosphere Reserve.



This map by Marcello Canuto displays widespread fires that took place in northwest Guatemala in April 2020.

For research teams, GIS is integral to the process of recognizing and categorizing structural sites within lidar data. Archaeologists use GIS collection apps and interactive maps to compare various visualizations of the landscape, such as hillshading, relief maps and bonemaps, and identify features of interest. After adding map coordinates and other identification for each point, teams create a map to guide researchers to find and ground-truth the lidar data. The 3D view provided by lidar accelerates the process.

"An archaeological project might take 10 years to excavate, investigate, or map a site… you might get 20 or 30 square kilometers of mapping done over a period of decade if you're really good at it," Canuto said. "With lidar, suddenly you get precise data over 300 square kilometers within six months. It's really quite amazing."

Steve Snow is an industry specialist for mapping, statistics and imagery at Esri. He has more than 18 years of experience working in GIS, mapping, charting, and remote sensing. Prior to joining Esri, he was a commissioned engineer officer in the US Army. He was also a Corps officer with the National Oceanic and Atmospheric Administration (NOAA), focusing on remote sensing, surveying, and charting for the US National Geodetic Survey Remote Sensing Division and NOAA's Office of Marine and Aviation Services. A longtime GIS and remote sensing professional, Snow focuses on applying remote sensing capabilities to solve user mapping challenges with the ArcGIS platform.

OGC and its Point Cloud Domain Working Group

Geospatial standards experts embrace lidar

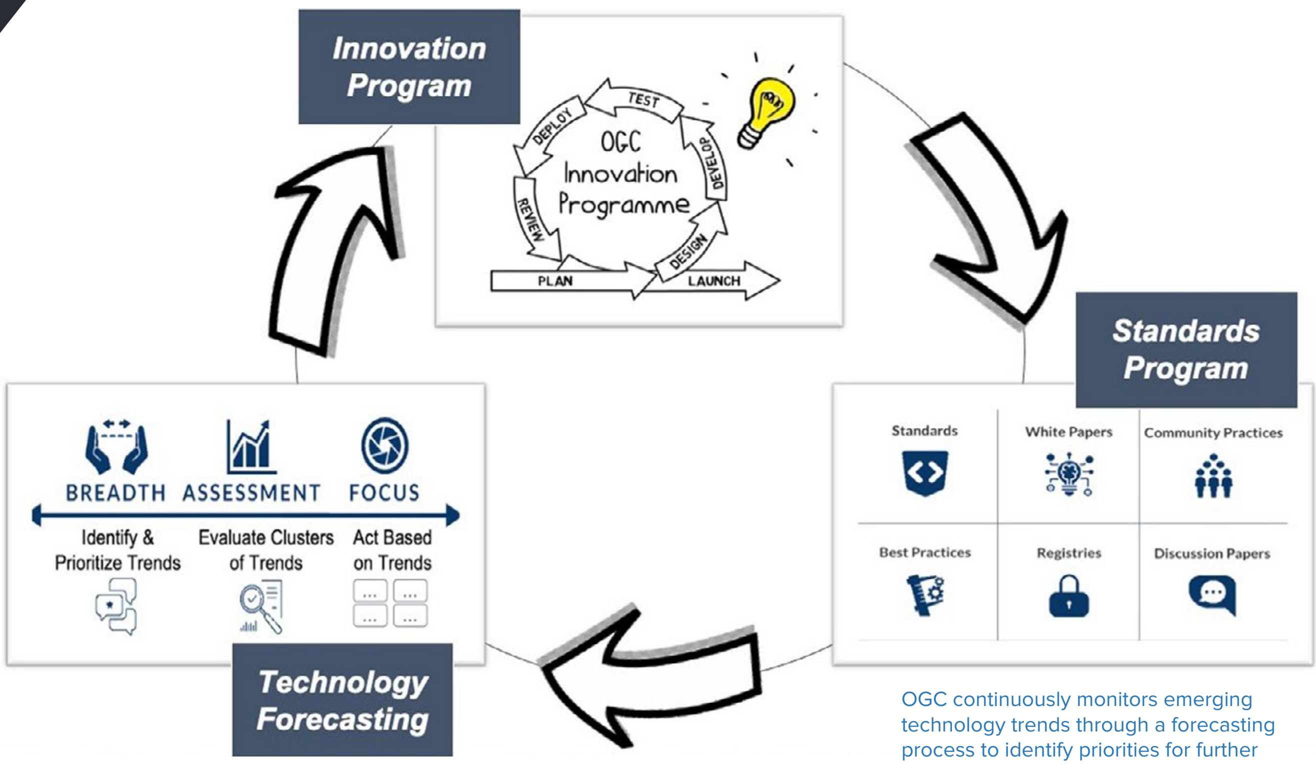
Lidar data is used to describe the real world or something existing at a location in the real world. The collected lidar point clouds are referenced to the real world and must often be considered in the context of other data used to represent features observed by other means. This means that lidar point clouds must be interoperable in a geospatial context with other information. Making this happen is the job of Open Geospatial Consortium (OGC) standards and innovation activities.

Founded in 1994, OGC is an international consortium of more than 500 businesses, government agencies, research organizations, and universities driven to make geospatial (location) information and services FAIR—Findable, Accessible, Interoperable, and Reusable. OGC's member-driven consensus process creates royalty-free, publicly available, open geospatial standards[1]. OGC operates a Standards Program to identify requirements for standardization and to publish resources such as Best Practices to describe the use of standards in real-world cases, user guides, developer resources, and content registries to aid in delivering interoperability solutions.

1 https://www.ogc.org/docs/is

OGC is a worldwide community committed to improving access to geospatial information. OGC serves as a trusted forum for discussion and development of interoperability solutions and free and open standards.

BY SCOTT **SIMMONS** & STAN **TILLMAN**



OGC continuously monitors emerging technology trends through a forecasting process to identify priorities for further investigation in the OGC Innovation Program as well as for consideration in standardization. The Innovation Program operates as a lab to incubate new standards topics as well as to test interoperability solutions that lead to improved standards.

Closely linked with this standard-development process is the OGC Innovation Program, a forum for OGC members to solve the latest and hardest geospatial challenges via a collaborative and agile process. OGC members (sponsors and technology implementers) come together to solve problems, produce prototypes, develop demonstrations, provide best practices, and advance the future of standards. Influencing both programs is a Technology Forecasting process led by OGC's CTO with engagement and review from OGC membership.

Within OGC, there are many groups that span a wide spectrum of domains. Standards Working Groups (SWGs) build and advance standards and supporting resources. Domain Working Groups (DWGs) serve as forums for discussions on topics around technical or practice areas that may lead to eventual standardization. In early 2015, however, a question was raised asking where point clouds fit into the OGC ecosystem. After discussion, it was clear that there was a need for a dedicated forum for debate regarding point-cloud data. In June 2015, therefore, OGC membership formed a Point Cloud Domain Working Group to discuss use cases, requirements, and capabilities for the collection, storage, and dissemination of point-cloud data from any source. This DWG was motivated by the fast-growing popularity and use of point-cloud technology. Naturally, lidar is perhaps the most abundant source of the data. This article serves to highlight the work to date of the DWG and identify opportunities to improve the lidar business through the smart application of standards and consensus.

OGC standards in action

OGC standards enable the power of location. The majority of databases and geospatial specifications rely upon the underlying model of OGC Simple Features standard to store vector data. Standards such as the Web Map Service (WMS) and OGC API—Features allow for dissemination of information in a consistent way to web-connected users. Other standards, such as the Geography Markup Language (GML) and Keyhole Markup Language (KML), provide a means to exchange geospatial data.

OGC standards are built to be interoperable such that data can be explored and disseminated in the manner best addressing a user's needs. It is paramount that the information be discoverable and predictably made available for view or further analysis. In assessing the variety of point-cloud encoding standards and specifications, OGC members realized that there were gaps in putting together a fully interoperable value chain from data collection through management to derived products.

The goals of the Point Cloud DWG

Before the DWG could begin its work, it was important to define the mission and goals to guide future activities. The DWG members arrived at a mission to broaden the understanding of point-cloud data interoperability requirements and use cases and to help drive activities to improve interoperability in the community.

As part of its charter, the DWG set forth the following goals to help establish the direction of its activities.

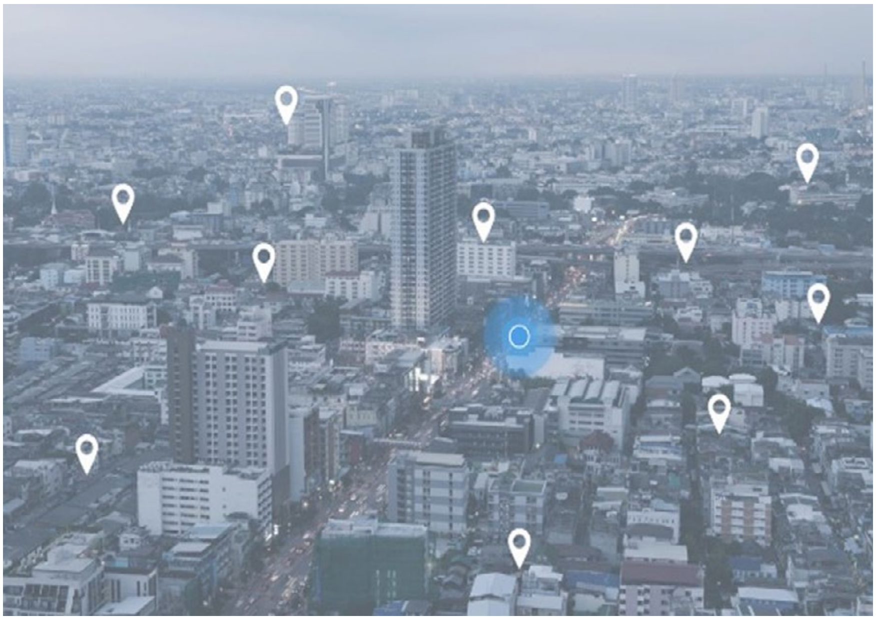
1. Understand implementation barriers for point-cloud communities and document those barriers in a format that can guide future technology design.
2. Identify interfaces and information encodings that complement the existing OGC standards but are directly tailored to the requirements discovered in understanding the needs of the point-cloud user community.
3. Promote the development of OGC Best Practices and standards to meet the point-cloud domain objectives. Candidate standards may come from external, market-established standards or from anticipatory standards developed in OGC initiatives.
4. Efforts should focus on working point-cloud issues and problems that result in a net gain for the community. In other words, efforts should help create interoperability without placing hurdles in front of the amazing innovation happening in the point-cloud community.
5. Define the supporting infrastructure for the community to achieve these goals.

Thus the DWG would serve as: a forum within OGC for point-based data; to present, refine and focus interoperability-related point-cloud issues to the OGC membership; and to serve where appropriate as a liaison to other industry, government, research, and standards organizations active within the point-cloud domain.

Work so far

Because point clouds are being used in so many domains and use cases, the DWG was quickly inundated with ideas and potential goals for the group. So the chairs of the DWG, Jan Boehm of University College London, Stan Tillman of Hexagon, and Peter van Oosterom of Delft University of Technology, decided to put out a survey to the entire community (both internal and external to OGC) to better understand how point clouds were being used. The survey received an encouraging 163 responses, each from a different organization. This was a very enlightening exercise, giving the DWG a variety of information including sources, formats, use cases, application areas, storage, attribution, data volumes, and tools. But, most importantly, the DWG was able to learn about the interoperability challenges facing the community. The following highlights emerged:

1. Interoperability is a challenge at all stages of handling of point-cloud data;
2. The biggest challenges come from analysis, dissemination, and acquisition; and



3. The biggest concern in the community centers around web service protocols, data models, and file formats/encodings.

After discussing results of the survey during sessions at the OGC Technical Committee meetings, it became clear that members did not want to invent a new encoding, but rather provide Best Practices for the use of existing encodings and perhaps endorsement of select encodings. It was also decided that we did not have enough knowledge to begin a service standard—the fear was that creating one too early would hinder innovation.

In response to this initial investigation, two activities began to form:

1. Community Standards are OGC Member-endorsed standards that were developed and are managed external to OGC. For instance, OpenFlight is a 3D modeling specification originally developed by a commercial entity (Presagis), but which has been made available on a free basis to anyone and approved by OGC Members as being an important part of the overall geospatial standards baseline. There are three highly relevant specifications that have been adopted as OGC Community Standards.
   a. LAS 1.4 is the fourth revision of the point-cloud binary format for laser-scanned data (LASer). Although ASPRS still maintains ownership of the LAS specification, OGC has adopted it as a recommended point-cloud encoding.
   b. 3D Tiles is a specification from Cesium, Inc. containing a data structure organized in support of streaming and rendering 3D geospatial content, including textures, solids, triangles, and point clouds.
   c. Esri I3S is for streaming large 3D datasets and is designed for performance and scalability. I3S supports 3D geospatial content and the requisite coordinate reference systems and height models, in conjunction with a rich set of layer types. The point-cloud portion of I3S represents a static tile set with data organized in separate files by attribute type. It is expected to be consumed by web clients over the internet. It is suitable to feed a browser-based renderer or data processing software, and it can be configured to store data in a lossless configuration.
2. Vendor Summits allow the DWG to host demonstrations by vendors of their current point-cloud technologies centered around a given theme. Typically, OGC Working Groups do not encourage promotion of product materials. In this case, however, it is important to understand the capabilities that already exist in the community. These Summits have included private companies, open-source groups, government agencies, and academia. To date, the DWG has hosted two such summits that covered the themes of streaming point clouds and visualization of point clouds.

What's next?

Where is the DWG going next? We plan to continue to host the Vendor Summits around themes such as storage, as well as keeping an eye out for additional proposals for Community Standards.

We are also beginning to learn enough from the community to propose a standard web service for the exchange of point-cloud data. We have seen that organizations like to control the content, format, and organization of the data. But perhaps a web service could be defined to standardize the delivery mechanism of the point-cloud data. This would be very similar to how traditional OGC services have been defined. The server can organize and store the data in any desired format while supporting one or more transfer encodings. Then the client would request the desired encoding based on what is available from the service. Obviously, there are many more details, but the next step would be to define a set of principles and goals for such a service and write a charter describing the creation of a new Standards Working Group to create the standard.

Conclusion

Whether it be charting shipwrecks on the ocean floor, mapping underground mines and caves, or enabling automated transportation systems to avoid obstacles, the use of point clouds is going to increase at a very high rate. Thus the Point Cloud DWG is working to harness the excitement, encourage the innovation, and propose the standardization for all of the systems to work in harmony.

Scott Simmons is Chief Operations Officer, and Executive Director, Standards Program at OGC. He works from home in Fort Collins, Colorado. He joined OGC in 2015 after a number of positions in the private sector and academia. Scott has BS and MS degrees in geology from the University of Texas at Austin and Southern Methodist University.

Stan Tillman is an executive manager—technical at Hexagon Geospatial in Huntsville, Alabama and is one of the firm's representatives to OGC. After BS and MS degrees in computer science from the University of Alabama in Huntsville, he joined Intergraph, now part of Hexagon, in 1989.

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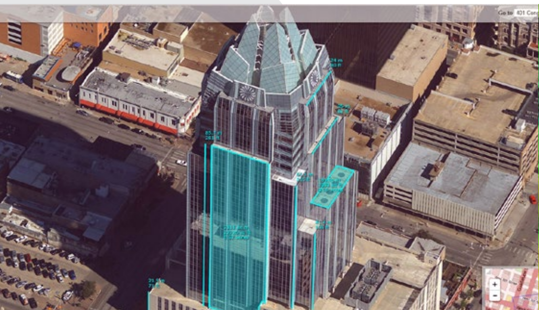
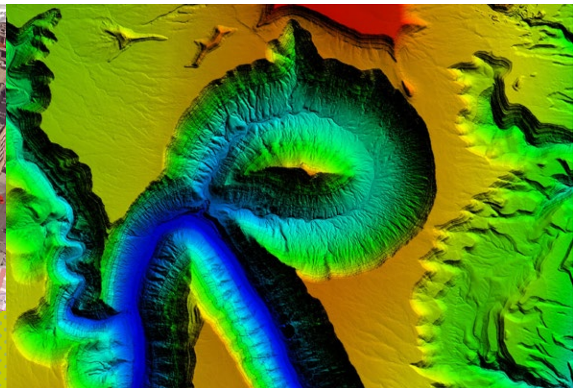
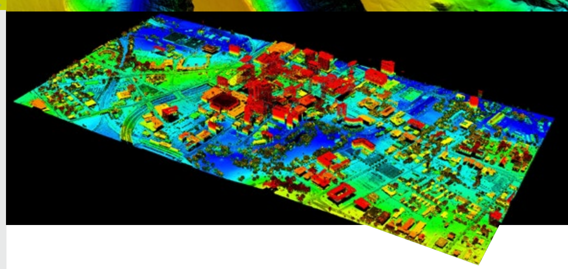
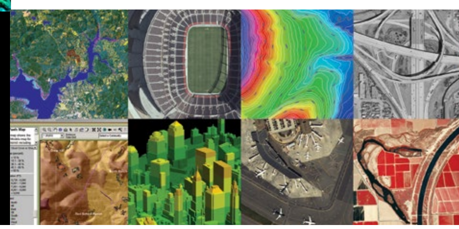




COMPANY PROFILE

Sanborn is an innovator in the modern geospatial industry, delivering state-of-the-art mapping, visualization and 3D solutions for customers worldwide. The firm operates a fleet of aircraft located strategically across the United States. Embracing cutting-edge technology, Sanborn specializes in oblique aerial imagery, aerial and mobile LiDAR, aerial orthophotography, 3D modeling and visualization software and services, SPIN indoor mapping , unmanned aircraft system (UAS) sales, services and image processing, and a host of geospatial software products.





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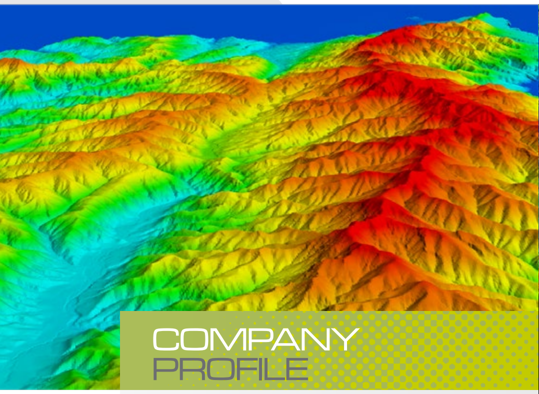

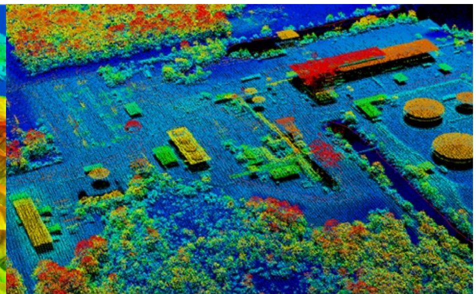

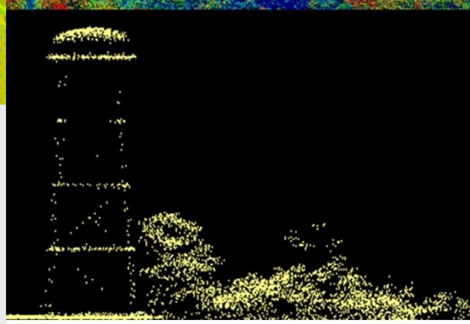

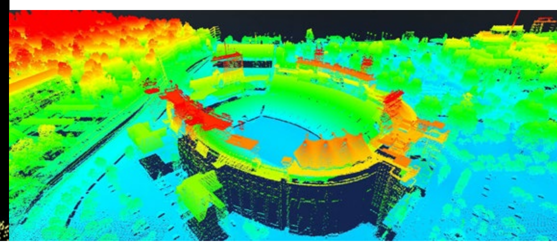

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Dewberry's geospatial and technology services team includes many of the most recognized and respected industry experts and thought leaders. The firm's team creates, analyzes, and builds tools to share geospatial data, as well as help clients integrate these tools into their daily lives. By fusing multiple data sets together, Dewberry provides clients with easy-to-use tools that simplify the use of information to allow for more effective and efficient decision making.

The firm's solid performance processes in geospatial technologies and corporate IT services led to it being appraised at Level 3 of the CMMI Institute's Capability Maturity Model Integration (CMMI) in Services and Development Models. In 2020, Dewberry also received the International Lidar Mapping Forum (ILMF) and Lidar Magazine's 2020 Outstanding Enterprise Achievement in Lidar award.

Dewberry works seamlessly to provide geospatial mapping and technology services across various market segments. With more than 30 years' experience, the firm is dedicated to understanding and applying the latest tools, trends, and technologies in support of its clients' program goals and objectives. Dewberry employs the latest GIS software and database platforms, including the full suite of ESRI products, and it was awarded the 2019 ESRI partner award for maximizing ArcGIS in service offerings. The firm's products and services include application, web, and cloud-based development; system integration; database design mapping; data fusion; and mobile solutions.

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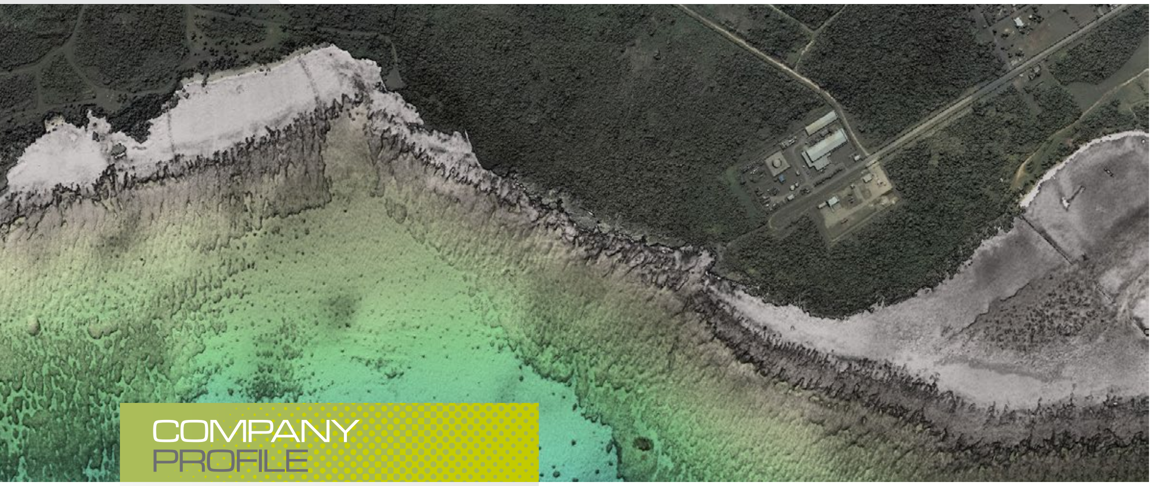

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- GIS

The coast and near shore of Tinian, one of the three principal islands of the Commonwealth of the Northern Mariana Islands, is captured in this topo-bathy image.
Image courtesy of NOAA and USGS

COMPANY PROFILE

Woolpert is the premier architecture, engineering, geospatial (AEG) and strategic consulting firm. We leverage the expertise of our global staff to elevate projects specific to each industry, while collaborating across markets to develop and apply the most effective solutions for public, private and government clients worldwide. Woolpert was founded in 1911 and has more than 1,000 employees working out of 40 offices in three countries. The firm has developed rich and strategic partnerships with key industry leaders to amplify and advance all AEG technologies. Woolpert has been named a Great Place to Work for five years and actively nurtures a culture of growth, inclusion, diversity and respect. For more information on Woolpert's services, projects, mission and history, visit Woolpert.com.

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Woolpert Augmenting Topo-Bathy Lidar Capabilities

Woolpert has long been known for its aerial and terrestrial lidar and remote sensing applications and capabilities. Recently, the firm assembled an agile team of hydrographers, surveyors and GIS professionals who use state-of-the-art technologies to create and advance seamless topo-bathy products in the coastal zone and inland riverine environments around the world.

Accurate bathymetric data is crucial for safe navigation and decision-making. Government entities, engineers and coastal managers rely on bathymetric mapping for accurate snapshots of the terrain below the water's surface for coastal mapping and charting, coastal resilience and management, and disaster response.

Led by Woolpert Vice President and Chief Hydrographer Carol Lockhart, Woolpert's maritime team generates everything from chart data inputs and classified point clouds to digital elevation models and identified feature classes. These support geospatial applications like coastal and riverine engineering and resilience, critical infrastructure design and assessment, habitat modeling, nautical charting and regional sediment management.

Woolpert collects bathymetric and hydrographic data using vessel-based sonar systems, manned aircraft, unmanned aircraft and satellite systems, utilizing its in-house fleet of aircraft, boats, sensors and survey platforms. The firm also leverages its network of trusted local providers and its relationships with key architecture, engineering and geospatial technology partners worldwide to provide optimal solutions to each client and every project.


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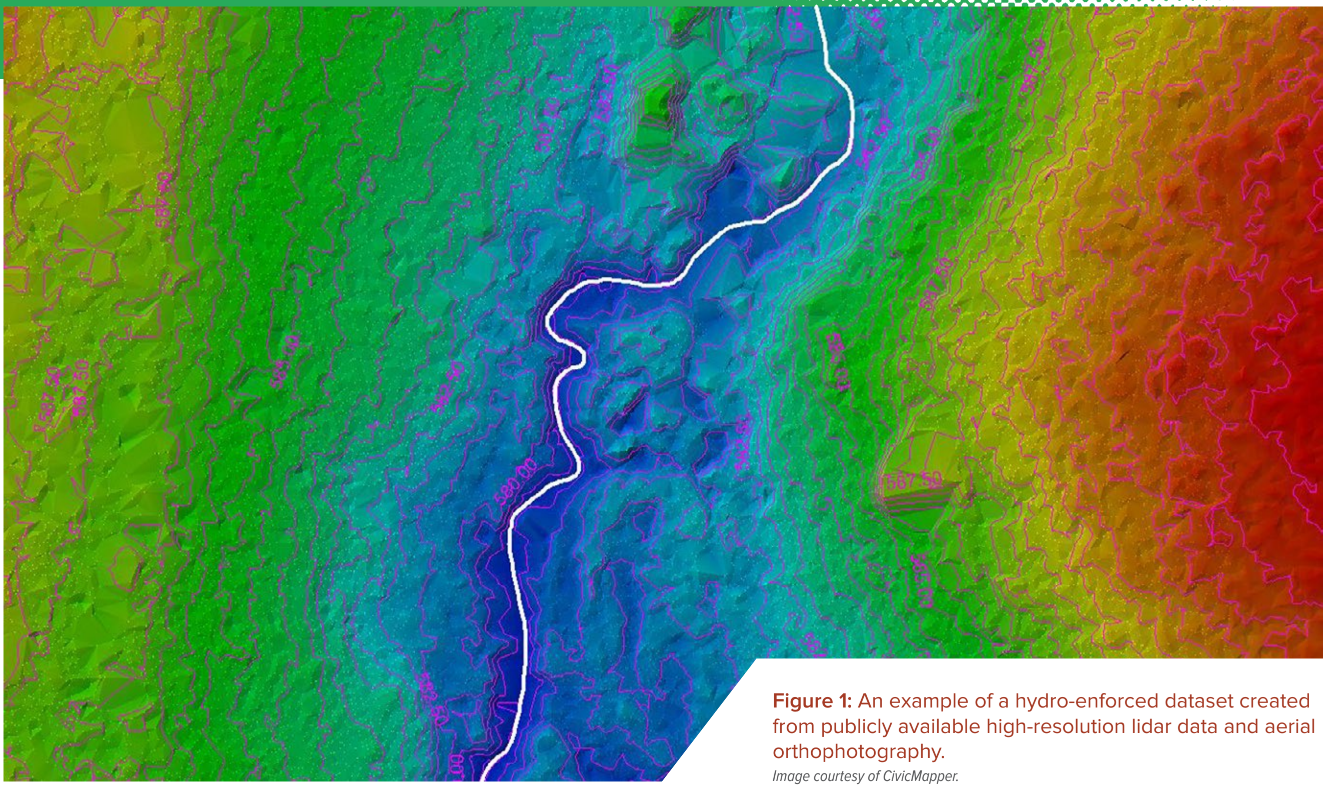

Figure 1: An example of a hydro-enforced dataset created from publicly available high-resolution lidar data and aerial orthophotography.
Image courtesy of CivicMapper.

Stormwater Management with Off-The-Shelf Lidar

Cost-effective hydrologic basin characterization using public lidar elevation data

Across the United States, state and local government agencies are funding the collection of lidar data to create high-resolution, high-accuracy digital elevation models. The availability of these and other open geospatial data has enabled workers to derive detailed information about terrain and land cover that can be used to inform new hydrologic models for use in stormwater management. The availability of quality level 2 (QL2) lidar data and corresponding high-resolution digital orthophotographs provides an excellent starting point for creating hydrologic surfaces used for characterizing hydrologic basins in urban environments (**Figure 1**).

Understanding hydrologic systems and the capacities of stormwater infrastructure is more important than ever. More frequent and severe storm events in the US are predicted to increase over the 21st century (Wuebbles *et al*, 2017),

BY EMILY **MERCURIO** & SRINI **DHARMAPURI**

causing additional strain on the nation's aging stormwater infrastructure. In the eastern United States, dozens of cities received record rainfall in 2018 and 2019, and winter rainfall records were broken across the southeastern US in 2020. More stormwater, combined with an estimated $105 billion investment gap through 2025 for water and wastewater infrastructure (ASCE, 2016), creates an extremely challenging problem for areas that are already suffering from the effects of a changing climate. It is therefore critical that these increasingly severe wet-weather events are better understood by local governments and regional authorities so that the disastrous effects of these storms on our communities can be mitigated (Mercurio, 2020). Though it is only part of the solution, the use of high-quality lidar data to create a digital twin of terrain provides a basis for modeling the accumulation and flow of water within a catchment basin.

The USGS 3DEP program

Development of hydro-processed digital elevation data for a whole state can be a lengthy process complicated by the timing of new lidar collections and the limited resources of available staff. To respond to the growing need for high-resolution elevation data, the USGS 3D Elevation Program (3DEP) was formed in 2014 for the purpose of acquiring a nationwide high-resolution elevation dataset by 2023. Under 3DEP, lidar data is being collected for many parts of the country, in most cases at QL2. The data will be available for use through public repositories. At the minimum, the user will have access to classified LAS files and USGS-based hydro breaklines. Since the data go through a QA/QC process, adjacent areas will be produced to the same data quality standards, allowing for the expansion of models to regional scales.

By May 2020, data from 3DEP was available or in preparation for more than 60% of the US, with many additional lidar collections planned (USGS, 2020a). Publicly available lidar, other high-resolution elevation data, and imagery datasets facilitate the understanding of hydrologic systems and inspire innovation in the earth sciences. The use of this data in hydrologic models and basin characterizations helps communities become more resilient to the impact of climate change, and provides some of the most powerful tools that professionals can use to quantify the impacts of stormwater on aging infrastructure. Smarter decisions in stormwater management can be made and the destructive toll from flooding caused by more frequent and severe storm events can be limited. The return on investment of the 3DEP program has been estimated at 5:1 (USGS, 2020b), with the potential to provide more than $690 million annually in new benefits to government entities, the private sector, and citizens.

> “The use of the lidar data in hydrologic models and basin characterizations helps communities become more resilient to the impact of climate change and provides some of the most powerful tools that professionals can use to quantify the impacts of storm water on aging infrastructure.”

Improving hydrographic mapping with lidar

Publications from the USGS and books such as *The DEM Users Manual* (Maune and Nayegandhi, 2018) give excellent definitions and descriptions of hydro-flattening, hydro-conditioning, and hydro-enforcement of digital elevation models. The data development processes help make sure that the behavior and movement of water across terrain are accurately represented in hydrologic models.

The role of breaklines in hydrologic data processing workflows is essential for developing a quality product. Breaklines are vector features (lines and polygons) that are created to safeguard the accuracy and cartographic quality of a topographic data product such as a digital elevation model (DEM) or orthophotograph. Topographic datasets differ greatly in the specification and accuracies to which

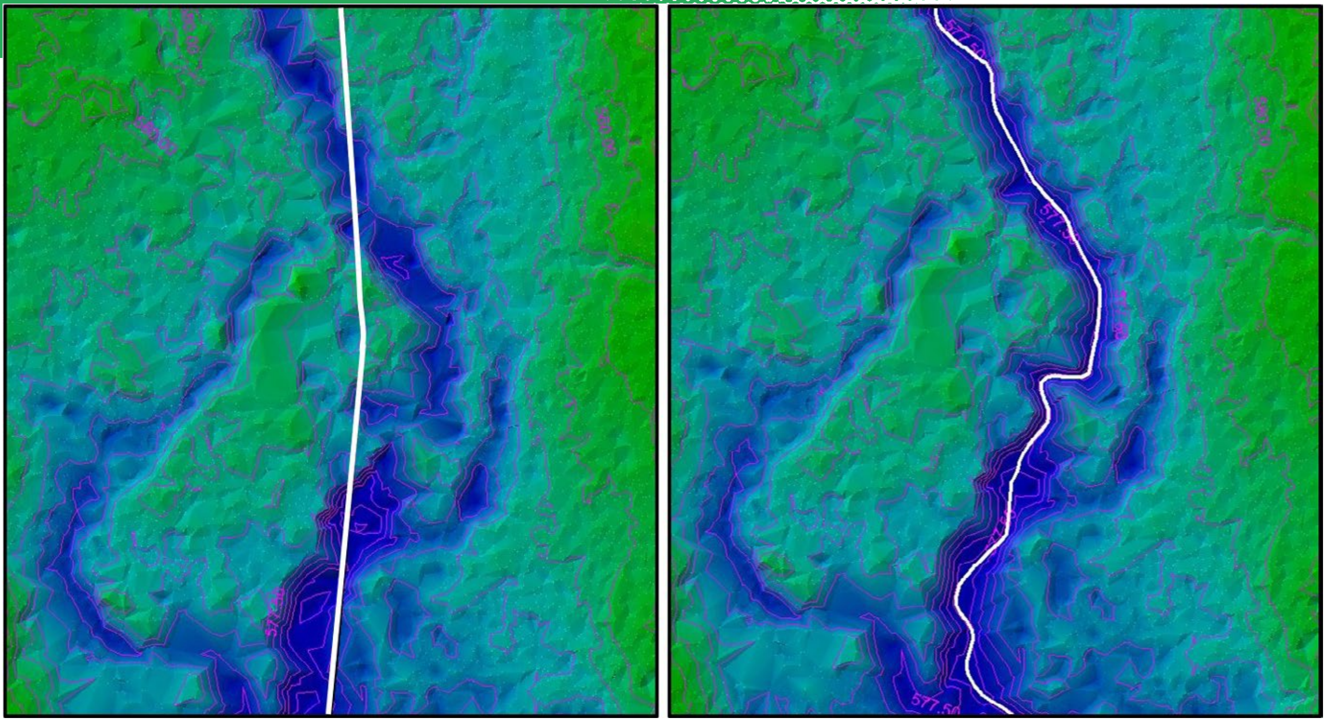

Figure 2: These images show a high-resolution lidar dataset of the same stream corridor. The image on the left is overlaid with the existing National Hydrography Dataset (NHD) flow line representing the stream. The image on the right is overlaid with a revised flow line that more accurately represents the stream centerline for this corridor with respect to the new lidar-derived elevation model.

Image courtesy of CivicMapper.

they were collected and there is a wide range of complexities in each collection area (**Figure 2**). As a result, there is no "one size fits all" solution for every project when applying breaklines for improving lidar data. Specifically, **hydro-flattening** is the processing of a lidar-derived surface (DEM or TIN) so that mapped water bodies, rivers, reservoirs, and other cartographically polygonal water surfaces are flat and, furthermore, level from bank to bank on a sloping surface. The use of breaklines ensures a flattened bank-to-bank appearance of rivers and streams, as well as a consistent downward slope referred to as "monotonicity." Also, breaklines undergird the proper processing of contour lines that do not cut across water bodies and closely delineate and portray rivers and streams. Currently, based on the USGS specifications, the creation of hydro breaklines primarily involves capturing rivers with width 100 ft or more and lakes/ponds more than 2 acres in size.

The incorporation of breaklines to impose continuous downward sloping of water flow is termed **hydro-enforcement**. A dataset that has been **hydro-conditioned** means that the entire surface of the digital elevation model has been processed so that the flow of water across the surface of a landscape will be continuous, even if it is outside the stream channel. When a dataset has been hydro-conditioned, catchments can be created and linked to neighboring catchments, effectively allowing for pour points to be modeled at any location within the basin.

Rather than simultaneously hydro-correcting data for a whole state, some regional agencies and local organizations are choosing to hydro-correct their elevation data on a watershed, sub-watershed, or project basis with the intention of making the data public and shareable once ready for publication. This approach can save time and costs, and also guarantees that the best available data will be used for basin characterizations that depend on high-quality and hydrologically corrected elevation models.

Basin characterization for local projects

Hydrologic basin characterization is a model-based method for quantifying the volume of stormwater entering and exiting a catchment, based on a variety of geospatial datasets and climate data including elevation, land cover, soils, and predicted rainfall. Results from hydrologic basin characterizations can be used to improve stormwater engineering plans and determine whether existing stormwater infrastructure is adequately sized for predicted storm events (e.g., 2-year, 5-year, 10-year storms). Impervious surfaces like pavement, roofs, and parking lots prevent the absorption of stormwater and create runoff that not only affects water quality but also exacerbates flooding in lower-lying areas. Identifying the location and change of impervious surfaces over time is critical for developing accurate basin characterization models. The estimates of impervious surface cover also serve as the basis for stormwater fee assessments in many communities, especially where these fees correspond to the percentage of impervious surface that covers a parcel.

Urban watersheds are prime targets for hydrologic basin characterization. They are the most impacted by climate and aging infrastructure and need to be better understood to protect people, property, and the environment. Hydrologic basin characterization in urban watersheds can also precede more resource-intensive stormwater management models (SWMM). For example, peak flow volume models such as TR-55 (Cronshey, 1986) can provide a lower-cost approach for characterizing smaller urban watersheds and for developing a set of key data that can be used in other analyses within the basin, including input to SWMM.

The availability of open, QL2 lidar and imagery across many states means that local and regional organizations have access to some of the most powerful sources of information for understanding urban hydrologic systems. Assistance from skilled private-sector partners can help fast-track hydrologic and basin characterization projects as well as provide guidance on future hydrographic data initiatives. Thanks to 3DEP data, there has never been a better time to start!

> “The availability of open, QL1/QL2 lidar and high resolution imagery across many states means that local and regional decision makers have access to some of the most powerful sources of information for understanding urban hydrologic systems.”

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Emily Mercurio, PhD, PG is the CEO and co-founder of CivicMapper. She leverages her 25 years of experience with earth science data and mapping technologies for leading the development and application of CivicMapper's products and services. Her career has focused on creating innovative and data-driven solutions to support decisions at the intersection of our natural and built environments. Emily is motivated by a desire to make geospatial data and technologies more accessible and usable by governments, non-profits, and businesses that are building a more informed, resilient, and sustainable world.

Srini Dharmapuri PhD, GISP is vice president and chief scientist, Sanborn. Dr. Dharmapuri's career in the geomatics industry has been extensive and widespread. He has over 30 years of global experience, including hands-on exposure in a variety of roles in remote sensing, lidar, photogrammetry and UAS. He has also held leadership and management positions where he successfully guided and provided support for his team. Prior to relocating to the USA, he was a senior scientist at India's premier space research institution.

Figure 1: SATW fact-sheet.
Image courtesy of SATW.

Cyberphysical Systems and Autonomous Mobility

Swiss physicist's assessment of AV progress to date

BY BERNHARD BRAUNECKER[1]

Background

The Swiss Physical Society (SPS) intermittently publishes short reports on events or publications of the Swiss Academy of Engineering Sciences (SATW). Recently SATW produced a fact-sheet on autonomous mobility (**Figure 1**)[2]. It describes the future of driving fully autonomous cars. Already enthusiastically hailed by many as an important historical milestone, autonomous driving is also perceived by some as an unnecessarily wasteful and overly expensive endeavor by major industries, ignoring the more urgent problems of our time. But there are many positive arguments, such as a reduction in the number of accidents and an increased mobility for the disabled, elderly persons and children.

Where do we stand today? And where is development heading? The fact-sheet comments in tabular form on the

2 https://www.satw.ch/en/early-identification/faktenblatt-autonome-mobilitaet/

1 Dr. Braunecker provided some input to our recent piece by Allen Cheves and Stewart Walker, "Schott at the sharp edge", *LIDAR Magazine*, 10(4): 6-12, Fall 2020. During the correspondence he suggested that we could publish the present article, which has already appeared in German: Braunecker, B., 2020. Cyberphysische Systeme und Autonome Mobilität, *SPG Mitteilungen*, 61, 44-46, June. As editor of *SPG Mitteilungen*, Dr. Braunecker gave us permission to publish it. Our version is based on an English translation available on the SPS website: https://www.sps.ch/fileadmin/articles-pdf/2020/Mitteilungen_Cyber-Auto_EN.pdf. We have made minor modifications to suit the style of *LIDAR Magazine*.

developmental stages of autonomous driving (3 = conditional automation, 4 = high automation and 5 = full automation) on the basis of criteria such as technical challenges, individual and social benefits, risks, social acceptance, legal aspects and estimated time horizons.

Key messages

The study assumes that, despite all concerns, the development of autonomous driving will continue worldwide and at great expense, simply because a phalanx of major technology and service companies see this as the key market of the mobility business. The rapidly growing technological possibilities in digitization, algorithms, networking and communication can be bundled and developed into sophisticated industrial activities—it is an opportunity that no modern nation can pass up.

On the other hand, the SATW study does not ignore the fact that the challenges facing the implementation of autonomous driving are so great that market penetration with partially or highly automated vehicles is not expected for at least twenty years, and fully autonomous vehicles will be on the market in about forty years. The difficulties are significant because, among other things, safety issues are paramount and collisions between passers-by and vehicles depend on so many factors—technical, environmental or psychological—that they cannot yet be sufficiently identified and evaluated.

High complexity

In order to get a feeling for the enormous complexity of this automated vehicular undertaking, we cite a lecture on 12 June 2018, at the Technology Day of the University of Applied

Science NTB in Buchs, Switzerland. A representative of a large automobile engineering company spoke about "new and integrated active chassis systems for future vehicle concepts". He mentioned that the software currently installed in a car will increase from 100 million lines of code to 200 billion in 2030. That would still be at level 4! Since the software will consist of many submodules, the consistency of all interfaces must be guaranteed—this is a very demanding task.

Equally thought provoking is the testing effort: "to prove safety with 95% confidence [needs] eight billion km of road testing [with] 100 vehicles 24/7 for 225 years". This is a troubling statement at a time when safety margins in many areas such as the space industry require at least eight sigma. Can (cyber-)physics help here?

Mini-Trams

The main problem is the unmanageable variety of possible interactions between vehicles but also between vehicles and pedestrians. How would a physicist proceed? One would first set meaningful boundary conditions, then carefully measure and finally compare experimental results with physical

Figure 2: Trackless tram in Zhuzhou, China.
Source: https://commons.wikimedia.org/w/index.php?curid=79705921.

models, thus minimizing deterministic and stochastic errors.

Meaningful boundary conditions are those that acceptably limit the performance requirements. When driving autonomously, what counts primarily is the permanent availability of vehicles that drive individually, safely and comfortably to a home address, but not, for example, the maximum speed or a minimum distance between vehicles.

Thus, one could consider autonomous mini-trams in regular traffic, running on tracks at a constant speed. This sounds rather unrealistic, but in the city of Zhuzhou in China whole tram trains are already running on normal main roads without rails, guided only by marked lines and stationary sensors at the roadside (**Figure 2**).

Stationary sensors are not a viable solution for regular road traffic, however, where driving on dense networks of secondary roads and side streets has top priority. For cost reasons alone, only vehicle-mounted sensors should be used—in combination with stationary global systems such as satellite navigation. But even sensors should only play a supplementary role, because the most obvious and safest solution would be to replace the usual road markings with weatherproof and physically optimized special paints that serve to guide the vehicle by means of suitable optical and magnetic sensors. Magnetic guidelines are already known from their use in factories, but using them in road traffic is probably somewhat novel. Road marking is simple, inexpensive, proven and tested, and it would cover all the streets of a particular city, including the suburbs, without restricting traditional, non-autonomous traffic.

This guidance would still need support by onboard GNSS, INS, LOPS, lidar and image processing sensors, which we describe briefly. A good summary is available online[3].

GNSS (Global Navigation Satellite Systems)

Various satellite systems can be used for navigation: GPS (USA), Glonass (Russia), Galileo (EU), Beidou (China), IRNSS (India) and QZSS (Japan). Direct positioning is accurate only to about ±10 m due to satellite errors (residual clock errors, orbit variations), dispersion effects in the ionosphere and troposphere, as well as multiple reflections off buildings and trees. In addition to technical measures such as the transmission of satellite signals in various frequency bands to eliminate frequency-dependent dispersion errors, complex configuration concepts such as DGNSS, SBAS and RTK reduce the error rates so that accuracies of only a few cm can be achieved. At the same time, the stability and robustness of position measurement has been much improved in recent years, together with a shorter acquisition time before measurements with cm accuracy are available. While a few years ago one had to wait up to one hour for the highest accuracy level, today it takes only a few seconds. To achieve these cm accuracies for a moving vehicle (called a 'rover'), the following approaches are used:

Differential GNSS (DGNSS)

A stationary GNSS station (base) calculates its actual position from the satellite data and compares it with its true position, which has been accurately measured previously using land surveying techniques. The deviations, caused by the aforementioned errors, are sent via radio link to the mobile rovers, which correct their position calculations. The position determination is based on the correlation of the transmitted code sequences of the satellites that are used.

Satellite based augmentation systems (SBAS)

Within a larger region, it is more cost-effective to replace the individual base stations with a network of stationary and accurately known GNSS receivers. These continuously send their

3 https://novatel.com/an-introduction-to-gnss

calculated position data to a central station. There the current correction data for each point in the region is calculated and sent to special geostationary SBAS satellites that retransmit it over the region. Every rover in the region can thus obtain the correction data valid for its location online.

Real-time kinematic (RTK)

Similar to DGNSS, a stationary base station is used as reference, which sends the correction data it calculates to each rover via radio link. The difference from DGNSS is that instead of code correlations, more computationally complex analyses of the code phases are carried out when determining the position. This leads to position accuracies of ±1-2 cm.

INS (Inertial Navigation Systems)

While the velocity and acceleration vectors can be derived with high accuracy from the position measurements of a GNSS sensor by differentiation, the determination of tilt angles is poorly conditioned. It is therefore better to measure them directly, especially if one wants to set certain tilt angles (tilting trains) or to compensate or damp stochastic tilt errors as in ships or aircraft.

INS sensors measure the linear accelerations and, by means of gyros, also measure the angular accelerations in the three main axes. Since the position and angles (roll, pitch and yaw) are obtained from the measured accelerations by double integration, the INS system can take over the function of the GNSS sensors in case of a temporary failure. On the other hand, the GNSS sensors, which measure absolute positions, can monitor the behavior of the two integration constants of the INS system. For mapping applications that use airborne photogrammetry and lidar, the sensitive position of the aircraft is monitored by INS sensors with a high clock rate of 200 Hz, whereby their zero drift is corrected by GNSS systems with a lower clock rate.

Figure 3: Leica BLK2GO handheld imaging laser scanner.
Image courtesy of Leica Geosystems.

LOPS (local optical positioning system)

This optical method is similar to GNSS, except that the rover is both code emitter and code receiver. The rover sends code-modulated signals to its chosen 'satellites' and measures the distances together with the two polar emission angles in its own coordinate system. Since LOPS uses laser light as code carrier, the optical 'satellites' are prisms or foils, but also highly reflective spots on objects like buildings. If one knows the exact positions of the reflectors in a local urban coordinate system, then the 3D current position and angular orientation of the rover can be determined by triangulation and compared with the GNSS measurements. Since the reflectors are passive and that the only time base is at the rover, one needs only three, not four reflectors. Combining GNSS as a passive global sensing method with LOPS as an active one can ameliorate problematic situations, such as the corruption of the GNSS data by fake signals produced by simple electronic devices, which must be immediately identified and eliminated to avoid serious disasters by misguiding. LOPS systems on vehicles can permanently change the code modulation of their lidar beams, so that their 3D-scan information of the environment (buildings, cars, etc.) is robust against attacks. Furthermore, LOPS can identify stationary or mobile objects which can scatter the GNSS signals: this again helps to improve and accelerate the GNSS algorithms[4].

Lidar

In lidar systems, laser beams are modulated in amplitude and phase (similar to GNSS signals) in such a way that distances can be measured. The 3D acquisition of a scene can be done by laser scanning or by sending out a fixed bundle of laser beams, called an "image ranger". Lidar systems built into vehicle headlamps can detect objects in the driver's field of view as well as determine their own position and orientation by scanning the environment. **Figure 3** shows a modern lidar system from Leica Geosystems, in which an eye-safe laser scanner captures objects from 0.5 m to 25 m or even up to 60 m away with a resolution of about 8 mm at clock rates of about 400 kHz. Integrated wide-angle and IR cameras as well as INS modules support the lidar system.

Line-Marking

How well a vehicle can be guided by means of marked lanes and GNSS sensors is demonstrated by a reverse variant, namely the line-marking of roads and (sports) arenas by means of

4 United States Patent US 7,742,176 B2 (22 June 2010), Braunecker *et al.*

Figure 4: Views of GNSS-guided line-marker.
Images courtesy of Fleet Line Markers Ltd.

GNSS and INS sensors and the use of stochastic estimation algorithms. In the line-marker shown in **Figure 4**, the spray nozzle is mounted on a motor-driven spindle, the position of which is guided transversely to the direction of travel, so that the line is marked without jittering in spite of driving errors and terrain irregularities[5]. Given a stationary RTK base station, line curves of any kind can be marked over areas with side lengths of several hundred meters, whereby several semi- or fully automated rovers can be in operation at the same time.

5 https://www.fleetlinemarkers.co.uk/satellite-guided-line-marking-machines.html

Figures 5 and 6 provide more detail. The RTK GNSS signals, together with the data from an INS sensor, are fed into a Kalman-filter algorithm, the predicted values from which are used to control the nozzle position.

Algorithms

The high performance of algorithmic estimation methods shown in the line-marking example could also help to ease the problem of erratic pedestrian behaviour. It is certainly not enough to be able to recognise from a vehicle that a person might cross the road, but how would she or he behave afterwards? A child is more likely to jump spontaneously into the street, but would just as quickly come back again, while an elderly person would only hesitantly step into the road, but would then react slowly in the event of a dangerous situation. It can be assumed that in the coming years it will be possible to anonymously query the movement profiles of a person at the side of the road, via mobile phone, smartwatch or health wristband, from the vehicle for a few seconds in order to predict the next step and *vice versa*. It is imperative, however, that the data be immediately deleted after the prediction.

Cyberphysical systems: digitization, artificial intelligence, new networking technologies and their physical modeling

As mentioned in the SATW fact-sheet, the above modern technological approaches are becoming increasingly powerful. A skillful combination of these will help reduce possible conflict situations for autonomous vehicles and characterize them by means of a kind of cataloging. Meaningful boundary conditions such as the use of guidelines with physically optimised paint properties, as well as sensor fusion combined with powerful adaptive algorithms, will significantly reduce the degree of complexity. Instead of extensive and ultimately irrelevant test drives over many villages, potential conflict situations could then be reliably modelled, simulated and verified in local test facilities, so that the results are applicable anywhere and at any time. The reliability of the measurements and their allocation then allows suitable countermeasures such as warning, braking, evasion, etc. to be taken in real situations.

Dr. Bernhard Braunecker, Leica Research Fellow (retired), studied nuclear physics at the University of Erlangen-Nürnberg (Germany) until 1972, then worked in applied optics at the Universities in Erlangen and Essen (Germany) and also at IBM San José Research Laboratory (USA) on optical information processing. In 1982 he joined Wild Heerbrugg in Switzerland, later called Leica Geosystems, leading R&D Optics including the optical design group. He retired in 2006 and founded Braunecker Engineering GmbH, Rebstein, Switzerland with focus on space optics and high speed scanning systems. He holds 40 patents and has written and edited numerous technical papers, books and book chapters.

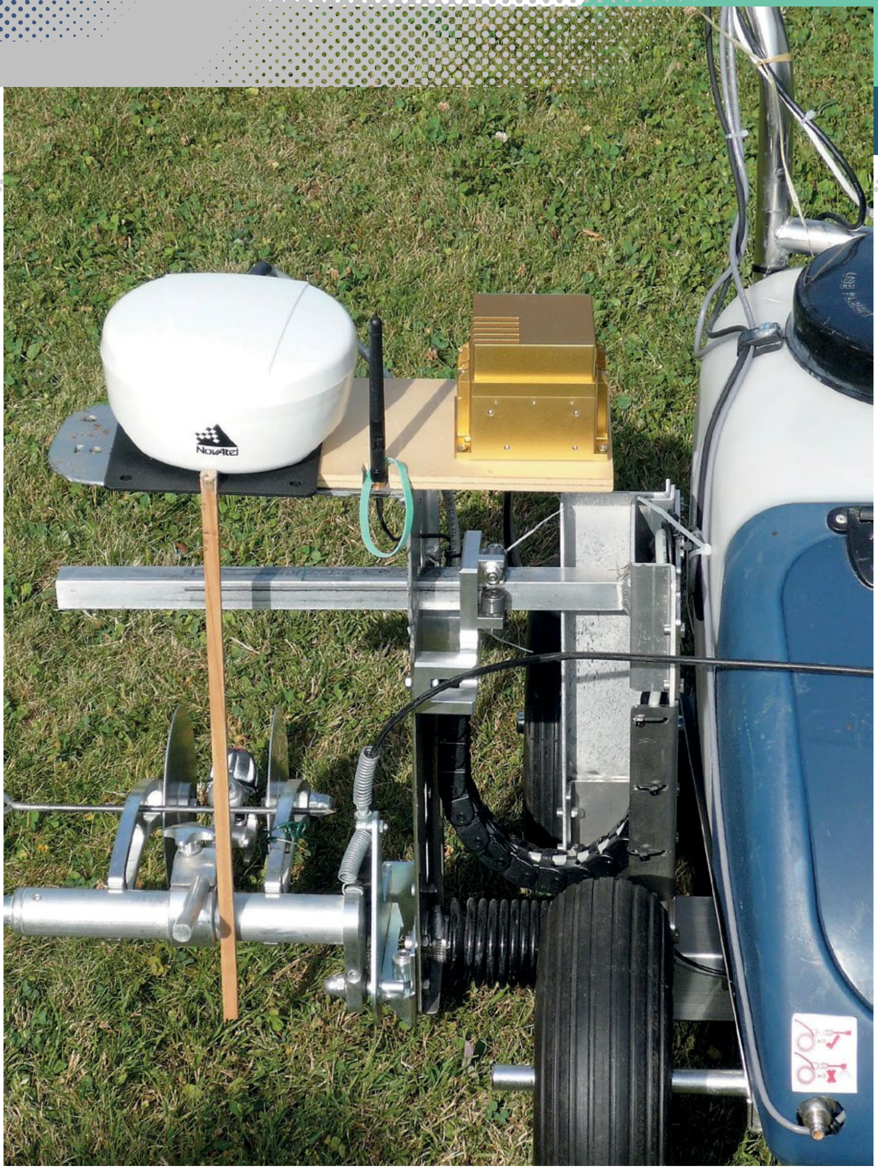

Figure 5: Close-up of prototype of the line-marker shown in Figure 4 with RTK GNSS antenna (left), INS sensor (right) and spray nozzle (below). Between the sensors it is possible to see the WiFi antenna for the data exchange with the RTK base station.

Image courtesy of Braunecker Engineering GmbH.

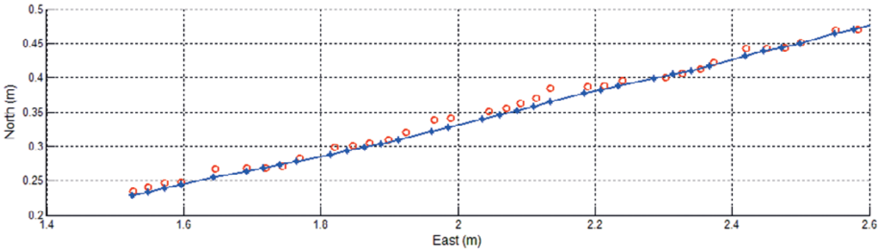

Figure 6: Extract from a measurement series for a straight line. The measured values, plotted in the east and north directions, show the movement of the line-marker at a deliberately slow driving speed of about 1 m/s. The red points are the GNSS positions (clock rate 20 Hz) with a variation of about ±1-2 cm, with which the line can be marked with acceptable quality. If the data is combined with the INS measurement values and fed into a Kalman-filter algorithm, however, the position of the spray nozzle is controlled according to the blue curve with deviations of only few mm from the ideal line.

Image and measurement data courtesy of Braunecker Engineering GmbH.


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- PHOTOGRAMMETRY

COMPANY PROFILE

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Owned and operated by geospatial professionals, Klau Geomatics has worked closely with NovAtel since 2015 to create professional solutions for the mapping sector. Our qualifications and expertise in surveying, geodesy and photogrammetry are the foundation for the company. We work to provide innovative solutions to the needs of the industry.

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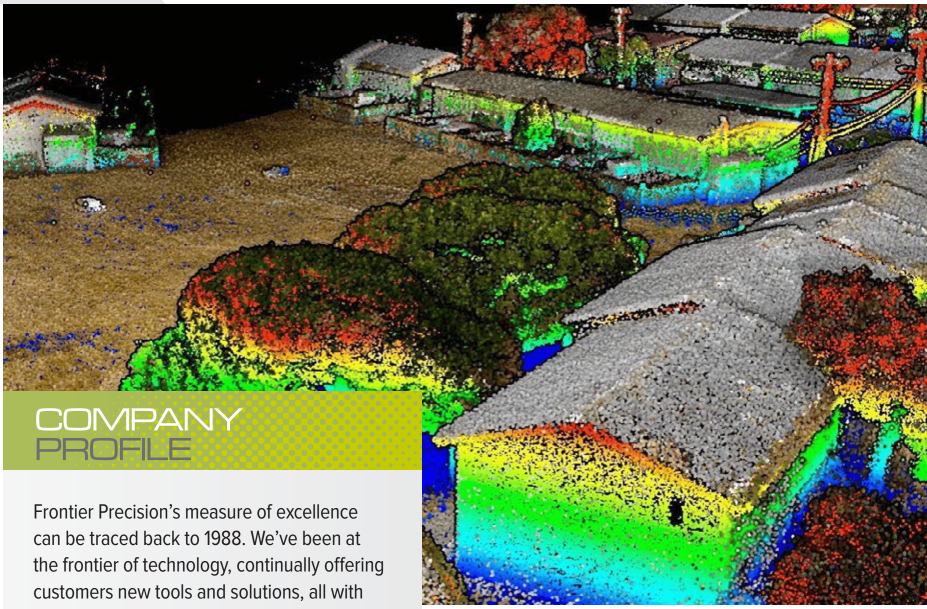
Frontier Precision



APPLICATIONS

- SURVEY
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- SCANNING
- MONITORING
- CONSTRUCTION
- MOSQUITO & VECTOR CONTROL

COMPANY PROFILE

Frontier Precision's measure of excellence can be traced back to 1988. We've been at the frontier of technology, continually offering customers new tools and solutions, all with our end goal of making our customers more efficient, productive, and profitable with today and tomorrow's technology. Frontier Precision is an employee-owned company—offering solutions in Survey, Mapping & GIS, Drones/UAS/Unmanned, Construction, Scanning/Imaging, Mosquito & Vector Control, Water Resources, Invasive Plant Control. We became one of Trimble's largest geospatial dealers worldwide by offering our customers the solutions they need. Every day, we bring it to life by seamlessly connecting our physical and digital worlds to use technology to improve how we all interact better with the earth—in all kinds of meaningful ways.

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- MAPPING
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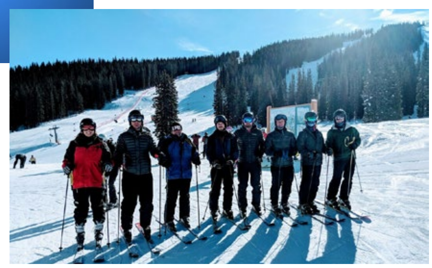
- MILITARY
- UNMANNED



COMPANY PROFILE

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The idea to develop the Snoopy and ScanLook LiDAR systems came out of our need to find an affordable light weight solution that was easy to use and operate. We have developed solutions for indoors and outdoors. The key technologist and principal investigators are Daniel and Jeff Fagerman. We are experienced in photo control work with conventional total stations, levels, etc., and also with the latest GPS technology. We consider software development a particular interest and hardware integration something we excel at. We seek out ways to improve workflows using existing technology in an unconventional way.

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TrueView 615/620

COMPANY PROFILE

GeoCue is the largest supplier of kinematic lidar processing tools in North America and LP360 is one of the world's most widely used tool for exploiting point cloud data. In 2014, GeoCue Group started a division focused on using small Unmanned Aerial Systems for high accuracy mapping. Leveraging our expertise in production, risk reduction, and point cloud processing tools, we are continuing to bring new services and products to market to provide surveyors and other geomatics professionals exciting tools for geospatial data extraction using low cost drones including Loki, our plug-and-play PPK direct positioning system, and now our new True View® lidar/Imagery fusion sensors.

GeoCue Group

Founded 2003

11-50 Employees

Huntsville, Alabama

geocue.com

APPLICATIONS:

- MAPPING
- PROCESSING
- SURVEYING
- UNMANNED
- AERIAL
- CONSULTING

True View® 615/620

The True View® 615/620 is a compact, survey grade lidar/camera fusion platform designed from the ground up to generate high accuracy 3D colorized lidar point clouds using the new RIEGL miniVUX-2UAV. Featuring dual GeoCue Mapping Cameras, a RIEGL miniVUX-2UAV laser scanner and Applanix Position and Orientation System (POS), the result is a true 3D high accuracy imaging sensor (3DIS).

With its wide 120° fused field of view, the True View 615/620 provides high accuracy 3D color mapping with excellent vegetation penetration and wire detection in a payload package of 3-3.5 kg. Our own True View EVO software is included for point cloud generation, colorization and a myriad of post-processing data creation and analysis tools.

The True View 615 can be upgraded to the True View 620 configuration via the addition of the external IMU and an internal interface board.

RIEGL

APPLICATIONS

- AIRBORNE
- BATHYMETRIC
- MINING
- MOBILE
- INDUSTRIAL
- TERRESTRIAL
- UNMANNED
- WIDE-AREA

COMPANY PROFILE

With 40 years experience in the research, development and production of laser rangefinders, distancemeters and scanners RIEGL delivers proven innovations in 3D. The combination of RIEGL's state-of-the-art hardware for terrestrial, industrial, mobile, airborne, bathymetric and UAV-based laser scanning with appropriate, equally innovative RIEGL software packages for data acquisition and processing results in powerful solutions for multiple fields of application in surveying. Worldwide sales, training, support, and services are delivered from RIEGL's Austrian headquarters and its offices in Vienna, Salzburg, and Styria, main offices in USA, in Japan, in China and in Australia and by a worldwide network of representatives covering Europe, North and South America, Asia, Australia, and Africa. The RIEGL headquarters provides more than 40,000 square feet work space for research, development, production, as well as for marketing, sales, training and administration. Another 350,000 square feet of open-air ground are used for product testing.

RIEGL®

Founded 1977
230+ Employees
Horn, Austria
Orlando, USA

Riegl.com

Innovation in 3D

RIEGL terrestrial laser scanners provide detailed and highly accurate 3D data rapidly and efficiently. Applications are wide ranging, including Topography, Mining, As-Built Surveying, Architecture, Archaeology, Monitoring, Civil Engineering and City Modeling.

RIEGL airborne laser scanners make use of the latest state-of-the-art laser and signal processing technology. They are exceptionally compact, lightweight and cost effective, and are designed to meet the most challenging requirements in airborne surveying.

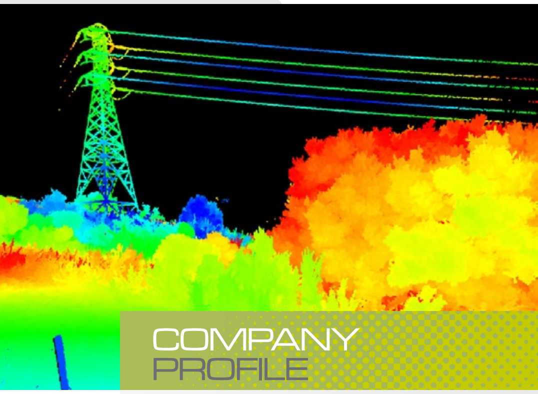
Unmanned Laser Scanning, utilizing high-end unmanned airborne platforms, provides the possibility to acquire data from dangerous and/or hard-to-reach areas, whilst offering a high cost to benefit ratio for numerous applications, for example Agricultural and Forestry, Defense, Wide Area Mapping, Flood Zone Mapping, Topography and Mining. For years, RIEGL Laser Scanners have been successfully used in this sector. Our current efforts in R&D guarantee to provide the user with state-of-the-art laser scanning engines of the highest quality, to meeting the specific challenges of surveying applications using advanced UAS/UAV/RPAS platforms. Furthermore, we are proud to be the first major LiDAR manufacturer to develop its own unmanned aerial system.

Mobile laser scanning describes terrestrial data acquisition from moving platforms (e.g. boats, trains, road and off-road vehicles) also known as kinematic laser scanning. Both RIEGL 2D and 3D laser scanners are ideally suited for mobile mapping applications.

RIEGL's industrial laser scanner product line is ideally suited to meet demanding industrial customer expectations.

RIEGL's software packages are the ideal companion software for RIEGL laser scanners. Furthermore, smooth data transfer to numerous third party post-processing packages is a matter of fact.

Acuity Technologies



APPLICATIONS

- AIRBORNE
- MINING
- INDUSTRIAL
- AGRICULTURAL
- MOBILE
- TERRESTRIAL
- UNMANNED
- MAPPING

COMPANY PROFILE

Acuity Technologies has been developing and marketing time of flight rangefinding and lidar components since 1993. Acuity's first complete scanning lidar system had a 120 by 360 degree field of view with two-turn lock to lock rotation.

In 2017 Acuity introduced the AL-500, a next-generation lidar significantly smaller than earlier systems with unlimited turret rotation, improved accuracy, reduced laser pulse width, and smaller laser spot size.

Acuity's new single axis AL-500AIR is based on the AL-500, with significant upgrades including multi-return detection, time sync inputs, and lighter weight composite structural components.

Acuity can incorporate scanning components into systems that meet customer requirements for performance and form factor that cannot be met with its standard products.

Acuity Technologies

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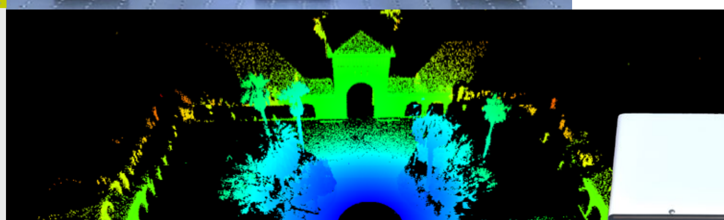
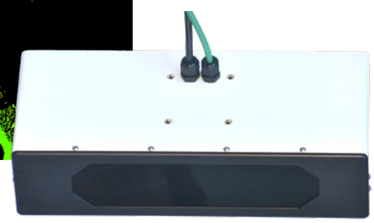




AL-500AIR: The Lightweight Heavyweight

The AL-500AIR is a lightweight single axis scanning lidar designed by Acuity for airborne mapping and continuous or batch industrial point cloud acquisition. Weighing only 1.3 Kg and consuming 6 to 50 watts, the AL-500 is well suited for small drones and UAS at altitudes up to 200 meters AGL.

The AL-500AIR features programmable laser pulse and line scan rates. Three versions with top pulse rates of 200,000, 400,000 and 800,000 offer different laser pulse power and maximum ranges of 300, 225, and 150 meters respectively. The AL-500AIR captures up to 4 returns per pulse up to 200,000 pulses per second and 2 returns up to 400,000 pps. The maximum line scan rate is 300 lines per second.

Scan rate, field of view, and laser pulse rate are controlled from the interactive host computer interface or through Acuity's PointWorks Application Programming Interface routines. Control and data communications use TCP-IP over a 100 Mb ethernet link.

For mobile systems, PPS and NMEA inputs are used to synchronize the AIR scan data with external time signals, allowing point-by-point transformation of scanner output to an inertial or ECEF frame of reference.

Acuity's PointWorks software is included with the AL-500 and AL-500AIR, with C++ source for control and data collection programming. Pointworks also provides interactive point cloud visualization and data export in standard file formats. For advanced processing, PointWorks' .LAS output can be used with any of several available point cloud manipulation and analysis packages.

AL-500 and *AL-500AIR* Lidar Systems

High speed scanning lidar systems for airborne and terrestrial surveying
15 to 300 scan lines per second
Up to 4 returns per sample
333 to 6667 points per 120° scan line
Three versions: 300, 225, or 150 meter maximum range
at 200,000, 400,000 or 800,000 samples per second
Range accuracy 8mm (1σ at 20 m). Angular accuracy 400μRad
IMU/GNSS timing inputs for mobile applications
Fully calibrated for signal strength, scanner geometry, temperature
TCP-IP command/data interface

AL-500AIR

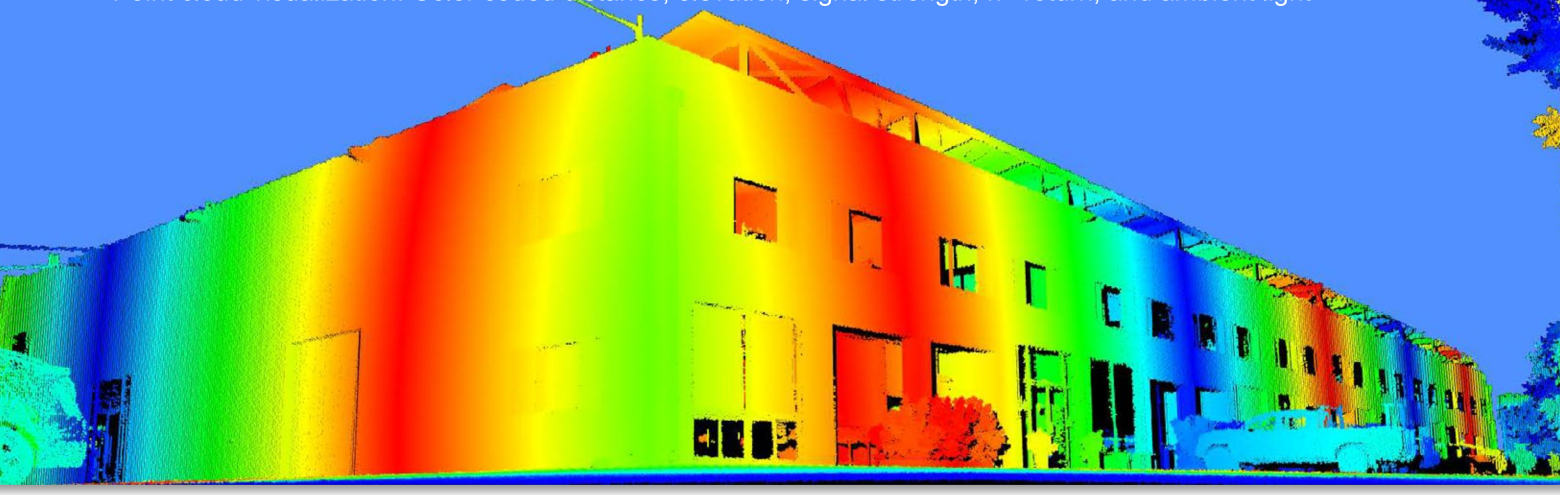
Airborne mapping, industrial process capture
11.49” (292mm) x 3.22” (82mm) x 4.74” (120 mm)
Up to 150 meter flight altitude
9.5 Watts at 100 lines /sec
2.9 lb (1.3 Kg)

AL-500

Terrestrial and mobile scene capture
12.67” (322mm) x 3.22” (83mm) x 4.74” (120 mm)
Two-axis scanning to 300 lines/sec and 10 rev/sec
Precision tip-tilt sensing for automatic vertical rectification

Acuity PointWorks Software

API with source code for controlling the AL-500 and AL-500AIR
Unlimited duration scan capture
.LAS and text file export
Point cloud visualization: Color coded distance, elevation, signal strength, n^{th} return, and ambient light



Acuity Technologies

www.acuitylidar.com
877-659-3406
Rangefinding and lidar systems since 1993
Designed and produced in the United States

Surveying Inland Waterways: A Florida Case Study

Topobathymetric lidar outperforms hydrographic technologies

Since the first of the three editions of *Digital Elevation Model Technologies and Applications: The DEM Users Manual* was published by the American Society for Photogrammetry and Remote Sensing (ASPRS) in 2001, Dr. David Maune, the "father of lidar in the U.S.", has enumerated his dreams for the national elevation program. By the third edition of the book in 2018[1], the first three of his dreams had been realized and the fourth, the development of a seamless 3D nation from the tops of the mountains to the depths of the seas, to include inland bathymetry, is the next frontier being pursued through the 3D Nation program of the U.S. Geological Survey (USGS). In particular, inland bathymetry presents interesting and exciting new challenges to the lidar community; in Florida, it is even more complex than in other parts of the country.

BY BY ALVAN **KARLIN**, JAMES F. **OWENS**, EMILY **KLIPP** AND AMAR **NAYEGANDHI**

1 Maune, D.F. and A. Nayegandhi (eds.). 2018. *Digital Elevation Model Technologies and Applications: The DEM Users Manual,* 3rd edition, American Society for Photogrammetry and Remote Sensing, Bethesda, Maryland, 652 pp.

Since 2004 and the first commercial use of aerial lidar bathymetry with the Optech SHOALS 1000T sensor[2], topobathymetric lidar has faced three basic challenges: the physics of light traveling through different media (air and water); the albedo of the submerged bottom; and water column turbidity resulting from dissolved particulate/organic matter, known as K_D, which is recognized to have an important role in obscuring the bathymetric ground from topobathymetric lidar sensors. Inland waterways in Florida, known for dark, muck-covered bottoms, combined with tannic, dark waters, make for exceptionally challenging conditions for surveying with light-based sensors regardless of the wavelength of the laser.

While the physical and hydrological characteristics of most of the larger inland waterways in Florida more closely resemble the Withlacoochee and Suwannee Rivers—with their slow moving, tannic water and dark bottoms—there are also several spring-fed river systems. Spring runs like the Crystal River, named because of the more than 20 first-order springs that supply the river with clear water, the Manatee Springs run into the Suwannee River, and the Rainbow River—a short tributary of the Withlacoochee River—are spring-fed with clear water and a hard, karst, lime rock substrate, making them good inland waterway candidates for topobathymetric lidar survey.

The Rainbow River (**Figure 1**) is a relatively short river run, about 5.8 miles from the first-order springheads in the Rainbow River State Park to the confluence with the Withlacoochee River in southwestern Marion County. Because of its natural beauty, the upper reach was designated by the state of Florida as an Aquatic Preserve in 1986 and an Outstanding Florida Water in 1987. The Florida Department of Environmental Protection (FDEP) manages the springhead as a state park, and the aquatic preserve for recreation, including tubing, rafting, and swimming. While resort housing has developed on the lower reaches of the river and along the Withlacoochee River near Dunnellon, FDEP closely regulates activities on the upper portion of the Rainbow River and has restricted most development. The Southwest Florida Water Management District

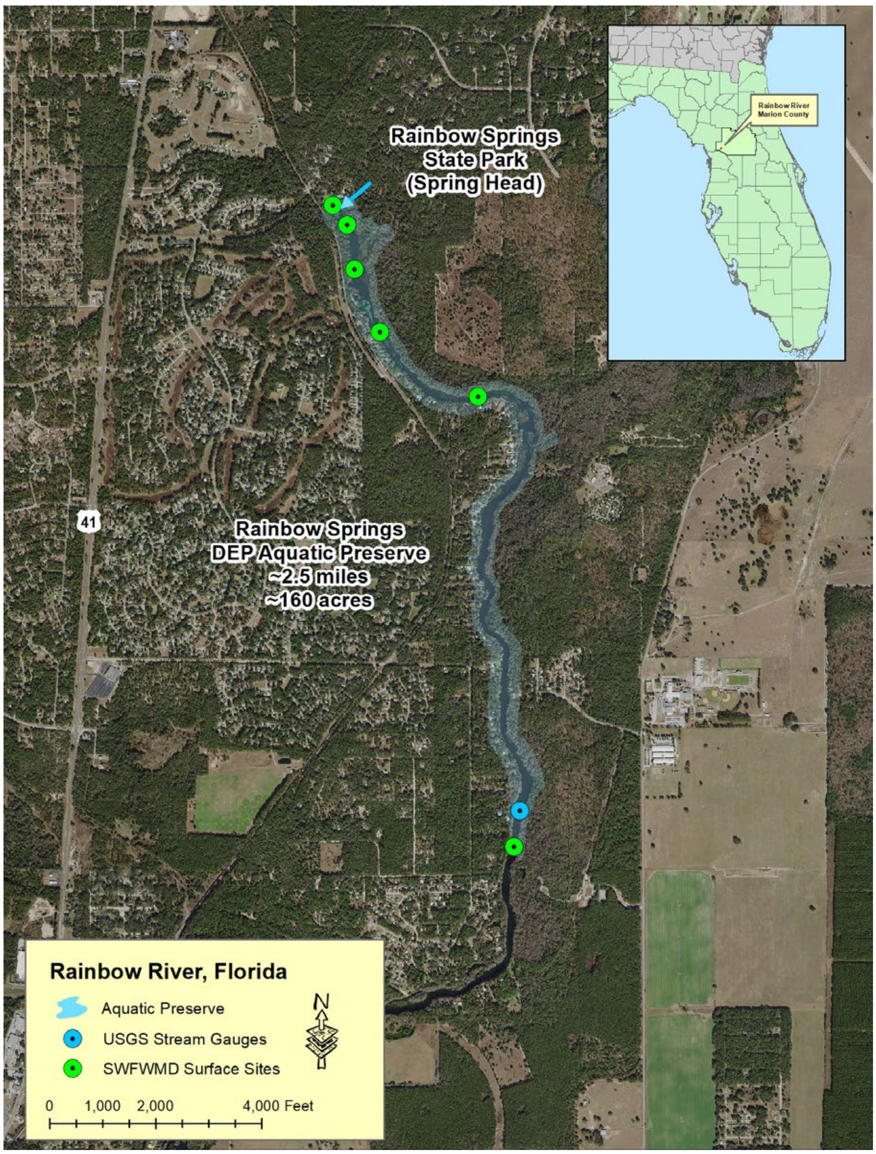


Figure 1: Rainbow River Aquatic Preserve in southwestern Marion County, Florida.

2 https://www.hydro-international.com/content/news/first-shoals-1000t-survey

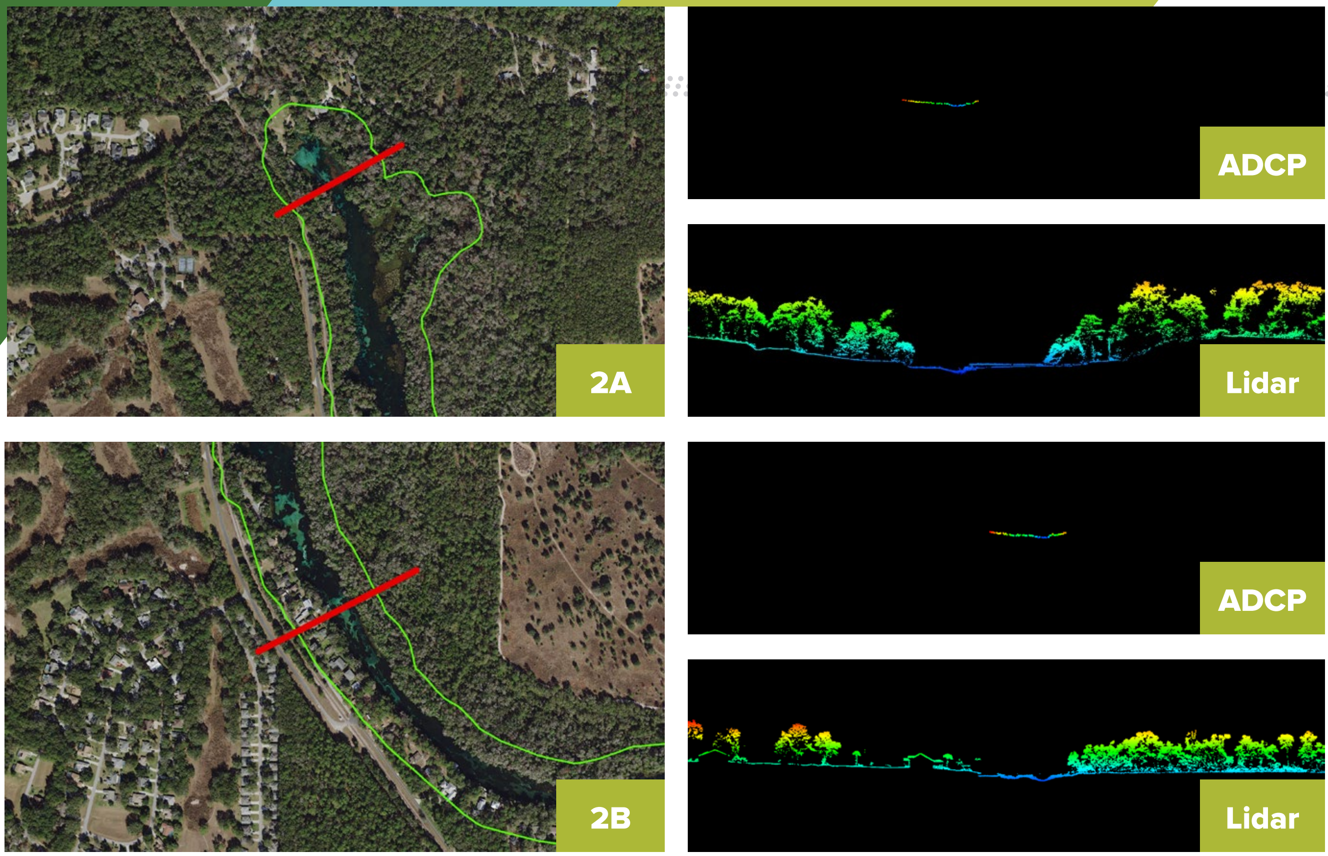


Figure 2: Lidar (red line) and ADCP profiles through the springheads (A) and a typical section (B) of the Rainbow River. Profiles are colored by elevation with blue points indicating lower elevations.

(SWFWMD) participates with FDEP in monitoring water conditions, nutrient content, submerged aquatic vegetation (SAV), and setting the minimum flows and levels, along the entire Rainbow River reach.

SWFWMD has been monitoring and mapping the SAV and bathymetry of the Rainbow River since the early 2000s. When these studies began, hydrographic mapping of the bathymetry was performed with single-beam echo sounder (SBES) technology. Profiles in proximity to the banks and along the thalweg were collected, georeferenced, and manually adjusted to a surface constructed from SWFWMD and/or USGS river gauges (**Figure 1**). More recently, in 2016 and 2017, SWFWMD used acoustic doppler current profiler (ADCP) technology to measure flow rates in the water column and to map bathymetry, again using the SWFWMD and/or USGS river gauges to estimate the water surface (**Figure 2**). Then, in April 2017, while on transit to the east coast of Florida, the National Oceanic and Atmospheric Administration (NOAA) collected topobathymetric lidar data for most of the Aquatic Preserve section of the river, including the springheads, as a proof-of-concept survey for inland waterways.

Past and present technologies

SBES instruments, also known as depth sounders or fathometers, determine water depth by measuring the travel time of a short sonar pulse or ping. The sonar ping is emitted from a transducer positioned just below the water surface, and the SBES receiver listens for the return echo from the bottom. On board the boat is a global positioning system (GPS) receiver registered to the sonar emitter and recording horizontal position locations. This technology does not include adjustments for pitch, roll, and heave of the boat on the water surface, and the echo-returns are corrected to a uniform water surface. SWFWMD worked with faculty from the School of GeoSciences of the University of South Florida (USF) to perform the SBES surveys. USF collected the bathymetric data using a Teledyne-Odem Digibar Pro system SBES fathometer and a Trimble R4 RTK GPS onboard a standard 15-foot flat-bottom boat. HYPACK (6.2) software was used to convert the measured sound velocities to water depth soundings.

There are places in the river where sandy sediments accumulate and support SAV (**Figure 3**). In these

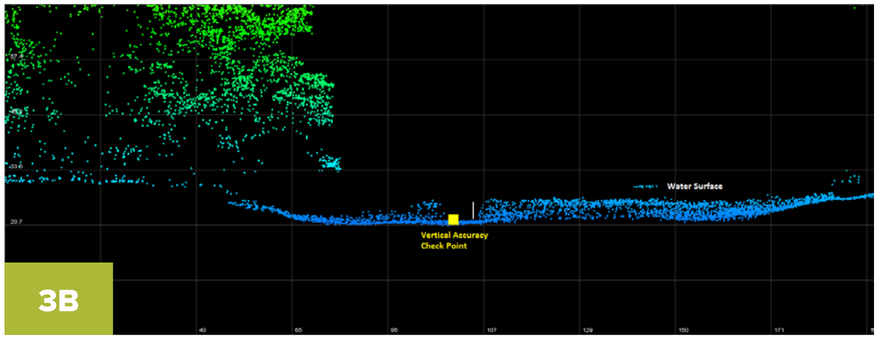


Figure 3: Photograph of tape/eel grass (A) and five-foot deep profile view of topobathymetric lidar point cloud through a section of eel grass (B) in the Rainbow River. The yellow square is a surveyed vertical accuracy check point and the white line shows the canopy height of 3.7 feet (roughly one meter), which is typical of the grasses.

areas, there was some doubt whether the SBES returns were reflecting from the bathymetric bottom or the vegetation. Additional measurements with a scaled-rod were used to verify SBES measurements. Where SBES measurements could not be verified, the scaled-rod measurements were used to measure the bathymetric bottom.

ADCP is a hydroacoustic current meter, similar to a sonar, used to measure water current velocities over a depth range by means of the Doppler effect of sound waves scattered back from particles within the water column. The profile recorder stops when the sonar ping returns from the bathymetric bottom surface. The ADCP was coupled to a survey-grade GPS for open water soundings, but near-shore soundings were degraded to GIS-level GPS locations because of overhanging tree coverage. The GPS receiver was mounted to the bow of a one-man kayak and the ADCP was suspended from a gunnel. GPS locations were referenced to a local base-station established on a SWFWMD geodetic marker. SWFWMD contracted with WaterCube, LLC, to perform the ADCP surveys. WaterCube used a Teledyne RDI ADCP sensor and SonTek 2G-PCM RTK-GPS receivers for multiple mapping missions on the river.

NOAA's National Geodetic Survey (NGS) acquired aerial topobathymetric lidar data using a Riegl VQ-880-G sensor over the upstream portion of the Aquatic Preserve area as a series of seven parallel flight lines (**Figure 4**). The lidar data was referenced to the Bronson, Florida (FLBR) Continuously Operating Reference Station (CORS)/ Florida Permanent Reference Network (FPRN) station, approximately 20 miles north-northwest of the Aquatic Preserve, during acquisition. It's important to note that the FPRN station at Dunnellon (DUNN) was not recording data at the time of the overflight. The lidar data was calibrated by NGS and delivered to Dewberry, a privately held professional services firm, for refraction correction and classification. The specifics of the NOAA overflight are given in **Table 1**.

Bathymetric lidar data must have a refraction correction applied, which adjusts the horizontal and vertical (depth) positions of each data point by accounting for the change in direction and speed of light as it enters and travels through water: this process is based on Snell's Law. The refraction correction was performed by Dewberry using the proprietary Dewberry Lidar Processor (DLP) tool. The refraction tool uses a modeled water surface and mission-smoothed best estimate of trajectory (SBET) data to correct the ranging and horizontal placement of all green (i.e. collected with 532 nanometer laser) lidar points initially classified as water column. This classification is based on breakline placement. The refraction tool creates a new output data file and does not modify the input files. Once the refraction corrections were applied using DLP software, the number of output files was verified to match the number of input files. LAS statistics were calculated on each refracted tile. The point class statistics were reviewed and any issues (e.g. presence of extraneous classes) were resolved prior to moving forward.

Advantages of topobathymetric lidar

When appropriate and applicable, as in this case of an inland water body with clear water and a reflective substrate, there are multiple advantages to using topobathymetric lidar over either SBES or ADCP technologies for bathymetric mapping. The most obvious include

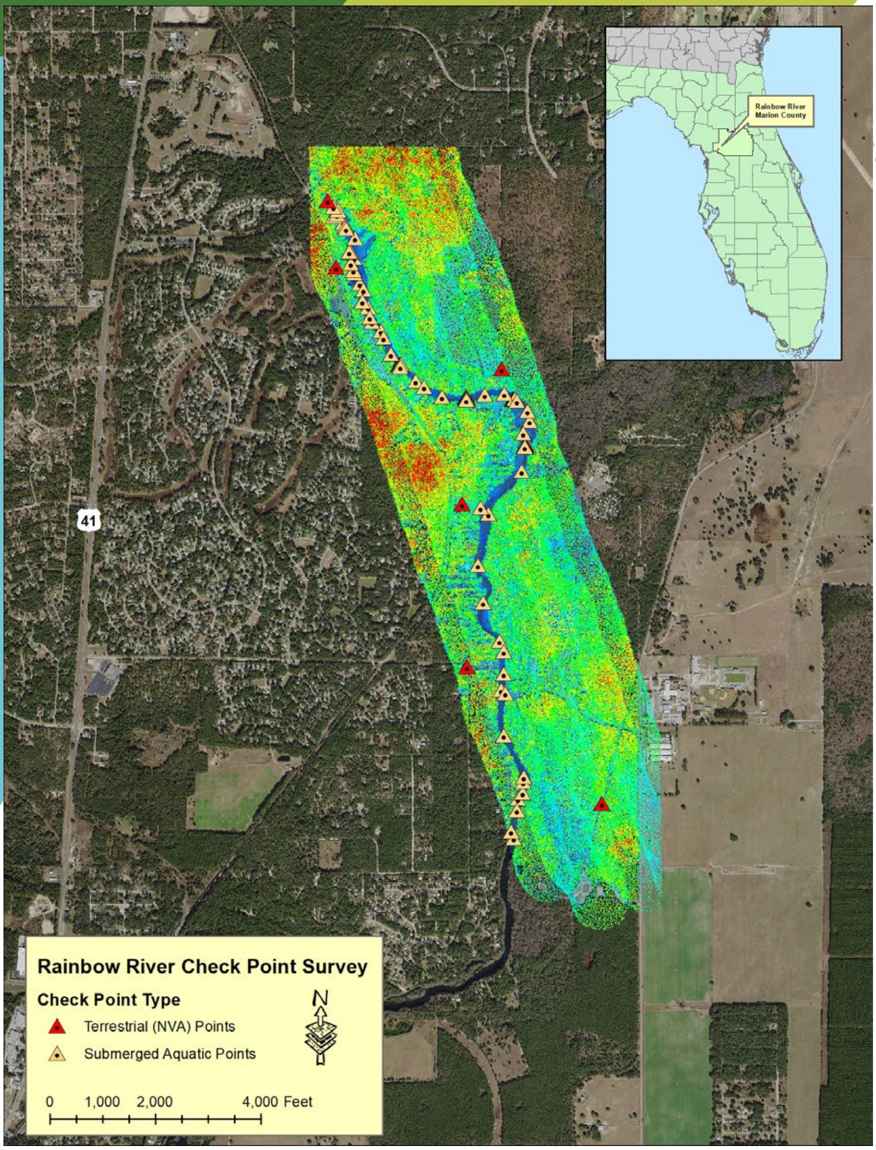


Figure 4: Distribution of vertical accuracy check points in the Rainbow River Aquatic Preserve, SWFWMD 2019.

data density, time efficiency, and cost, summarized in **Table 2**. On a per point basis, the cost decreases from roughly one dollar per point for SBES to about 50 cents per point for ADCP, and to one cent per point for lidar—with a 50 times increase in cost efficiency for lidar rather than ADCP, and more than a 100 times cost efficiency over SBES. Similarly, because lidar is a swath technology rather than a point-beam technology, the acquisition time is minimized while the cost per data point and point density are maximized.

The increased point/pulse density of the topobathymetric lidar is accompanied by several side and/or unexpected benefits.

Both of the acoustic surveys are conducted from boats on the water surface. SBES and ADCP are restricted to survey where the boat can be accommodated, and the water depth can support the beam travel time through the water column. As the acoustic surveys are collected from a boat floating on the water surface, the technology does not collect data on and above the banks. Additionally, as both the SBES and ADCP technologies are dependent on GPS to directly geoposition the soundings, and as those GPS positions are severely degraded when under dense vegetation, neither can provide accurate bathymetric and positioning data near the banks of the river.

Aerial topobathymetric lidar is not dependent on the water depth in the same manner as SBES and ADCP. While laser extinction is a function of laser power and water depth, modern sensors function well to depths of about 10 meters, depending on water clarity and bottom reflectivity. The sensor is flown in an aircraft at modest elevations, about 400-600 m above ground level. In general, flights at these elevations produce a swath with of 300-500 m. With normal pulse repetition rates, between two and eight pulses reach the surface (and below); and, with the forward-facing laser, ground/surface penetration through trees is generally good to excellent. **Table 1** gives the parameters for this mission and **Figure 2** illustrates 10-foot-deep profile views through the springhead and a typical section of the Rainbow River comparing the lidar profiles to ADCP survey profiles.

Although the primary goal of SBES and a secondary goal for ADCP was to map the bathymetry of the Rainbow River, SWFWMD has been monitoring and mapping the abundance and health of the submerged vegetation. The predominant SAV species, tape/eel grass (*Vallisneria americana*) and strap-leaf sagittaria (*Sagittaris kurziana*), typically grow in the soft sediments captured in depressions and holes in the porous limestone karst substrate (**Figure 3**). Because lidar produces multiple returns, as opposed to SBES, which produces a single return, or ADCP, which measures current flow, the SAV canopy can be measured and quantified.

Item	Description
Acquisition date	16 April 2017
Sensor	Riegl VQ-880-G
Altitude (m AGL)	400
Flight speed (knots)	100 +/- 10
Nominal swath width on the ground (m)	335
Scanner pulse rate (kHz)	145
Scan frequency (Hz)	80 lines/second
Nominal pulse width (ns)	15
Aggregate nominal pulse spacing (m) – all returns	0.64
Aggregate nominal pulse density (pulses/m^2) – all returns	3
Aggregate nominal pulse spacing (m) – bathy returns*	2.9
Aggregate nominal pulse density (pulses/m^2) – bathy returns*	0.3
Measured terrestrial vertical accuracy ($RMSe_z$) (m)	0.03
Bathymetric accuracy ($RMSe_z$) (m)	0.31

Table 1: Lidar data acquisition parameters and summary statistics for the Rainbow River Aquatic Preserve survey, April 2017.

** Bathy returns = bathymetric returns from classes 40-45*

Accuracy assessment

When considering accuracy assessment of the three datasets, it is important to consider that the datasets are temporally distinct from each other, with SBES being the oldest (2015), separated by several years from the ADCP and lidar missions, and that the vertical accuracy check points were surveyed by SWFWMD in 2019. As the river bottom is dynamic and continually changing, vertical accuracy statistics computed against non-concurrently surveyed check points should be considered with that caveat.

It is also important to recognize that USGS, ASPRS, and the International Hydrographic Organization (IHO) vertical accuracy specifications for topobathymetric lidar are a function of uncertain coefficients and water depth. As expected, the vertical uncertainty increases with increased water depth, but not as a linear function. Given water depths for Rainbow River of between three and nine feet, expected vertical uncertainties for QL1b through QL3b data are in the 0.25-0.30 m (10-12 inches) range (at the 95th percentile).

In 2019, SWFWMD used the FPRN and NRTK-GPS methodology to survey 106 submerged check points in the river channel and six terrestrial, non-vegetated vertical accuracy (NVA) check points along the bank (**Figure 4**). To verify the GPS-derived check points, independent manual soundings were made and corrected to the leveled water surface. **Table 3** summarizes the accuracy statistics for SBES, ADCP, and lidar as measured by the SWFWMD vertical accuracy check point survey.

The $RMSE_Z$ errors for the three technologies are very comparable, in the 0.31–0.36 m range. It is also apparent that the mean errors for ADCP and lidar are of the same range, about 0.15 meters (six inches), but in opposite directions: lidar reported deeper bathymetry than ADCP. Finally, the most interesting result is that the error range for submerged bottom was smallest for the lidar survey, as compared with either SBES or ADCP. The narrower range of errors most likely resulted from the increased point density of the lidar survey.

Conclusions

Inland waterways present the next major challenge to topographic mapping from the tops of the mountains to the depths of the seas. In Florida, these challenges are exacerbated by mucky, non-reflective substrates and water column turbidity. However, in spring-fed reaches, such as the Rainbow River, topobathymetric lidar presents a cost- and labor-efficient alternative to more conventional hydrographic mapping. Absolute accuracies comparable

Method	Data Density (number of "points" collected)	Duration of Data Collection	Approximate Project Cost ($K)
SBES	21,558	3 man-days*	24
ADCP	862,893	6 man-days* (2 kayaks)	150 (for 3 surveys)
Lidar	18,918,044	20 minutes (on-line)	35 (does not include ground accuracy check survey)

Table 2: Advantages of using lidar rather than acoustic technologies.

** Time on-water collecting data at eight hours/day* or superior to those achieved through traditional single-beam echo sounders and/or acoustic doppler column profilers were achieved. Side benefits include simultaneous floodplain and bank mapping, and multiple lidar returns provide estimates of submerged features. This proof-of-concept study should be taken as a positive step for the use of topobathymetric lidar for inland waterways.

Acknowledgements

We thank Mike Aslaksen and Rudy Troche from NOAA/NGS for their assistance in making this project possible, C. Wayne Wright for helping to process the lidar data, and Danielle Rogers and Jordan Miller from SWFWMD for participating in the project. ■

Alvan "Al" Karlin, Ph.D. CMS-L, GISP, is a senior geospatial scientist at Dewberry and formerly from SWFWMD, where he managed all of the remote sensing and lidar-related projects in mapping and GIS. With Dewberry, he serves as a consultant on Florida-related lidar and imagery projects, as well as general GIS-related projects. He is the immediate past president of the Florida Region of ASPRS, an ASPRS Certified Mapping Scientist – Lidar, and a GIS Certification Institute Professional.

James F. Owens, PSM, is the survey manager for SWFWMD. Jim oversees all District land and hydrographic survey activities. Jim has been involved in both inland and marine hydrographic survey for the District and in private practice. For the District, Jim has been directing aerial and lidar control and vertical accuracy check point surveys since 2006 and has participated in District-wide topographic and boundary survey.

Emily Klipp is a project manager with Dewberry and has more than 12 years of experience working with topographic and topobathymetric lidar data. She specializes in geospatial project planning and management, QA/QC of topographic and bathymetric data, vertical and horizontal accuracy assessments, and creation of a variety of digital mapping products using various software platforms. She currently manages projects for USGS, NOAA, USACE, SWFWMD, and other state and local governments, including aerial lidar acquisition, remote sensing, photogrammetry, and map production. Emily is a member of ASPRS.

Amar Nayegandhi, CP, CMS, GISP, is a senior vice president and director of remote sensing at Dewberry. He oversees the geospatial and technology services group for Dewberry's contracts with federal, state, and commercial clients. With more than 20 years of experience, he is a recognized expert in topographic and bathymetric lidar data acquisition and processing. He is a past director of the ASPRS Lidar Division, an ASPRS Certified Photogrammetrist and Certified Mapping Scientist – Remote Sensing, and a GIS Certification Institute Professional.

	SBES	ADCP	Lidar
Number of check points	30*	93	93
Mean error			
Submerged bottom	0.44	0.12	-0.15
Terrestrial	N/A	N/A	-0.05
Error range			
Submerged bottom	0.0 – 1.43	-0.61 – 0.55	-0.83 – 0.10
Terrestrial	N/A	N/A	-0.11 – 0.05
$RMSE_z$			
Submerged bottom	0.36	0.32	0.31
Terrestrial	N/A	N/A	0.03

Table 3: Vertical error statistics for SBES, ADCP and lidar surveys of the Rainbow River Aquatic Preserve. All values are in meters.

**SBES soundings within 20 feet of a SWFWMD check point; N/A = not-applicable*

Silvia, continued from page 64

throughout the industry, despite the requirement to adhere to the ASPRS Standard Point Class tables. This is particularly prevalent in legacy datasets preceding the current tables, or datasets utilizing LAS Domain Profiles.

Neutral arguments:

- The description field can be used to add clarity for a specific application without modifying the existing name or meaning in the ASPRS Standard Point Class tables.
- Entries in the VLR can include classifications not present in the LAS file, such as including Class 9 (Water) in an edge tile that doesn't happen to have any water points.

The consensus as I understood it was that the purpose of the VLR is to provide clarity to human users who are interacting with the LAS file contents, particularly for the first time. Although the new VLR will allow user-defined entries for each of the ASPRS reserved point classifications, the specification must emphasize the importance of compliance with the meaning of the existing standard to improve interoperability.

Other action items

In addition to the above discussion, we received or refreshed the following specific action items:

- Create example LAS with the new classification table VLR.
- Close the existing ExtraByte thread and create a new one consolidating the previous discussions of standardized ExtraBytes.
- Fix typo in Table 17 header.
- Add wiki page for System ID.

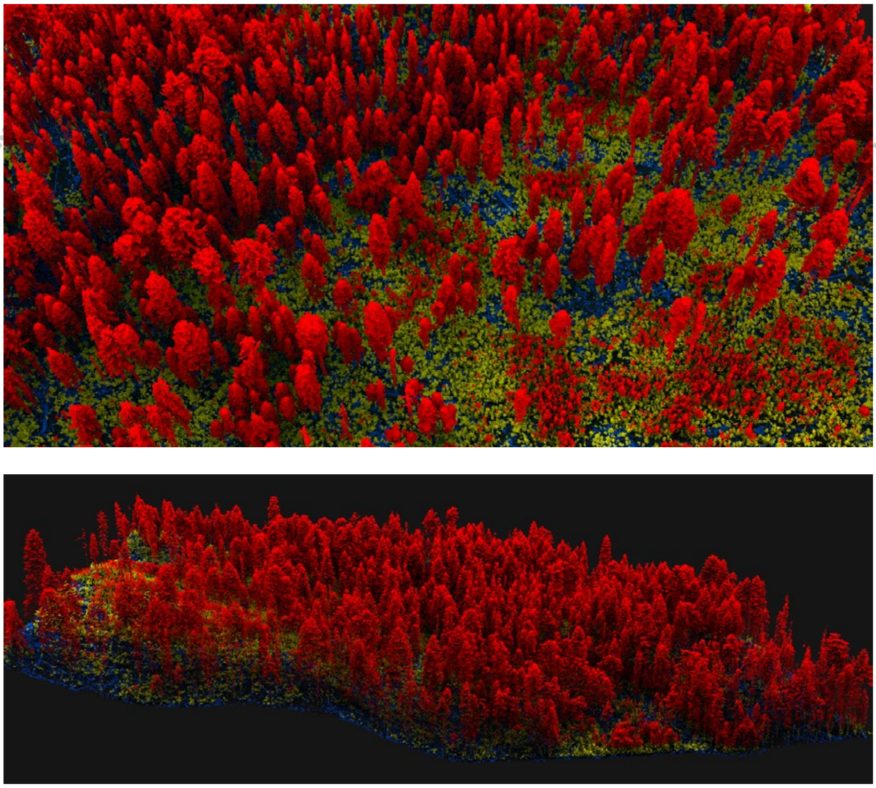


Figure 2: Forestry applications frequently require classifications of different vegetation layers, but the distinction between Low, Medium, and High Vegetation must necessarily vary between forest types. An updated Classification Lookup VLR v2 could provide a means for the LAS file to document itself.

Keep an eye on the ASPRS newsletter and the LAS homepage[3] for the final review of LAS 1.4 Revision 16, which is expected to go forward for publication by the end of 2020.

Welcome new members

In November, the LWG welcomed new members Nick Kules (Dewberry), David Stolarz (ASPRS), Rupesh Shrestha (Oak Ridge National Lab) and Ezra Che (Oregon State University). These new memberships highlight the shift of the LWG's composition from sensor manufacturers toward software developers and data users, which mirrors the natural shift of the remote sensing community from acquiring data to maximizing the utilization and value of point cloud datasets.

To join the LWG, you must be a paid member of ASPRS, so that the organization can continue its leadership position in the remote sensing community.

For those who haven't been able to attend any of my presentations on the present and future of the LWG, the October/November 2020 issue of *LIDAR Magazine* includes an article on the inner workings of the LWG and LAS itself[4].

3 www.lasformat.org

Evon Silvia, PLS, is a solutions architect with NV5 Geospatial, Corvallis, Oregon. With his diverse background in civil engineering, land surveying, sensor research, and computer programming, Evon looks at remote sensing a little differently. He has an MS in geomatics and civil engineering from Oregon State University with a focus on lidar and joined Quantum Spatial in 2011 to advance its land surveying and lidar processing divisions. As chair of the ASPRS LAS Working Group, Evon is passionate about data quality and strives to improve collaboration and communication in the remote sensing community.

4 Silvia, E., 2020. LAS: what's on the horizon, *LIDAR Magazine*, 10(5): 12-16, October/November 2020.

EVON SILVIA

LAS To Have New Classification Lookup VLR

The LAS Working Group's (LWG) meeting on 16 November 2020 focused primarily on the updated Classification Lookup Variable Length Record (VLR) proposed in Issue #82[1] and developed over the past year. If you aren't familiar with VLRs, they are a means to customize and extend the LAS header with user-defined data such as lookup tables, indexing data and coordinate system definitions. Learn more in §2.5 of the specification[2].

Before we go into depth, let's review some background of the LAS Classification Lookup VLR. The latest edition of the LAS 1.4 specification (Revision 15) includes the venerable Classification Lookup VLR (§4.1), which dates all the way back to the original publication of LAS 1.0 in 2003. The VLR is composed of a simple array of 256 16-byte blocks—one byte for each classification number and 15 bytes for each classification description (**Figure 1**).

Despite its pedigree, the Classification Lookup VLR has been widely ignored for over 17 years. A brief survey of the community failed to produce a single person or example file using it. The reasons appear to be threefold:

1. It is quite easy for the VLR to fall out of sync with the file contents.
2. 15 bytes isn't nearly enough for a description.
3. It was never clear how to use the VLR, so external files were utilized instead, such as a README text file, metadata, reports and custom file formats for visualization software.

1 https://github.com/ASPRSorg/LAS/issues/82
2 http://www.asprs.org/wp-content/uploads/2019/07/LAS_1_4_r15.pdf

4.1 Classification Lookup

User ID	LASF_Spec
Record ID	0
Record Length after Header	256 records * 16 bytes per struct

```
struct CLASSIFICATION {
    unsigned char ClassNumber;
    char Description[15];
}; //total of 16 bytes
```

Figure 1: The current LAS 1.4 Revision 15 definition of the Classification Lookup VLR includes space for only 15 characters for classification names or descriptions, which isn't nearly enough.

Nevertheless, the existence of external files with this exact information confirms its potential usefulness, particularly for handoffs of data between firms, departments or large data repositories, because external metadata is easily separated from the LAS. In addition, the meaning of each point classification is not always apparent in point cloud visualization software, and a lookup table is often helpful for human users attempting to interpret what they see.

The ASPRS Standard Point Class tables (Tables 9 and 17 in LAS 1.4 R15) attempt to add clarity by providing standard meanings of a range of values, such as "Ground" for Class 2. But many are intentionally vague and the precise interpretation will vary by application. For example, Classes 3-5 are reserved for Low, Medium and High Vegetation respectively. One application may define Low Vegetation as being 0.5-2.0 meters, while another may define it as 0.0-3.0 meters (**Figure 2**). Both definitions are equally valid.

The current proposal is to add a second version of the Classification Lookup VLR (v2) that allows for longer classification names and adds a description field for each classification.

In the November LWG meeting, therefore, we had significant discussion and disagreement over whether the lookup table should be allowed to deviate from the ASPRS Standard Point Class tables, i.e. whether point classes 0-63 (which are technically reserved for ASPRS) should even be allowed in the Classification Lookup VLR v2.

Arguments in opposition:

- Allowing deviation directly violates the existing specification, which explicitly requires compliance with the ASPRS Standard Point Class tables.
- Free-form classification names prevent machine interpretation of the classification table and therefore automatic filtering—e.g., a ground triangulation routine couldn't infer which classification(s) to use.

Arguments in favor:

- Allowing deviation enables non-English speakers to override the classification names with the equivalent phrasing in their own language.
- There is already widespread usage of the reserved classifications

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