LIDAR MAGAZINE

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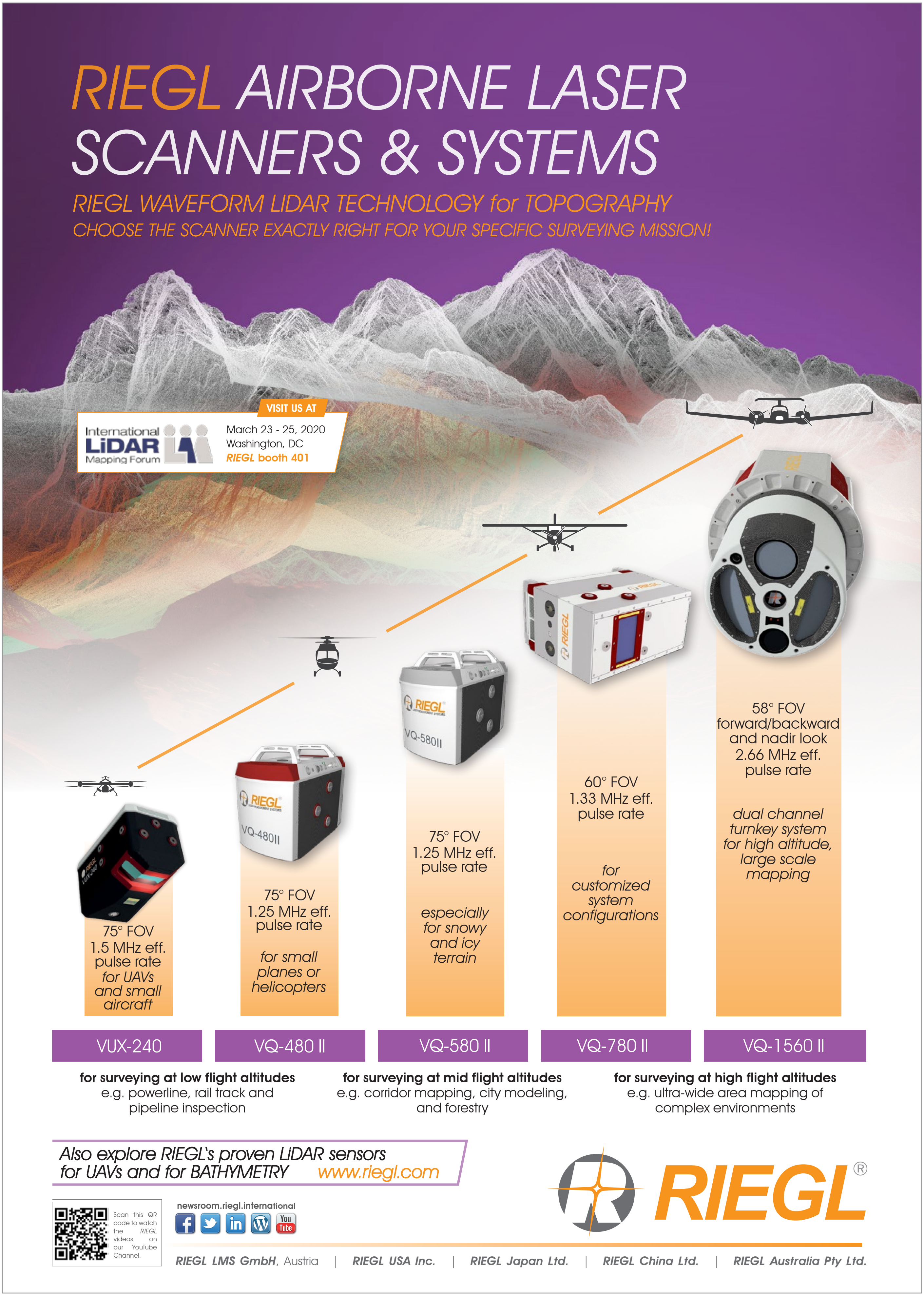
JAN/FEB 2020

THE PAST AND FUTURE OF HANDHELD SCANNING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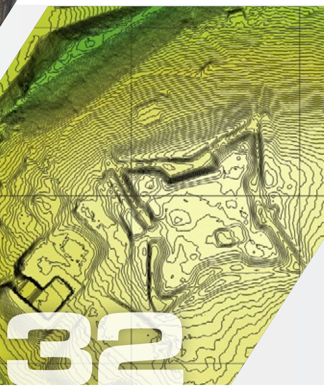

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◀ ON THE COVER

A technician collects data with the Paracosm PX-80 SLAM system, developed for capturing both indoor and outdoor spaces. The device utilizes a Velodyne VLP-16 lidar sensor.

DR. A. STEWART WALKER

Starting at the Top

The new year peaked early for *LIDAR Magazine*! I was invited to attend the GeoBuiz Summit, which took place from 12 to 14 January 2020 in Monterey, California, billed as, "The only geospatial business leaders' conference that brings together thought leaders and decision-makers from North America, the IT and geospatial hub of the world. Join us to understand the future business directions and digital transformation trends." This prestigious conference, of which I was told this was the sixth iteration, is run by the well known Geospatial Media and Communications organization from India, which publishes *Geospatial World*, and conducts geospatial market research. The organization's conferences take place all over the world, the best known being the Geospatial World Forum events. Its CEO, Sanjay Kumar, is a familiar figure on the world geospatial stage and his aspirations to run high-level events and leverage the power of the geospatial industry by persuading people and organizations to work together have made their mark. More recently, he has been instrumental in the foundation and success of the World Geospatial Industry Council (WGIC), an association of companies representing the entire ecosystem of the geospatial industry[1].

Around 150 movers and shakers from the geospatial world gathered in Monterey. The exalted level of the attendees was manifest at the opening session, during which Sanjay, Scott Pace (US National Space Council), Jack Dangermond (Esri) and Steve Berglund (Trimble) shared the stage. Steve was on fine form, having only a week before ascended to the post of chairman, relinquishing his CEO position—to CFO Rob Painter—after 20 spectacular years at the helm. The meeting consisted mainly of panel discussions, both plenary and parallel. The magazine's role was to moderate a panel on "Miniaturisation and Innovation in Sensors", the first of three panel discussions in a parallel session on New Space. Between the first and second of these panels was a lightening talk by famous visionary Michael Jones.

The panelists were Anthony Baker, CEO, Satellite Vu, United Kingdom; Chris McCormick, chairman and founder, Planet IQ, Colorado; and Jean-Francois Gauthier, VP sales and marketing, GHGSat, Canada. Each of these represented a start-up in the process of raising capital and launching a constellation, each to sense different phenomena—heat of buildings; the atmosphere; and gases such as methane and CO_2. They were deeply knowledgeable and easily answered the set questions as well as some from the engaged audience. Other space start-ups, such as Capella Space, the subject of an article

1 www.wgicouncil.org

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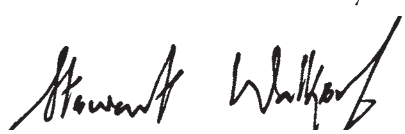
on page 38, featured in other parts of the summit and, of course, one must wonder how the New Space market will evolve. In the 1960s or early 1970s, ambitious geofolk wrote software for least squares adjustments, stoically punched on decks of cards, but now they seek venture capital and launch satellites … will there be a shaking out or will the sky indeed go dark? Smallsats with lidar remain elusive, but SAR smallsats are here, sure to make a difference especially with measurement of small changes in elevation through time.

A member of a panel on "Realtime analytics and the location economy" on the opening morning was Arra Yerganian, chief brand officer of Tivity Health. This is not a geospatial company, but it's well known to your reporter—it runs the Silver Sneakers program through which those of a certain age can enjoy gym facilities free of charge! At lunch on the second day I met Dr. Erwin Frei. I had last talked to Erwin at a Leica sales conference in the glorious Swiss resort of Wildhaus in the early 1990s. For a while he managed the Leica plant in San Ramon, California, manufacturing TLS systems following the acquisition of Cyra. Now he is head of hardware for Palo Alto start-up DeepMap, which provided top-of-the-line mapping for AVs. His founder and CEO, Dr. James Wu, was formerly chief architect at Baidu and his CV also features Google and Apple! The last plenary on the first day was a panel discussion, "Investors: mentoring and driving geospatial innovation", expertly moderated by Nigel Clifford of Marlin Equity Partners. The panel was asked whether there is anything special about the geospatial industry in terms of the financing and nurturing of start-ups. "Not really" was the consensus! Nor was there anything especially forbidding about the regulatory environment, which was less intense than that of the pharmaceutical industry. The second day opened with a strong plenary, "GEOBIM: driving digitalization of construction and engineering industry", moderated by Nadine Alameh, CEO of OGC. There was lively discussion of whether the construction industry is still living in the dark ages or whether, with digital twins and the sharing of voluminous high-quality data, it is already enjoying time and cost savings as well as a reduction in waste. And on several occasions, attendees directed questions to the podium on new export controls that include "geospatial imagery software specially designed for training a deep convolutional neural network (deep CNN) to automate the analysis of geospatial imagery and point clouds"[2]. One of the government experts who ventured a response was Kevin O'Connell, director, Office of Space Commerce, US Department of Commerce. His advice? The controls are in a period of public comment—use it!

The final plenary was a discussion on "The big debate: data protection and privacy conundrum—who and how much?" A large panel representing academia, government and private industry was spiritedly moderated by Sanjay and there was no question of the gravity of the issue and the intolerance of any "head in the sand" attitude. WGIC has just drafted a report, "Geospatial information and privacy: a quick scan of privacy legislation in selected countries," which should prove a useful resource as the debate continues. The meeting ended with a glass of champagne to celebrate Sanjay's 50th birthday, underlining the friendly environment in which the thought-provoking panel discussions, lunch-time round-tables and networking took place. It was a privilege to be invited.

Your reporter's week was not over, however. I had an absolutely fabulous meeting with Quanergy Systems in Sunnyvale, California, one of the big automotive lidar players whose systems have entered the UAV-lidar world. Quanergy's M8 is included in systems integrated by the familiar UAV-lidar integrators who often feature in *LIDAR Magazine*, for example in GeoCue's True View product. I met with CTO and co-founder Dr Tianyue Yu, and marketing communications manager, Sona Kim. The discussion will be published as a full article soon, but it came at a strange moment. On 7 January, Velodyne LiDAR had announced the shift of founder and CEO David Hall to the position of chairman and the accession of CTO Anand Gopalan to the top spot[3]. I met with Quanergy on 15 January and, indeed, one of my questions was about succession planning. The following day, Quanergy announced that CEO and co-founder Dr. Louay Eldada would step aside, retaining a consultant/evangelist role[4]. Indeed he had left the board a couple of days before I arrived and had been replaced as CEO by board chairman Dr. Kevin Kennedy[5]—there is never a news famine in Silicon Valley!



A. Stewart Walker // Managing Editor

2 https://www.jdsupra.com/legalnews/bis-publishes-a-temporary-unilateral-55841/

3 https://lidarmag.com/2020/01/07/velodyne-lidar-announces-anand-gopalan-as-new-ceo/

4 https://www.bizjournals.com/sanjose/news/2020/01/17/founder-steps-down-as-ceo-of-sunnyvale-lidar.html

5 https://www.bloomberg.com/news/articles/2020-01-16/quanergy-ceo-steps-down-after-driverless-tech-unicorn-stumbles

Using PX-80 to generate a colorized point cloud of a complex indoor environment.

The past and future of handheld 3D scanning

Handheld SLAM-based lidar scanners are changing the way we think about 3D capture

In the past few years, SLAM-based handheld lidar scanners have made a big entrance into the 3D-capture market. These solutions are becoming popular not simply because of their speed, low cost, or ease of use—but because the combination of these three factors has opened up entirely new use cases for 3D capture that weren't possible with traditional methods.

Florida-based Paracosm[1] is at the forefront of this development. Its flagship product, the PX-80 handheld lidar scanner, has helped surveyors to capture large indoor and outdoor areas that would have been prohibitively slow with conventional methods, enabled AEC firms to capture building sites with a frequency that they never considered before, and allowed total beginners to capture 3D data that would have once required a team of trained professionals.

1 https://paracosm.io/.

BY SEAN HIGGINS

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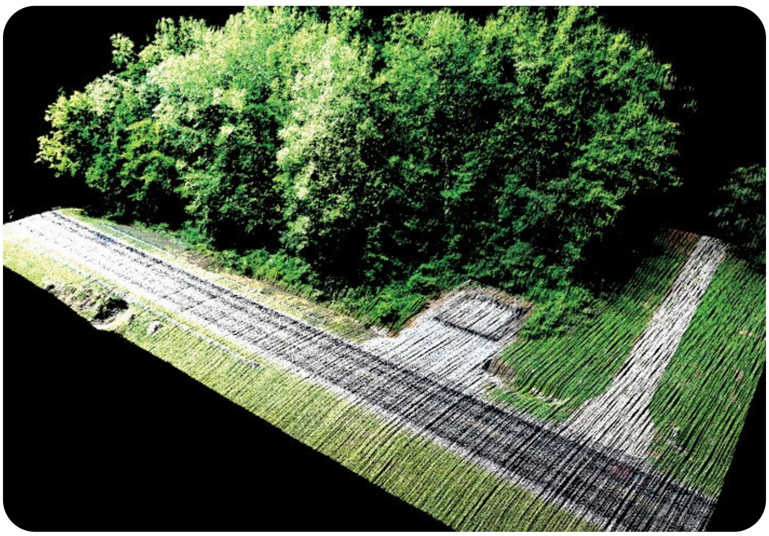
UAS LIDAR/Imagery Sensor Fusion



Dual Cameras

LIDAR Scanner

Google Processor

TrueTrack Flightlines

Workflow Software

Applanix Positioning

The True View 410 is the industry's first integrated LIDAR/camera fusion platform designed from the ground up to generate high accuracy 3D colorized LIDAR point clouds. Featuring dual GeoCue Mapping Cameras, a Quanergy M8 Ultra laser scanner and Applanix Position and Orientation System (POS), the result is a true 3D imaging sensor. With its wide 120° fused field of view, the True View 410 provides high efficiency 3D color mapping with vegetation penetration in a payload package of 2.2 kg.

GeoCue Group

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PX-80's proprietary SLAM was developed for capturing both indoor and outdoor spaces.

From consumer roots

Readers may not expect that Paracosm was founded to develop 3D-mapping technology for consumer applications—and that today's PX-80 enables a wide variety of use cases precisely because it developed out of those consumer tools.

Paracosm was co-founded by current president Amir Rubin, an engineer who cut his teeth at a range of startups in the surprisingly tech-friendly Florida university town of Gainesville, which gave rise to well-known companies such as WebMD and the defunct music streaming platform Grooveshark. After a decade working as an engineer and developer in other people's companies—and a short time developing a patented system for weighing livestock using only an RGB camera—Rubin gathered a team to start working toward his own vision: a product that would enable anyone to map the world in 3D.

At first, Rubin explains, that took the form of a low-cost 3D technology for collaborative mapping. This technology caught the attention of Google, which enlisted Paracosm to help on an ambitious initiative called Tango, the world's first 3D-mapping smartphone.

Amir Rubin, president and co-founder of Paracosm.

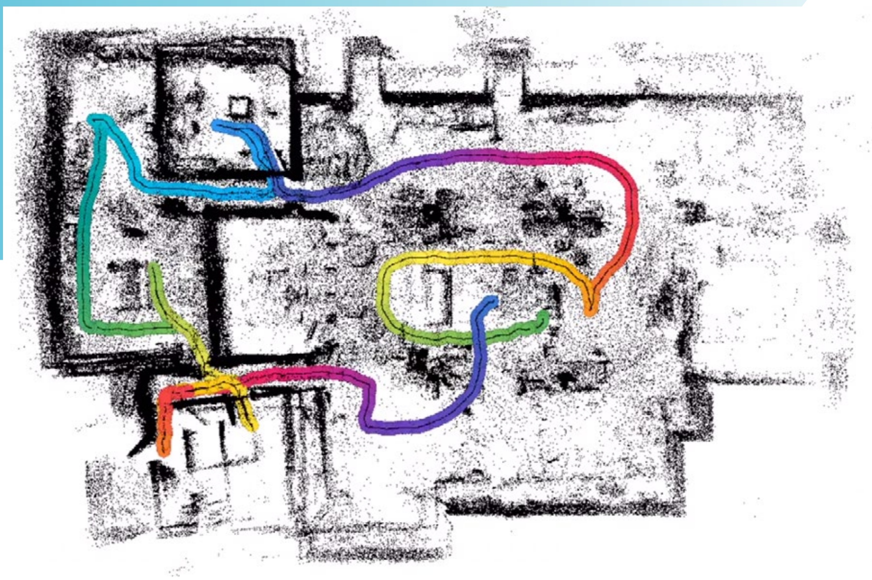
In 2015, Paracosm finished developing its own low-cost, consumer-grade, handheld 3D-mapping system. Though the tool attracted interest and investment from consumer robotics companies such as iRobot, it also caught the eye of a group that would prove more important to the company: engineers, contractors, and building surveyors. These forward-looking professionals saw that low-cost, SLAM-based 3D scanners had potential far beyond consumer applications.

"We started getting calls out of the blue," says Rubin. "They saw our handheld scanning system and started asking if they could use it to scan MEP[2] spaces, to do basic building survey, or to monitor their construction sites."

The only problem was that the system relied on 3D data from a structured light sensor, a consumer-grade 3D-capture technology that Paracosm used because it was small and inexpensive. In other words, the system was optimized for consumer use, which limited its performance in more demanding applications. Rubin explains, "That's when we re-imagined our tech from the ground up and asked ourselves, what does a perfect, fast, handheld building scanner look like?"

The result is PX-80, a handheld, SLAM-based, lidar scanner optimized for commercial applications. It features a Velodyne VLP-16 lidar—often seen in autonomous vehicles—alongside a panoramic camera and a survey-grade inertial measurement unit (IMU), all of which it uses to produce accurate 3D

2 Mechanical, electrical and plumbing.



As you walk through a space with the PX-80, the SLAM tracks your path and creates a coherent point cloud of the environment.

point clouds and automatically colorize those point clouds while the user moves at a walking pace. Since it began shipping in 2018, PX-80 has seen use in over 15 countries, and in applications such as MEP capture, 2D floor-plan generation, mine mapping, construction monitoring, and forestry.

A cutting-edge technology under the hood

Paracosm’s core product, however, isn’t scanning hardware. The Paracosm technology that has survived the transition from consumer-grade to survey-grade mapping, and all the hardware iterations in between, is its 3D-data processing algorithm.

This algorithm is built on a technology known as SLAM, or simultaneous localization and mapping. SLAM technology has its roots in robotics, where it was developed to help machines navigate unknown environments, a devilishly complex task that requires locating the machine in a new space at the same time as it maps that space for the first time. A SLAM algorithm works by gathering data from sensors onboard the robot—such as RGB cameras, lidar sensors, and IMUs—and fusing those data together to make its sophisticated calculations.

SLAM algorithms can be optimized for mapping applications, facilitating the development of lidar scanners that don’t need a tripod or GNSS to return precise, accurate results. The SLAM powering the PX-80, for example, can determine exactly where the scanner was on a job site or building when it captured each photo and each portion of the point cloud. “You can think of each position, each step that it calculates on your walking path, as a virtual tripod,” says Rubin. “We use these to position the points captured by the lidar.”

This means that a SLAM-based handheld scanner like the PX-80 enables users to perform a capture at a regular walking speed. Thus SLAM-based scanning is much faster to capture large indoor and outdoor environments in 3D than traditional methods and offers the bonus of real-time tablet-based feedback on the scan being captured.

SLAM’s benefits do come wi tradeoffs. In exchange for the g increased speed and lower cost capture, SLAM generates data accuracy than traditional meth

The system utilizes a Velodyne VLP-16 lidar sensor.

Paracosm’s handheld PX-80 fuses data from an RGB sensor, a lidar and an IMU to produce accurate and colorized point clouds as the user walks.

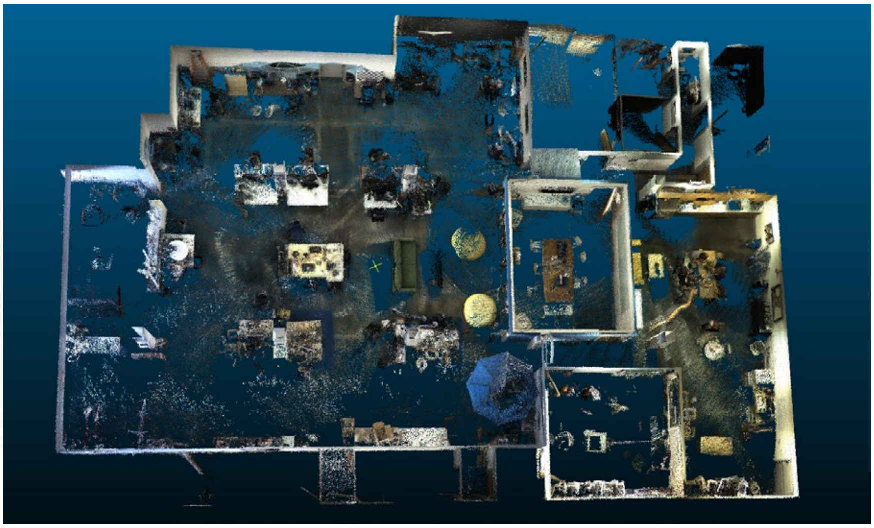
An automatically colorized PX-80 point cloud of the interior of the Paracosm office.

PX-80, for instance, offers 1-3 cm global accuracy, whereas the top tier of tripod-based lidar systems perform in the millimeter range. However, many find that the reduction in overall cost and increased speed more than make up for this difference—whether that holds true for a project depends on whether the SLAM device offers good enough accuracy for the final project deliverable.

The deliverable determines the tool

When British general contractor nmcn learned about handheld 3D capture, they saw the technology's potential. Like the engineers who called Amir Rubin in Paracosm's early days, nmcn saw that handheld scanning could speed up their workflow and reduce costs, helping them to capture 3D data more regularly than traditional methods.

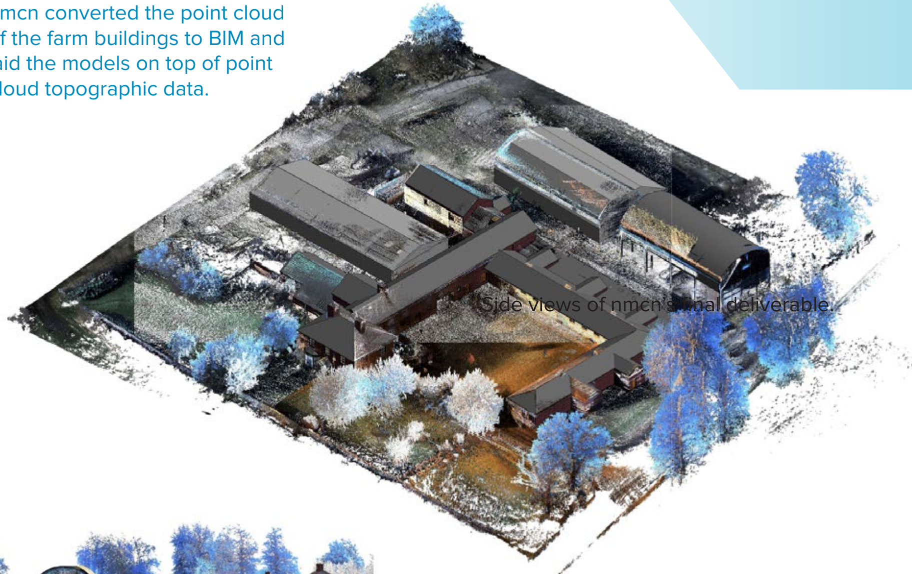
To test a PX-80 SLAM-based handheld lidar scanner, nmcn handed it to their head of digital transformation, Gary Ross. A mechanical engineer with no scanning experience, Ross received 15 minutes of training and set off immediately to scan a complex of derelict farm buildings. At the same time, a team from a 3D-scanning service provider captured the site using



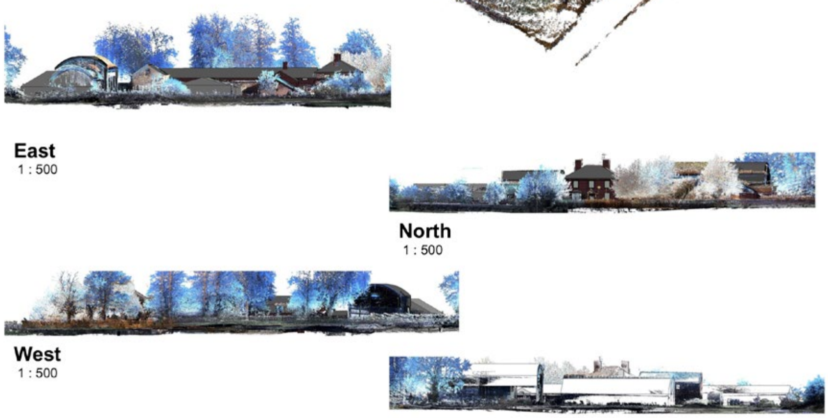
Floor-plan view of a PX-80 point cloud.

An uncolorized PX-80 point cloud of the Paracosm office.

nmcn scanning for their farm refurbishment project.



nmcn converted the point cloud of the farm buildings to BIM and laid the models on top of point cloud topographic data.



Side views of nmcn's final deliverable.

tripod-based lidar scanners. Both data sets were used to generate 2D floor plans and 3D BIM models.

In a final review, Ross argued that handheld SLAM-based scanning hit the right combination of speed, cost, ease of use and accuracy for the final deliverable they wanted. He says the PX-80 allowed him to capture the site at 1/10 the cost and 1/8 the time of traditional methods. He also notes that when nmcn generated models on top of the two point clouds, and then laid the models on top of one another, "There was 39 mm difference over the entire site, which spanned 57 m. The inaccuracies of modeling over the point cloud could have caused the 39 mm difference on either drawing, and as such the scanner technology was neither here nor there."

nmcn determined that handheld lidar scanning won't be appropriate for final deliverables that require sub-millimeter accuracy, but that hasn't stopped PX-80 from changing the way the firm thinks about 3D. "This sort of shift in cost and time and skills needed leads to a complete re-think of how and why we use laser scans," Ross says. Where, in the past, nmcn would scan a project once—at most—now, they can start to use scanning as a regular part of their process. "Certainly the scanner can now be used on every project, no matter how large or small."

As proof, Ross offers a list of potential applications for handheld SLAM-based lidar scanning that includes floor-plan generation for asset management, as well as topology capture, construction progress monitoring, as-built generation, dilapidation monitoring, and logistics/traffic management, among many others.

Ross concludes by noting that the value nmcn finds in handheld, SLAM-based 3D capture is simple: it brings his team data that they would never have seen before. "As data is central to our effectiveness and efficiency gains as we develop," he says, "this is a great leap forward in the data we can interrogate, analyze and measure—thereby improving the efficiency of our projects."

Sean Higgins is the former managing editor of 3D-scanning industry publication *SPAR3D.com*, where he provided broad coverage of innovative commercial 3D technologies for five years. Currently, he heads up content strategy at Paracosm, where he develops materials to educate new and experienced 3D professionals about SLAM-based handheld lidar solutions.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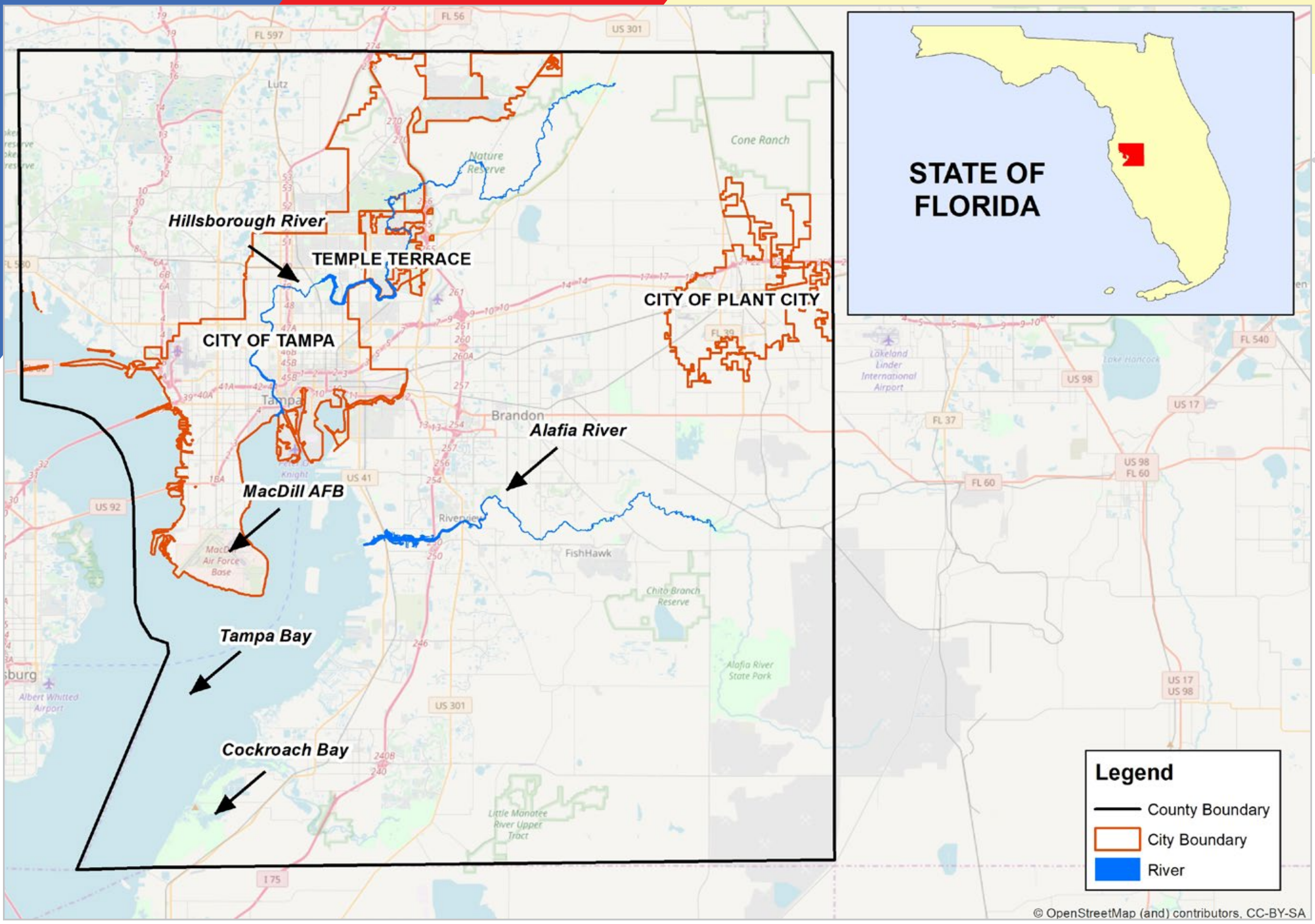


Figure 1: Location and boundaries of Hillsborough County, Florida.
Source: http://www.census.gov., 2020

Why Invest in High-Density Lidar?

Southwest Florida maps once, uses many times

Tropical Storm (TS) Debby rolled through the Tampa Bay, Florida, area in late June 2012, dropping over 12 inches of rain in a 24-hour period, very close to the design storm for water modeling. Following TS Debbie, the area did not see any major tropical storms or hurricanes until the summer of 2015, when it experienced record-breaking, non-hurricane-related rainfall. In a series of summer 2015 rainfall events, the region received more than 38 inches of rain during a two-month period. These deluges led to isolated flooding throughout the region and the need to reexamine and update existing stormwater and flood models.

The Southwest Florida Water Management District (SWFWMD), through its Watershed Management Program, cooperates with counties and cities to maintain and update stormwater/surface water—also hydrological and hydraulic (H&H)—models for the district's 16-county area, which includes Hillsborough County and the City of Tampa. Since SWFWMD is a Federal Emergency Management Agency (FEMA)

BY AL **KARLIN**, AMAR **NAYEGANDHI** AND KEITH **PATTERSON**

Cooperating Technical Partner (CTP), the floodplain delineations that result from the H&H models are used to update the Digital Flood Insurance Rate Maps (DFIRMs). Therefore, the base H&H model topographic data must conform to the FEMA guidelines for topographic mapping[1] and the use of lidar technologies. The existing county lidar data, acquired in 2007, however, did not meet FEMA and U.S. Geological Survey (USGS) specifications (USGS LBS v1.3)[2] and could not be used for updating the models.

Because lidar forms the topographic basis for the stormwater model updates and the existing 2007 lidar data was not meeting the FEMA/USGS specifications, a new lidar survey was necessary. Accordingly, SWFWMD partnered with the Public Works Department of Hillsborough County and the Stormwater Engineering Division of the City of Tampa to plan and fund a new lidar mission for the county and city.

During the planning phase, it was determined that there would be multiple uses for the new data beyond the stormwater/surface water modeling. A "map once, use many times" approach to the project emerged and was embraced by the three cooperating partners. With this agenda in mind, SWFWMD issued a request for proposals, and, rather than specifying any particular sensor or technology (linear, Geiger, flash, etc.), provided a set of highly detailed specifications for both the expected point cloud and breaklines for the potential responders to consider.

1 FEMA, 2016. *Guidance for Flood Risk Analysis and Mapping: Elevation Guidance*, 17 pp, May.

2 Heidemann, H.K., 2018. *National Geospatial Program: Lidar Base Specification*, version 1.3, 101 pp, February.

Characteristic	Specification
Sensor	RIEGL VQ-1560i (SN2221277)
GPS/IMU	Applanix POS 6487/Trimble AV37
Airframe	Cessna T206H (Stationair)
Flight dates	31 Jan 2017—4 March 2017 (9 missions)
Flight altitude	4300' AGL (1036 m)
Ground speed	120 knots (61.7 m/sec)
Flightlines	110 (+3 calibration lines)
Overlap	60% sidelap
Aggregate nominal pulse density	24 pulses/m^2
Aggregate nominal pulse spacing	< 0.2 m
Non-Vegetated Vertical Accuracy (NVA)	10 cm (rmse) from NAVD88
Vegetated Vertical Accuracy (VVA)	+/- 19 cm from NAVD88

Table 1: Hillsborough County mission lidar acquisition design and specifications.

Dewberry won the solicitation, in part because the firm presented a sensor-agnostic approach. Rather than proposing a sensor or lidar technology, Dewberry proposed to determine the sensor(s) and flight plan(s) that would best meet the multiple needs of the cooperators, and still remain within budget. In 2016, after a thorough review, Dewberry helped SWFWMD determine that the best course of action would include a new Riegl VQ-1560i sensor and a flight plan to utilize an aggregate nominal pulse density (ANPD) of 24 pulses per square meter, which would accomplish the "map once, use many times" objective.

The mission was planned for a single sensor during the early winter of 2017 (15 December 2016 - 28 February 2017).

MISSION DETAILS

Hillsborough County, approximately 1192 square miles in extent, is located on the west coast of Florida with Tampa Bay along its western boundary. The lidar acquisition was planned to exceed the FEMA/USGS pulse density/spacing specifications for FEMA/USGS Quality Level 1 (ANPD > 24 pulses/m^2) and map to—at a minimum—North American Vertical Datum of 1988 (NAVD88) 0-feet (ellipsoidal height adjusted to orthometric heights using GEOID12B) on the tidally-influenced western boundary. The mission specifics are given in **Table 1**.

CHALLENGES TO DATA ACQUISITION

The Hillsborough County area of interest presented three major challenges to the collection mission, including weather, airspace accessibility, and tides.

1. Although late-fall/early-winter is typically the driest portion of the year, the late summer and early fall of 2016 were exceptionally rainy (12 inches of precipitation through November) as Hurricane Hermine brushed the area, leaving some wetlands and low-lying areas saturated into the late fall and early winter months. As it was paramount to collect the data during the driest portion of the year, and having recently followed an abnormally rainy period, acquisition missions were curtailed for a

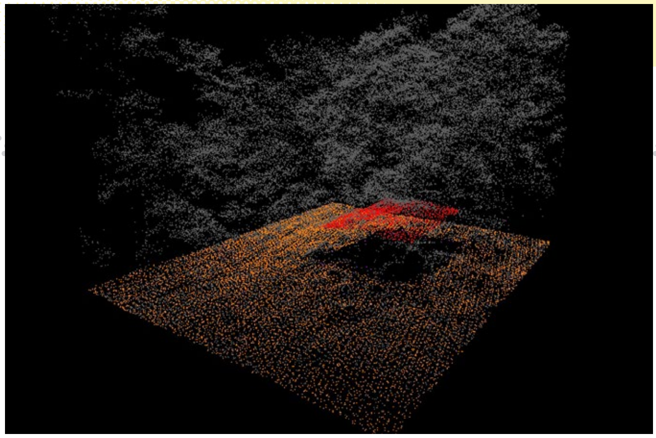


Figure 2a: Aerial image showing areas in unincorporated, rural Hillsborough County where buildings are obscured/partially obscured (yellow circle) by tree canopy.

Figure 2b: Obscured shed roof (red points) in the yellow circle (above) in the high-density lidar point cloud.

minimum of 72 hours following a rain event over half an inch. This was necessary to permit water levels to recede and soils to drain.

2. Tampa is home to MacDill Air Force Base, which serves as the headquarters for the Southern Command (USSOCOM), and Tampa International Airport (TIA), a 24-hour, international service airport. Airspace issues in the control of these installations required close coordination with both Federal Aviation Administration and Military Air Traffic Control.
3. One of the goals of the project was to collect elevation data to a minimum of NAVD88 0-feet along coastal features. This southwestern portion of the peninsula of Florida experiences two daily tidal cycles: when missions extended over six hours in duration, therefore, tidal variations along the coastline, through Tampa Bay, and into the Hillsborough and Alafia Rivers required careful monitoring. The tidal/temporal variations necessitated a series of elevational-stepped CoastalFeature polygon breaklines.

SPECIAL CONSIDERATIONS and CHALLENGES

CoastalFeature-Breakline: The eastern Gulf of Mexico typically experiences two low tides and two high tides per day, which complicates mission planning along the coastline. As budget would not permit tide-synchronized collection, coastal tidal stations were required to be monitored during acquisition, and, in order to maximize acquisition efficiency, the mission specified that ground would be collected to, at minimum, NAVD88 0-feet. This resulted in temporal variation along Tampa Bay and upstream into the Hillsborough and Alafia rivers, so a series of CoastalFeature breakline polygons were developed to indicate the end of mapping; this feature was not designed to represent the shoreline.

Hydro-Breaklines: Breaklines are typically collected to support a lidar-derived digital elevation model (DEM) to be used for H&H modeling. USGS LBS v1.3 specifies breaklining waterbodies over two acres as polygons, and rivers/streams over 100 feet wide as dual-line drains. The breaklines are collected at the water's edge. These data are then used to hydro-flatten the DEM. Hillsborough County contains only two rivers, however, the Hillsborough River and the Alafia River, which exceed the 100-foot-width criterion in some places. Similarly, most stormwater retention ponds in the county are under two acres; typical engineered stormwater retention ponds average approximately 0.5 acre. Finally, there are hundreds of miles of water conveyances (creeks, channels, ditches, canals, etc.) that are under 10 feet in width, but are important to the stormwater/surface water models.

To accommodate the H&H models, (1) waterbodies 0.5 acre or larger were captured as single-elevation (Z-locked) polygons, and (2) all flowing rivers, creeks, and ditches over eight feet wide were collected as dual-line drains (DLDs), with two lines representing the opposing banks with varying elevations, but monotonically flowing downhill. After inspection of the classified bare-earth data, it was determined that drains less than eight feet wide that were not flowing were clearly visible in the point cloud, so these drains were not breaklined. Drains that were flowing and less than eight feet wide, however, were captured as varying elevation, monotonically flowing downhill, single-line drains (SLDs) along the thalweg of the drain.

Connectors: Although major bridges carry traffic over Tampa Bay, most roads are maintained at ground level and drains are carried under roads by pipes and culverts. Upon inspection, the headwalls on pipes were often visible in the point cloud but the invert elevation of the pipe was difficult to determine. Because the drains, DLDs, and SLDs were interpolated into the DEM for hydro-conditioning, it was necessary to insert hydro-connectors to represent the under-road pipes. These connectors served as place-holders for surveyors to measure the invert elevations for H&H modeling.

Building Footprints: Impervious surface characterization was a consideration of the cooperators. H&H models take into account both directly connected impervious area (DCIA), including paved roads, driveways, sidewalks, and parking lots, and non-directly connected impervious area (nDCIA), including rooftops, in their surface runoff calculations. For this project, the cooperators agreed to include American Society for Photogrammetry and Remote Sensing (ASPRS) Class 6 (rooftops) classified in the lidar and to use that classification to derive rooftop—dripline—polygons for nDCIA estimates. The highest ground elevation within 2.5 feet of the dripline polygon, plus one-half foot was used as the base elevation of the foundation and interpolated into the DEM.

The three cities in Hillsborough County, Tampa (1855), Temple Terrace (1920), and Plant City (1885), are all older cities incorporated over a century ago. While newer subdivisions are being built, there are also unincorporated, rural tracts dating to the early 1950s. Typically, the roofs in all but the newest subdivisions are partially, if not totally, obscured by grandfather trees, over 50 year-old oaks, and other species, as in the example below. Here, although the lidar penetrated through the trees and reflections were recorded from the rooftop, automated filtering routines failed to properly classify all of the returns (**Figures 2a and 2b**). Thus considerable manual classification was required.

FLY ONCE, USE MANY TIMES: NOVEL USES FOR HIGH-DENSITY LIDAR

While it was clearly acknowledged that the main purpose of the new QL1+ lidar would be to update H&H models for floodplain delineation, the cooperators also wanted the data to serve additional purposes. Below are a few additional uses of the data, beyond the H&H modeling.

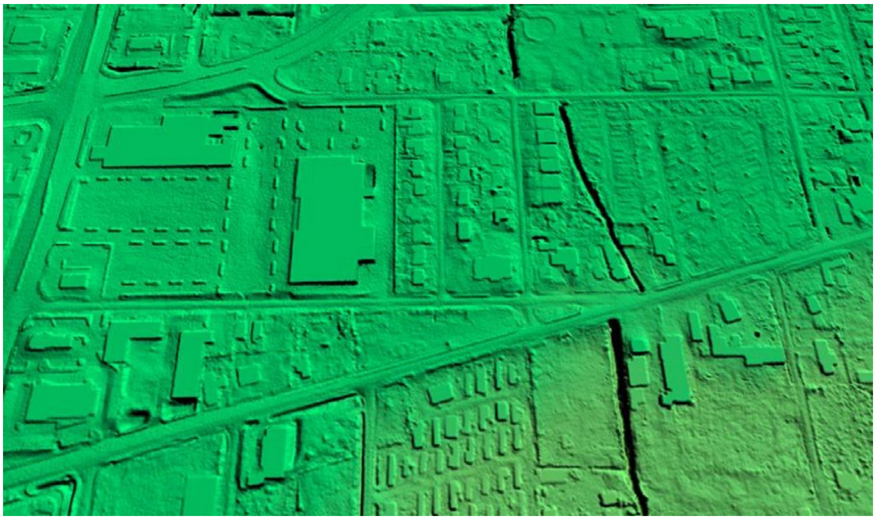


Figure 3: Modified digital terrain model (DTM) with building footprints interpolated from driplines. Building rooftops were conflated and used to create slightly elevated building footprints as rendered in GlobalMapper.

City of Tampa

To facilitate the evaluation of structure flooding, well-defined rooftop/dripline polygons were extracted from the ASPRS Class 6 high-density lidar. The rooftop/dripline polygons were conflated to the highest ground (ASPRS Class 2) elevation within 2.5 feet, then an additional 0.5 feet added to that elevation to estimate a finished floor elevation for non-elevated buildings. The finished floor elevation was assigned to the rooftop/dripline polygon and was used to interpolate the rooftop/driplines into the DEM (**Figure 3**). This resulted in building pads being visible in the DEM with elevations approximating the finished floor.

Users were enthusiastic. "I really like how the footprints of the structures are more extruded in the DEM, which helps us evaluate structural flooding more accurately for floodplain mapping purposes," enthused Ben Allushuski, CFM, Stormwater Engineering Division, Transportation and Stormwater Services Department, City of Tampa.

"I am just starting to work with the Hillsborough County data and am loving the point density," added Dr. Steven Fernandez, School of Public Affairs, University of South Florida.

Hillsborough County Planning

The Hillsborough County Planning Department faces an issue with each new subdivision: the street map requires updating as the new streets are paved. In the past, the task of adding the new streets to the county map had been performed either by extracting the data from CAD drawings, georeferencing the

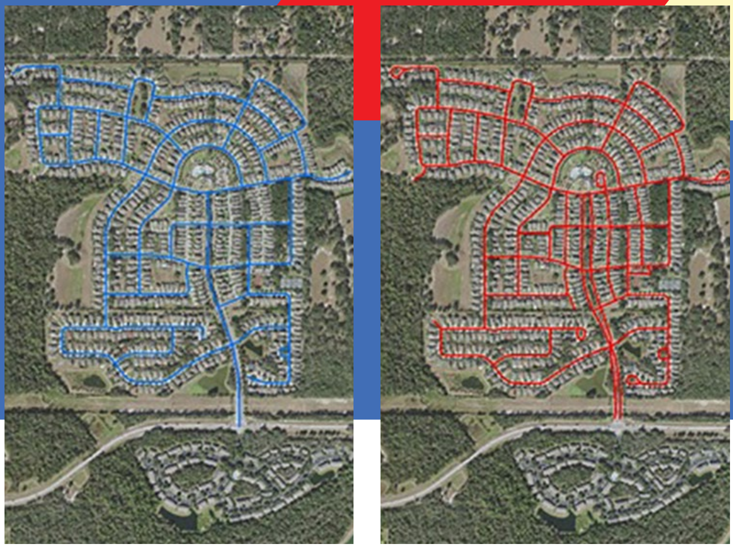


Figure 4: Maps showing results of comparing heads-up digitizing of street features (in blue, in left-hand panel) from recent imagery versus pavement feature extraction from lidar (in red, in right-hand panel) intensity imagery. There was almost complete correspondence of the final vectorized maps.
Courtesy of Hillsborough County, Public Works.

Figure 5: Map showing impervious road surface feature as extracted from the high-density lidar.
Courtesy of Hillsborough County, Public Works.

CAD data to imagery and then trying to fit the data, or by heads-up digitizing from newly flown aerial imagery.

To test the effectiveness of using the lidar intensity imagery to extract the curb-to-curb pavement in a new subdivision, the Hillsborough County Geospatial Services Department conducted an experiment. The best compilers and analysts were given a recent aerial image in RGB format and instructed to compile the street map. A second analyst was given the intensity imagery for the same new subdivision and instructed to use Esri Image Analyst tools to extract the road network. Both sets of analysts were timed, as a measure of effort, and the results analyzed for spatial accuracy as judged by a third reviewer. Total impervious surface area was reported. The results indicated (1) no difference in the centerline configuration (**Figure 4**), (2) less than 3% difference in total length, (3) between 6 and 8% difference (cul-de-sacs and other variables) in total impervious surface (**Figure 5**), and (4) a more than 50% increase in efficiency using lidar intensity to map the new subdivision.

"I also really, really like how you can very clearly see the end of pavement on the streets, the high points in the road and where the curbing is located," commented Allushuski.

Southwest Florida Water Management District—Survey Section

Although the major use of the high-density lidar data at SWFWMD is for H&H modeling and floodplain delineation by the Engineering and Watershed Management Section, the district often finds additional uses for the data. James Owens, PSM, Survey Supervisor, was tasked with a boundary survey for a coastal parcel in Cockroach Bay, Hillsborough County, Florida.

Three elements were to be mapped: (1) the mean high water level (0.35' NAVD88; not shown), (2) the safe upland line (SUL), i.e. a line at or above the mean or ordinary high water line used to calculate the acreage of land (0.85' NAVD88; blue line in **Figure 6**), and (3) a boardwalk and deck, which was in a state of disrepair (**Figure 7**). Further complicating the survey, the Cockroach Bay parcel in question was heavily overgrown with black mangrove trees and other vegetation, making conventional survey reconnaissance difficult (**Figure 7**).

Although the lidar-generated 0.85-foot NAVD88 contour showed a much more aggressive position than the surveyed SUL, it closely follows the surveyed Mean High Water (MHW) line. Since the expected Vegetated Vertical Accuracy (VVA) for the lidar was ~0.6-feet NAVD88, it was not surprising that the lidar-derived contour would fall somewhere between the MHW and the SUL. Hence, the lidar-derived contour served as a guide for the ground surveyors.

"The lidar-derived contour of the MHW line (0.35 feet NAVD88) and Safe Upland Line (0.85 feet NAVD88), and the verified location of the boardwalk, were extremely useful in the course of doing the survey," confirmed James Owens, Survey Supervisor, Southwest Florida Water Management District.

University of South Florida—School of GeoSciences

Drs. Shawn Landry and Ruiliang Pu have an ongoing research project aimed at improving the accuracy of the

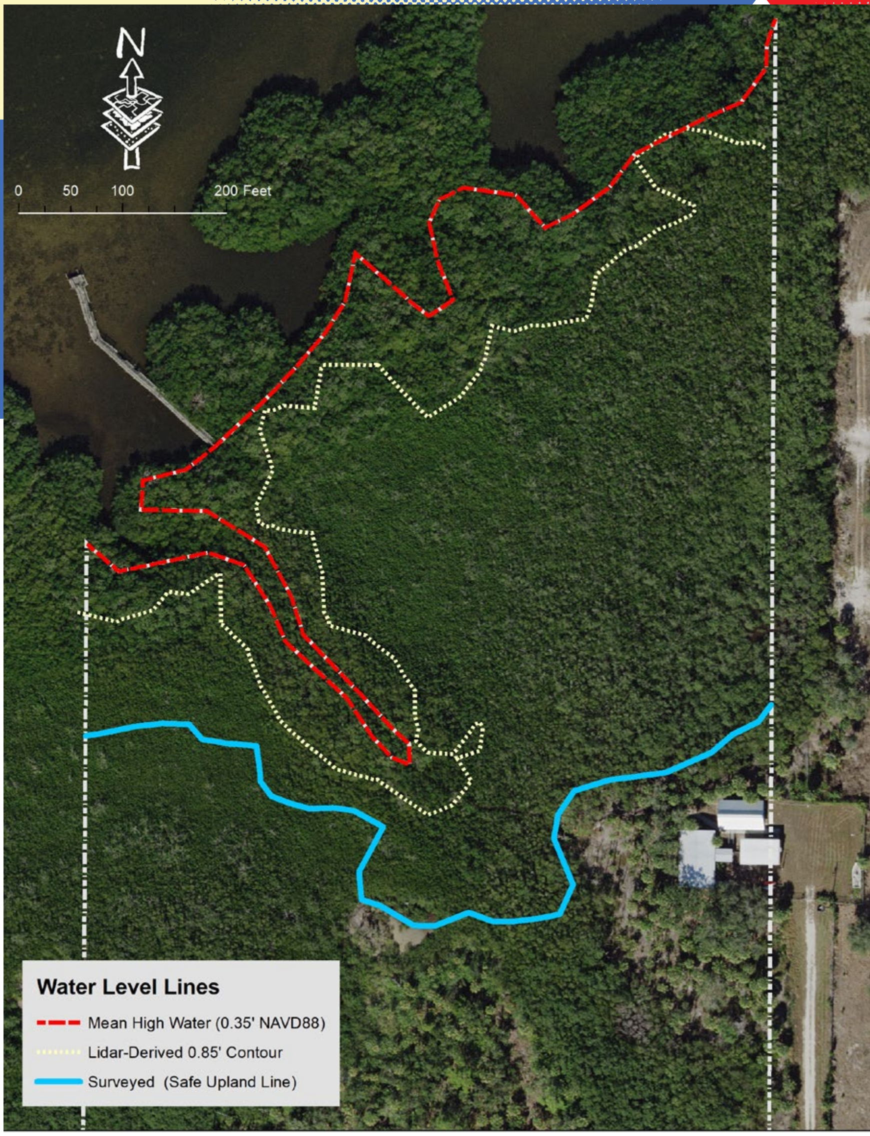


Figure 6: The Cockroach Bay, Hillsborough County parcel (gray line) showing the SUL as surveyed (blue line), the 0.85-foot NAVD88 contour as generated from the lidar (yellow) and the MHW (0.35' contour) as surveyed (red).

University of South Florida—USF Library

Dr. Lori Collins in the Digital Heritage and Humanities Center Libraries is utilizing the Hillsborough data to examine archaeological sensitivity (very high site-potential) areas. Much of Collins's research examines site location and land management concerns. She uses DEM and DSM modeling with site location data to better delineate boundaries for ancient shell mounds and middens and to examine potentials for erosion and impact in relation to the known locations. The lidar-derived DEMs and DSMs are also used for prospecting purposes and target areas for ground truth verification.

A graduate student in geoscience, Kyutae "Simon" Ahn, is also benefitting from the high-density lidar data, which he is using as part of a project where he is combining terrestrial laser scanning (TLS) data with airborne laser scanning data (ALS) in order to efficiently map structures and built environments (**Figure 10**). He has been surveying the University of South Florida (USF) Library structure

mapping of urban tree species using multispectral imagery. Their most recently published article explained the use of multi-seasonal imagery (four images spanning the seasons). Since acquiring the 2017 high-density lidar for the Tampa study area, Landry and Pu have processed a high-resolution (0.5 m) normalized DSM (height above ground) raster dataset from the LAS data (**Figure 8**). The lidar-derived nDSM (**Figure 9**) combined with the multi-seasonal imagery within an object-based image analysis framework improved the accuracy of tree-species mapping.

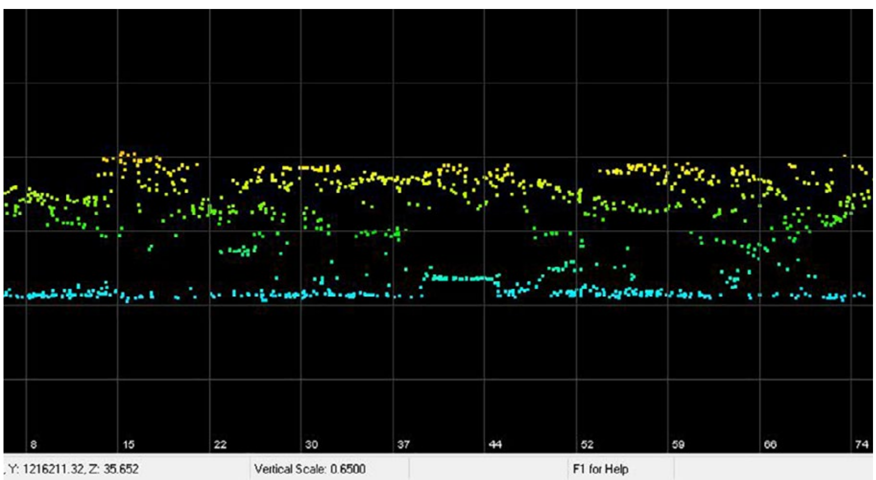


Figure 7: Profile view showing the elevated boardwalk under dense vegetation.

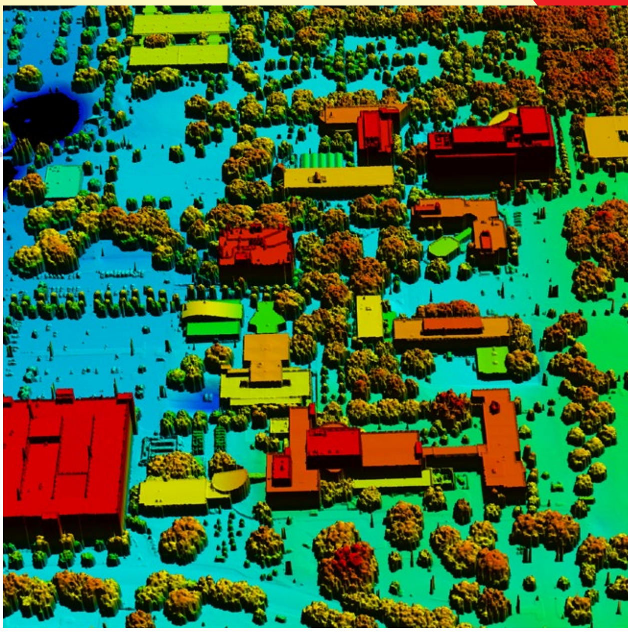


Figure 8: Digital Surface Model (DSM) derived from the high-density lidar, as rendered in QT Modeler.
Courtesy of Dr. Shawn Landry, School of GeoSciences, University of South Florida.

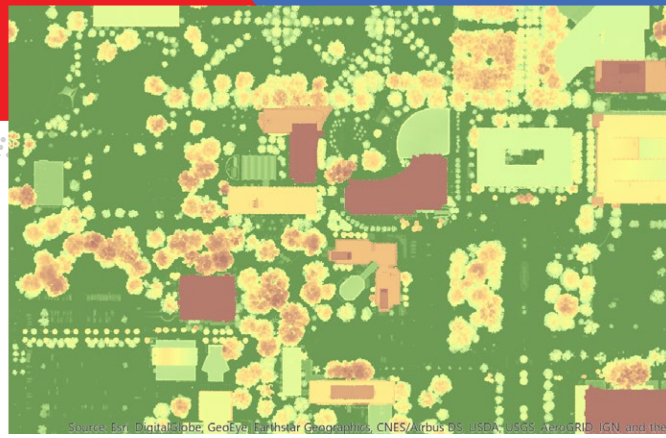


Figure 9: Normalized Digital Surface Model produced by combining high-density lidar with seasonal imagery as rendered in Esri-ArcMap.
Courtesy of Dr. Shawn Landry, School of GeoSciences, University of South Florida.

Figure 10: USF Library rendered with high-density airborne lidar fused with terrestrial scan lidar.
Courtesy of Dr. Lori Collins and Simon Ahn.

and related neighboring buildings on campus, using the ALS data to provide coverage for large landscapes and areas such as rooftops, and determining best approaches for combining data to represent and study architecturally complex buildings.

CONCLUSIONS

The final lidar dataset was delivered to the three cooperating agencies at the end of June 2018, so the projects illustrated above were based on interim deliverables. While the SWFWMD will be using the data primarily for FEMA floodplain updating, the county and city have additional uses. Those proposed include a tree canopy survey and heat island analysis, solar potential for roof exposure on both public and residential buildings, road and road feature/signage extraction, and public right-of-way slope/aspect determination for maintenance.

Alvan "Al" Karlin, PhD, CMS, GISP is a senior GIS professional at Dewberry, and was formerly with the SWFWMD, where he managed all 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 has a Ph.D. in computational theoretical genetics from Miami University in Ohio. He is the immediate past president of the Florida Region of ASPRS, an ASPRS Certified Mapping Scientist—Lidar, and a GIS Certification Institute Professional.

Amar Nayegandhi, CP, CMS, GISP is 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 over 20 years of experience, he is a recognized expert in topographic and bathymetric lidar data acquisition and processing. Amar has a bachelor's degree in electrical engineering from the University of Mumbai and a master's degree in computer science from the University of South Florida. He is the director of the ASPRS Lidar Division, an ASPRS Certified Photogrammetrist and Certified Mapping Scientist—Remote Sensing, and a GIS Certification Institute Professional.

Keith Patterson, PMS, GISP is a senior project manager at Dewberry. He manages multiple lidar, remote sensing and image interpretation projects for federal and state clients. As a Florida-licensed Surveyor and Mapper, Keith is responsible for assuring that data meet Florida state standards and ASPRS accuracy specifications. He received his bachelor's degree in geography from the University of South Florida. Keith is also a GIS Certification Institute GIS Professional.

Acknowledgements: As with most large, county-wide projects, many people are involved in multiple aspects. We want especially to acknowledge the contributions of the following: Robin Bailey, Yuan Li, Jim Owens and Nicole Hewitt, from the SWFWMD; Fred Hartless and the Hillsborough County Geospatial Services Department (Freddy Delgado-Rivas, Terri Dempsey, Sarita Karki, Sarah Ellis, Erick Sumner, Chin-Feng Ho); and Ben Allushuski and Alex Awad from the Stormwater Engineering Division, Transportation and Stormwater Services Department, City of Tampa. Special thanks are due to the contributing faculty from the University of South Florida: Drs. Shawn Landry, Lori Collins and Stephen Fernandez.

The team preparing for UAV-lidar flights at Sand Canyon, Colorado, USA.

MAPPING HISTORY:

Routescene's UAV-Lidar Solution

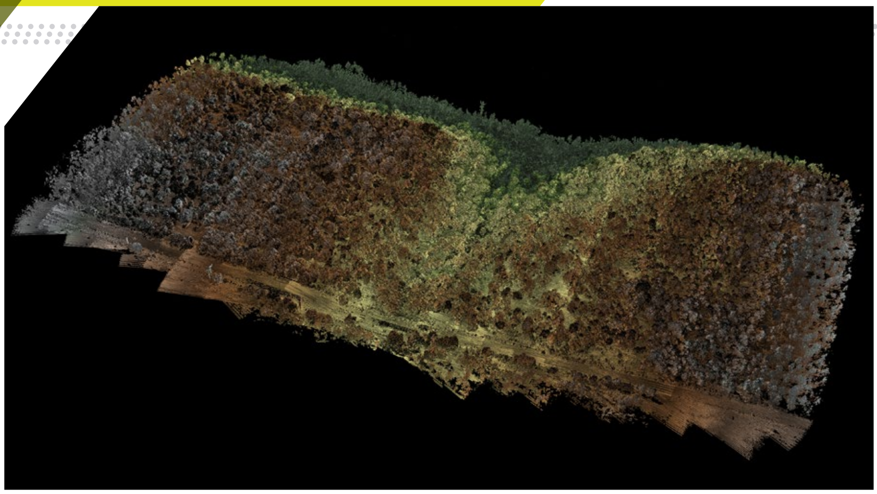
How Routescene is using innovative technology to help clients unearth their potential

BY GERT RIEMERSMA

Since its conception, Routescene has been committed to providing a unique, end-to-end solution for all its clients. Its lightweight lidar solution, built for use on unmanned aerial vehicles (UAVs), provides technology that is transforming the surveying market.

Routescene was founded by Gert Riemersma in 2005, in Edinburgh, Scotland, to design and manufacture 3D mapping solutions. The company was an early adopter of lidar and UAV technology, and launched its UAV-lidar solution in 2013. This system comprises hardware (the LidarPod) and software (QA Monitor and LidarViewer Pro), which makes data collection and processing easier and quicker. With a growing customer base in the USA and Canada, Routescene established its North American office in Durango, Colorado in 2017.

Working with UAV-lidar is much more than adding a lidar sensor to the bottom of a drone. Fundamental to Routescene's success is a carefully



Sand Canyon—over 3.2 billion points were collected during the survey and processed.

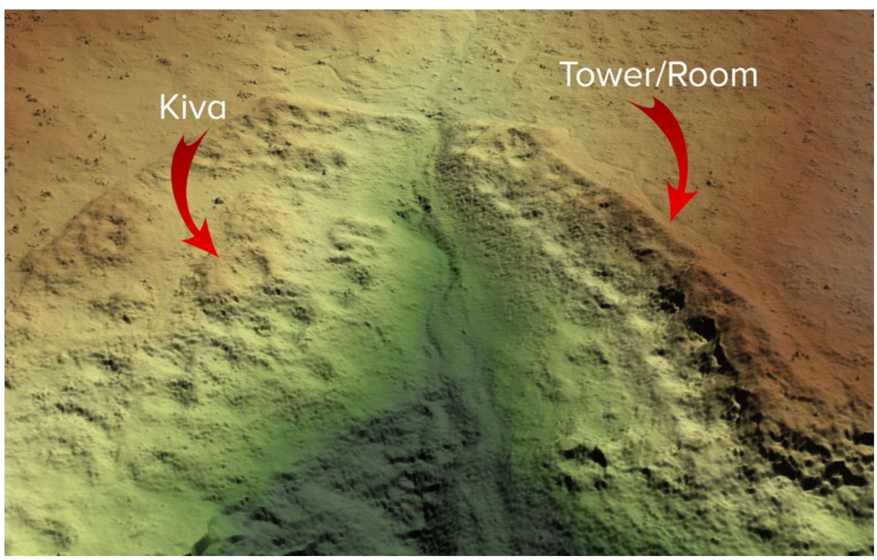
thought through six-step workflow which spans the entire utilization of the solution—from survey and project planning, data acquisition, data processing to the final outputs or 'actionable information.' This workflow is a set of orchestrated and repeatable procedures and processes, so every survey and subsequent data analysis is undertaken in a systematic, streamlined way, ensuring the best possible outcomes each time.

Planning and technology

Routescene recommends that every project starts with a meticulous flight-planning process by taking into account the objectives and the terrain of the survey area. In the project described here, surveying the culturally rich Sand Canyon, Colorado, USA, the aim was to generate a high-resolution digital terrain model (DTM) devoid of trees and shrubs and to identify the location of ancient dwellings called 'kivas' in the undergrowth. This required a great deal of planning to accommodate the uneven terrain and a consideration of the chosen technology.

The Routescene system provided an excellent solution for Sand Canyon and many other projects. A key factor the team considers is penetrating vegetation in order to achieve the most points per square meter. This is accomplished by the integrated Velodyne HDL-32E in the Routescene LidarPod. The Velodyne HDL-32E is a premium lidar scanner with a proven record of robustness, high accuracy and high resolution. Its superior-quality laser diodes are at least twice as accurate as those in the Velodyne Puck (VLP-16). The latter is designed for mass production and low cost, and thus uses lower-quality laser diodes, perfect for object detection where accuracy is not the main consideration.

The HDL-32E's high update rate of up to 1.4 million points per second creates a high-resolution point cloud to enable detailed analysis of the final terrain model. Overall, with the HDL-32E we achieve a final output resolution of an impressive 400 points/m^2. The HDL-32E has been used in hostile and rough environments over its lifetime and is well designed and built. This is important given the typical location of a mapping project, in a remote place where equipment failure is costly and would cause significant delays. The HDL-32E has a maximum range of 110 m. This is benchmarked at 10% reflectivity on a white surface. Given that natural features have a lower reflectivity, the "usable" range is around 80 m. This "usable" range is determined by experience and analyzing the results of previous surveys. The Puck (VLP-16) also has a maximum range of 110 m, but the "usable" range is around 60 m. This has an



Completed DTM showing 700-year old dwellings called 'kivas'.

impact on the flying altitude of the UAV and the swathe of the collected data. With a HDL-32E the UAV can fly higher and collect a broader swathe.

Processing the data

In surveying, we know that creating a bare-earth model or DTM is one of the most critical steps in lidar data processing on which subsequent analysis is based. For example, all classification processes start with establishing bare earth. Typically the main aim is to achieve as high a resolution DTM as possible, devoid of trees and shrubs. The secondary objective usually is to ensure a high degree of accuracy, often relative accuracy to enable comparison with other datasets. Designed for use on UAVs, Routescene's LidarPod includes a carefully selected array of sensors to ensure that the solution is fit for purpose across a range of different surveying and mapping applications.

The team aims to simplify and reduce the time customers spend post-processing lidar data. Achieving bare-earth modelling and the final results quickly and efficiently is the ultimate goal. After every mission, the data is downloaded from the LidarPod and inspected using Routescene's proprietary LidarViewer Pro software. This software provides a framework on which to build a lidar processing workflow, using the Filter Development Toolkit to create and apply specific filters to the collected point cloud, to achieve the most accurate final deliverable as quickly as possible.

> "The Crow Canyon Archaeological Center was excited to discover previously undocumented structures."

Quality assurance

Routescene has a strong ethos of quality assurance and quality control (QA/QC), with foundations in land survey training enhanced by the author's many years working in the offshore industry, where QA/QC is of paramount importance. As part of the standard QA process, Routescene advocates that every survey has ground control, established by accurately surveying ground control points (GCPs) and placing Routescene lidar targets on them.

In the Sand Canyon survey, a discrepancy was identified in the positions of the control points relative to the processed point clouds. In case additional data needs to be collected at a later date, be it unplanned or planned, as standard practice Routescene permanently marks each GCP using a peg driven into the ground. This best practice allowed the survey team to revisit the site to resolve the discrepancy. It was mid-winter by now, however, and the GCPs were located under a foot of snow and resurveyed. After extensive analysis, it was revealed that the use of Microsoft Excel to store the GCP coordinates was detrimental. Excel rounds all numbers to six decimal places and, as it was storing geographical coordinates, this caused the team to lose up to 4 m of accuracy. Reloading the original raw data into another format restored the accuracy, but left the ground survey team members rather displeased—a lesson learned!

The Routescene method

Overall the Routescene solution is founded on the principles of quality surveying. For every client, the team takes a unique and tailored approach. In the historic Sand Canyon, this method paid dividends. Although the site was studied, mapped and excavated between 1984 and 1995 using traditional survey techniques, the Crow Canyon Archaeological Center was excited to discover previously undocumented structures. The lidar image proved to be the best tool for visualizing the ancient site in detail and to plan future preservation. Removing the need for meticulous ground surveys, the impressive data accelerated understanding of the Pueblo area and has allowed the client to concentrate its future work on the newly found structures.

With every client and project, Routescene's approach is unique. From uncovering the secrets of historic sites to helping to create preservation plans, it is not only the technology but the people behind it that satisfies clients. With lidar technology and years of experience, Routescene continues to thrive no matter the challenge.

Gert Riemersma, CTO of Routescene, has 20 years' experience as a hydrographic surveyor and has been a private pilot since 1986. He has worked with lidar since 2008 and UAV-lidar since 2013.

For more information please visit www.routescene.com.

Return to Glory

Geomatic Solutions Aid Restoration of Historic Structures

BY GREGORY **LEPERE**

Historic structures and architectural wonders like the Notre Dame Cathedral in Paris rely on the inventions of their era to stay standing for hundreds and thousands of years. But when natural or human-caused destruction strikes in modern times, it is often geospatial data that holds the most promise of restoring them to their former glory.

As 3D digitizing becomes increasingly valuable in historic restoration, the technical aspects of surveys and point clouds will only grow in importance. Let's take a closer look at setup, instrumentation, project examples, and the potential benefits of technology advances in 3D laser scanning.

Geospatial data supports revival of world-famous church

With the Notre Dame Cathedral, it was obvious from the moment of the April 15 fire that the structure would be scanned multiple times to accurately determine damages and structural stability and compare with past scans. Point clouds from scans will support the restoration lifecycle, including knowing how to handle the destruction, determining how to support work around existing architecture, and

finally, informing decisions on building features, such as replicating what existed before or creating something new.

Such a project benefits from using surveying companies with specific knowledge of the best workflows for historic preservation and restoration. These specialized companies often have teams that include surveyors, scanning technicians and restoration professionals trained and experienced in historic building materials and techniques.

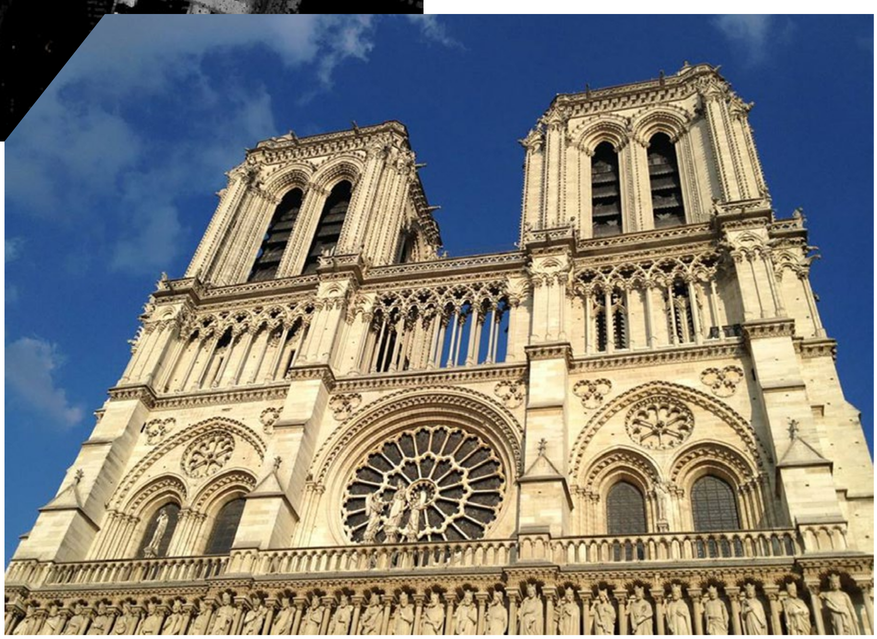
Instrumentation and setup support restoration

The Notre Dame Cathedral restoration also heightens the sense of urgency for structures and monuments without digital records to get point clouds created before disaster strikes or natural elements erode their splendor.

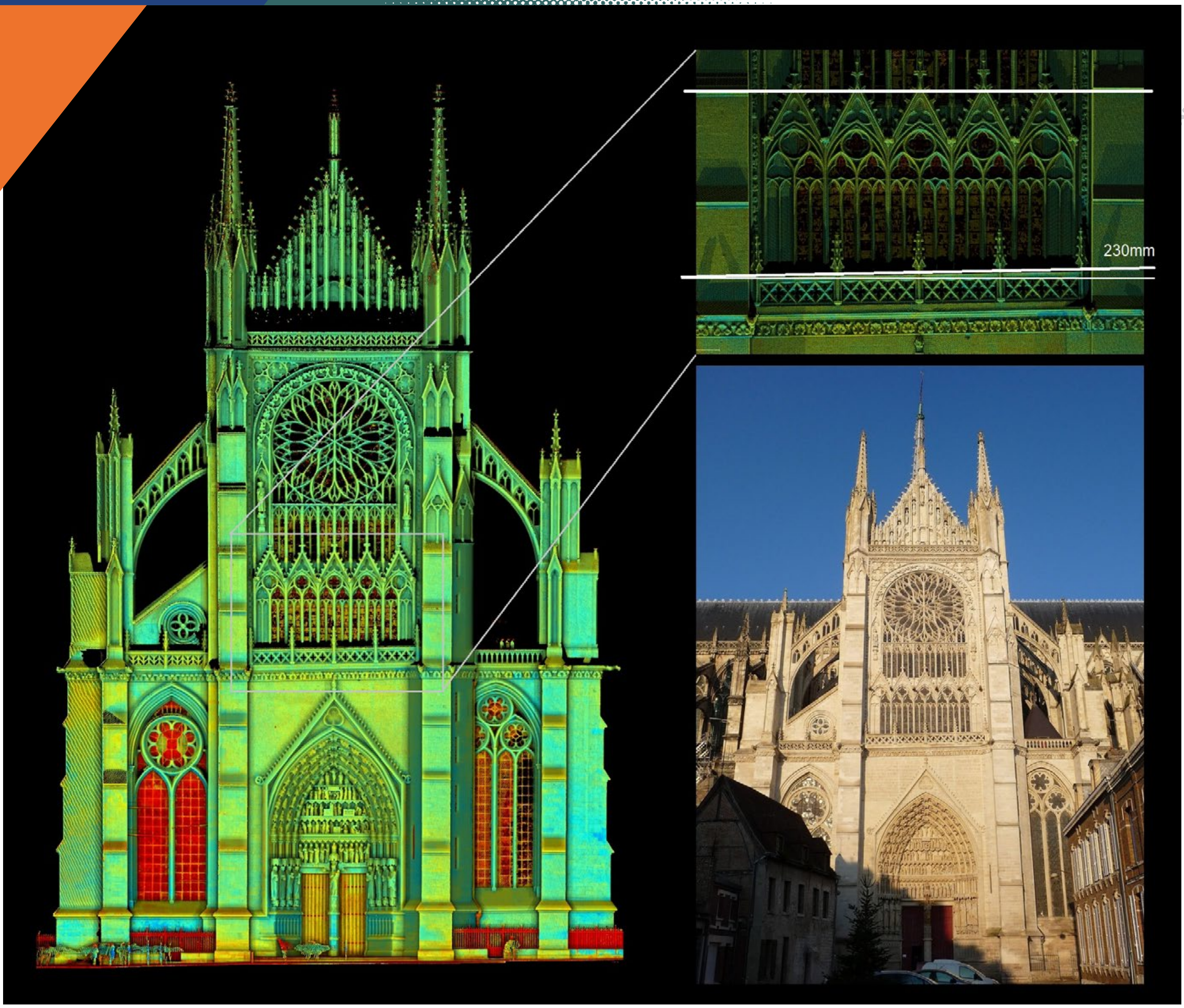
With this in mind, let's explore the measurement configuration inside and out, as well as the setup process to create a digital record to aid historic project restoration:

- For scanning small or medium sites, use one or multiple 3D laser scanners, with the setup dependent on size, budget and criticality. Solutions could include a laser scanner and/or a scanning total station, tripods, batteries, and data storage (USB key or SD card). Also recommended, but optional, are black and white targets, spheres and/or survey prisms, as well as an external high-end camera and panoramic head for higher-quality imaging.
- For larger sites, in addition to the above list, black and white targets, spheres and/or survey prisms must be used. If you aren't using a scanning total station, you will need one total station or one GNSS receiver to establish a control network, which is a skeleton of precise known targets covering the entire site and serving as a reference for all scans to guarantee accuracy over the entire site.
- For continuous monitoring of the critical elements of a building, you will want one, or more often, multiple high-accuracy total stations mounted 24/7 on stable permanent pillars. The setup should also include a number of monitoring prisms to be installed on the critical elements of the building, monitoring controller(s) to provide a continuous connection between the total station(s) and the monitoring control center, and real-time control software.

Left: This colored point cloud of the Notre Dame Cathedral in Amiens, France, shows orange triangles that are scanner positions. The ones that appear to be inside the building are actually scanner positions going around it.



The splendor of Notre Dame Cathedral in Paris is evident before the April 15, 2019, fire, which destroyed the building's spire and most of its roof, and severely damaged its upper walls.



In these images of Notre Dame Cathedral in Amiens, France, the zoomed portion (top right) of the point cloud of the south facade that includes the Golden Virgin Mary reveals the right side of the balcony is 230 millimeters, or about nine inches, higher than the left. The misalignment may be perceived as a perspective issue from the ground, but scan data confirm it is tilted. Historians dated the stones and found both the right and left of the facade were built first, and when it came time to link them, the architect apparently decided to tilt the balcony to fix the alignment issue.

Techniques reveal more detail

While missing elements, such as roof segments, can't be measured, fallen or partially destructed elements can be scanned, measured and virtually repositioned to understand what is really missing and provide understanding on how it has been destroyed.

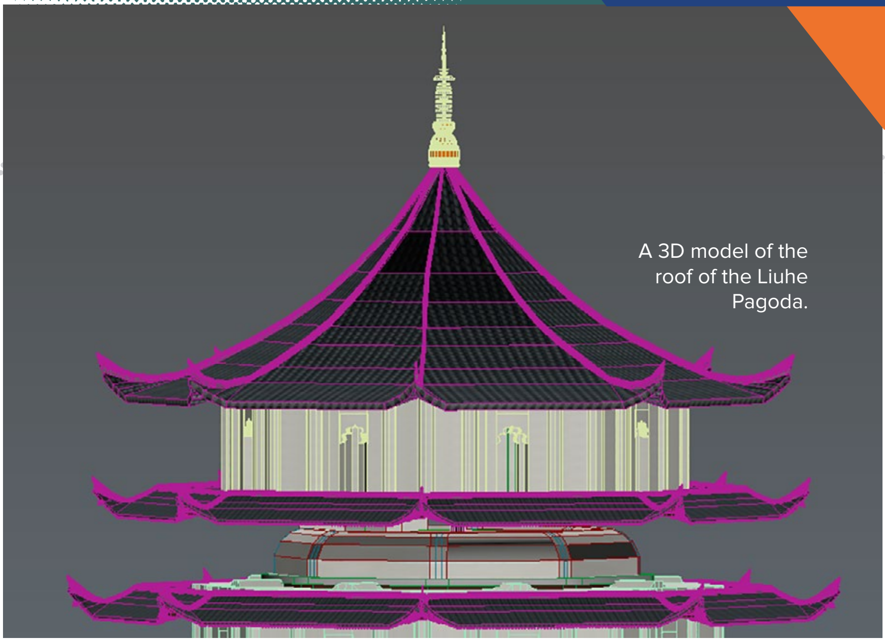
A major consideration in point clouds is photo texture, or the addition of color and texture to a point cloud or mesh to add rich visual detail. To get photo texture, you have two options: an internal camera of 3D laser scanners, selected most often for simplicity and productivity, or an external high-end camera and panoramic head for more expert control and higher-quality imaging.

Historic restoration with 3D models: Three examples

Liuhe Pagoda (China): Reviving a cultural landmark

Liuhe Pagoda (or Six Harmonies Pagoda) in China's southern Hangzhou, Zhejiang province has a rich cultural tradition dating back to its construction in A.D. 970. In its more than 1,000 years of existence, the 13-story octagonal building made 95% of wood has lived several lives, including destruction by warfare in 1121 and full reconstruction by 1165.

In 2013, the tourist attraction began its fourth major repair and renovation. To preserve the complete, true appearance, the owner entrusted Beijing TiTest Technology Corp. to scan the whole interior and exterior, which occurred



A 3D model of the roof of the Liuhe Pagoda.

over six months to allow for the gradual restoration of missing parts, one by one.

The workflow included scanning of the original building (3 minutes per station), modeling the original building to find the missing parts (2-3 hours per station), designing the missing parts and testing their assembly (4-6 hours), crafting the missing parts by hand (3-5 days), assembling the missing parts on site (4-5 hours), scanning again for quality assurance (QA) and quality control (QC) (3 minutes per station), processing point clouds for the harshness inspection (QA/QC) (3-5 hours), and lastly, processing a very detailed 3D model for documentation (2-3 days).

Using a compact 3D laser scanner to scan the whole 527 station, the original point cloud data volume reached 363 gigabytes, with 23.03 billion three-dimensional points collected.

Kennecott Mines National Historic Landmark (Alaska, USA): Restoring a treasure

Located in eastern Alaska, the Kennecott Mines site was declared a U.S. National Historic Landmark in 1987. When the National Park Service (NPS) acquired Kennecott in 1998, it began the lengthy effort to preserve the site and determine which buildings should be stabilized or rehabilitated after nearly 80 years of neglect.

Archaeologists worked to map the site, but by 2018, the NPS started gathering additional data as part of a project to stabilize the upper seven stories of the mill and found the 2000 data lacking in detail and accuracy.

To provide the necessary precision, 3D laser scanning was deployed. A team from Frontier Precision Inc. selected the Trimble SX10 scanning total station and the Trimble TX8 laser scanner for the bulk of the work, which tied scans to existing control points and used traverse or resection functions to establish georeferenced 3D positions on each setup point. The team also used Trimble R8 and R10 GNSS receivers to extend control throughout the site. In addition to scanning, the Trimble SX10 used direct reflex (DR) measurements to capture individual points on the building that could identify key features and be compared to the point cloud for quality assurance.

Technicians processed the data using Trimble Business Center (TBC) software to combine the traverse and GNSS results and work on scanning data from the SX10. They used the Trimble RealWorks survey workflow to process TX8 data to project coordinates. Multiple scans were merged quickly, and teams created colorized point clouds for visualization. At the end of the three-day project, technicians delivered a single TBC dataset containing all point clouds, images and survey data.

The intricacy of the design of Liuhe Pagoda, at 13 stories high, made it a challenging restoration project.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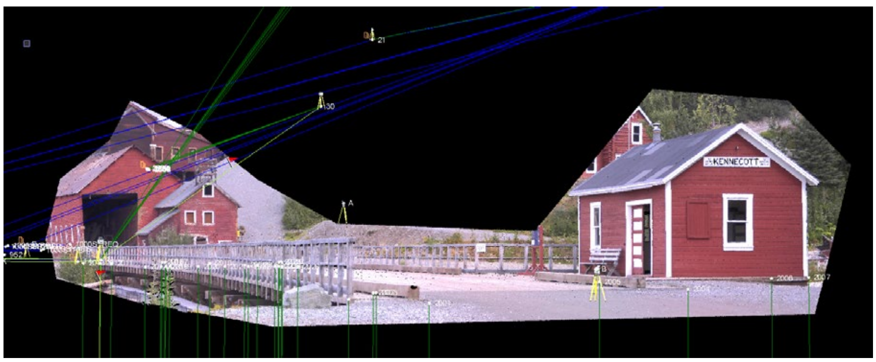
The site's iconic 14-story structure received raw ore delivered by aerial trams from mine entrances in the mountainside above and delivered processed copper to railcars at the base of the structure.



A georeferenced Trimble VISION photo mosaic of the Kennecott mill from the valley floor. Blue lines show GNSS measurements, green are from SX10 traverse and direct reflex data.

Church of Saint Simeon Stylites (Syria): Promise of restoration

Initially scanned for preservation, the Church of Saint Simeon Stylites—in the north of Syria—dates to the fifth century and now stands partly destroyed by a Russian rocket attack in 2016. If it becomes possible to restore the church, the scans can be used as a historical record of the structure, making them very valuable.

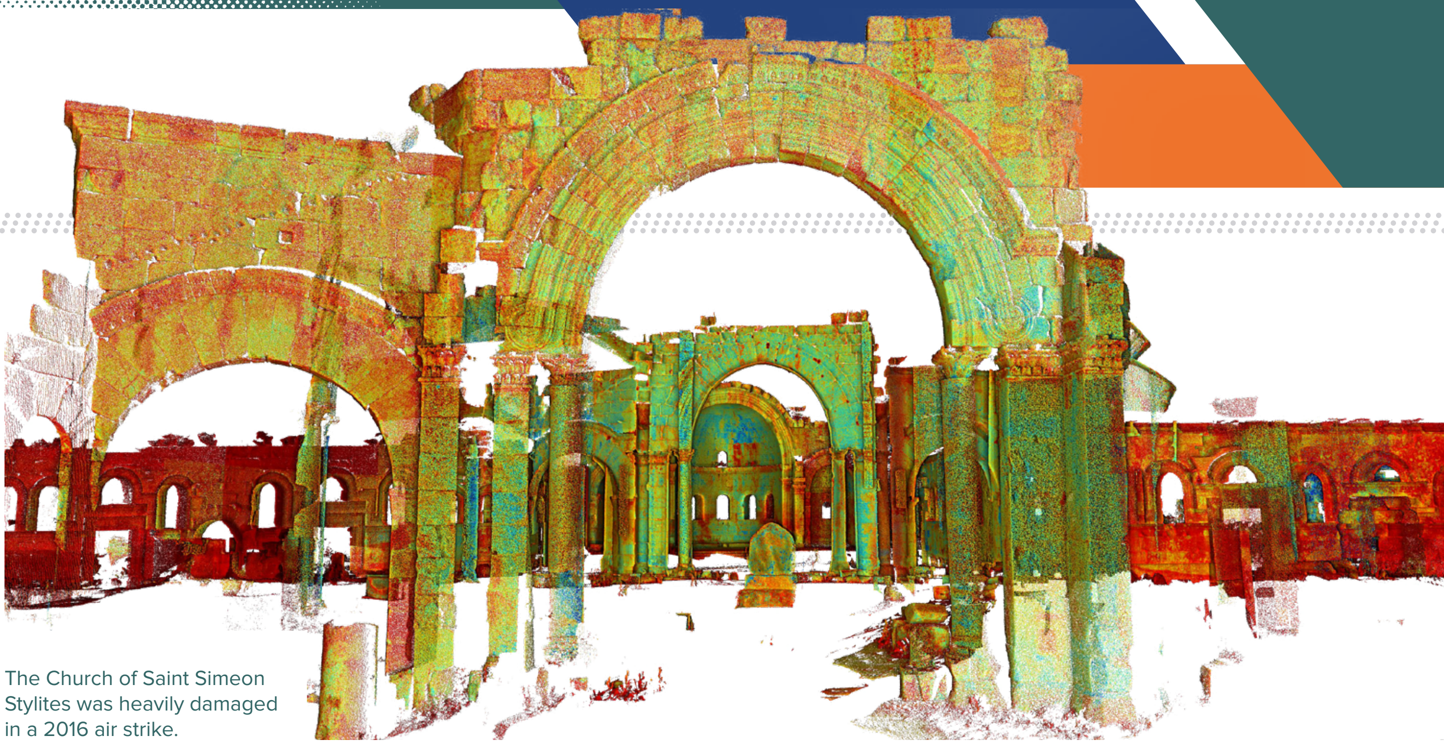
Since 2003, the site has been the object of digital surveys, according to a paper published in 2011 in the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences.

Authored by M. Kurdy, J-L. Biscop, L. De Luca and M. Florenzano, the paper includes a description of work done at the site by Yves Egels, ENSG, in 2004. Using a Trimble GX scanner, Egels did 36 stations to collect 250 million points all over the cruciform church, which is composed of four basilicas in cross formation around an octagonal drum centered on the famous pillar where Saint Simeon lived and preached for four decades. Registration was done using spheres.

Once the data was gathered and geo-referenced, the whole point cloud was cleaned of unnecessary points, sampled and cut into various elements, following construction logic consistent with reconstruction techniques. The data made it possible to determine how the building was created, including the central octagonal drum. It also enabled the creation of a 3D hypothetical reconstruction.

Simplicity increases accessibility

While manufacturers are working hard to simplify the process of completing a single scan, high-level expertise is still required for a full project like a cathedral. The registration process, or the combining of scans in an accurate



The Church of Saint Simeon Stylites was heavily damaged in a 2016 air strike.

way, is one of the remaining barriers to simplifying large projects.

The first developments to provide a pre-registration in the field were only a half-step in the right direction. Extensive processing and validation were still necessary back in the office. To make scanning really simple, a project should be done and final when finishing on site, with no disappointing surprises later. Full registration in the field including refinement to obtain an accurate registration, colorizing, reporting and exporting data in the right file format is a game changer.

Conclusion: Maturity brings benefits

3D laser scanning has come a long way since its beginnings in the late 1980s. Performance, size, weight and productivity have greatly improved, while the total cost of ownership has come down.

Still, compared to other optical measurement instruments like levels, theodolites or total stations, maturity in 3D laser scanning isn't completely there. Most manufacturers still recommend a yearly calibration to maintain the expected specifications; and standard warranty periods are in general just one year, while all other optical instruments provide two years. With its automatic calibration feature, the recently announced Trimble X7 scanning system is addressing this and other challenges users previously faced with 3D laser scanning technology.

As 3D laser scanning becomes a more mature technology, similar to optical instruments, we will see a much broader use of this fantastic technology. Each new innovation is making it easier and faster to capture precise 3D scanning data to produce high-quality deliverables.

With this growing accessibility, geospatial professionals won't have to be scanning experts to also benefit from the technology, enabling them to branch into new lines of business, like historic restoration. ■

Shown inside the Landesmuseum in Zürich, the Trimble X7 scanning system, available in early 2020, exemplifies the maturation of 3D laser scanning technology that can support the collection of critical data on historic structures to enable their future restoration after disaster or deterioration.

Gregory Lepere, marketing director of Optical & Imaging for Trimble Geospatial, has been fascinated with cathedrals since he was a boy growing up in France and has participated in 3D laser scanning of many historic structures during his geospatial career, including Notre Dame in Amiens, his hometown.
Email: *gregory_lepere@trimble.com*

Lidar Sheds Light on Architecture of 18th Century British Fort

Public-domain lidar data facilitates Canadian archaeology

BY KEVIN CORBLEY

At ground level, a wooden blockhouse is the best indication that the Nova Scotia site once served as a military fortification. Otherwise, all that remains of Fort Edward is a series of grass-covered mounds and ditches, its classic design lost to the elements—until recently. An archaeologist is using lidar and 3D visualization to bring the 18th century fort back to life so its star-shaped architecture can be studied in detail for the first time.

Also hard for a visitor to imagine, standing on what is now a national historic site managed by Parks Canada, is the critical role Fort Edward played in the development of two cities located more than 2000 miles apart—Halifax and New Orleans. In 1750, the British built the fort 60 kilometers north of Halifax to protect the Crown's interests there. The location of the outpost was chosen to keep an eye on French Catholics, known as the Acadians, who lived in the area.

"The French were eventually driven from the region…and Fort Edward

then served as the deportation center," said Dr. Jonathan Fowler, owner and principal of Northeast Archaeological Research and an associate professor of archaeology at nearby Saint Mary's University. "The Acadians ultimately arrived in New Orleans, where they became known as 'Cajuns.'"

The fort, however, was designed first and foremost for defensive purposes. Fowler explained that the advent of gunpowder gave rise to a rapid change in the architecture of military fortifications. Tall stone walls, easy targets for cannon fire, were replaced by low-profile battlements built of timber and dense earthworks. The 'star fort,' with four, five, six or more defensive bastions providing 360 degrees of protection, was common in the 18th century.

"Fort Edward was originally timber and earthworks, but most of the timber is gone now, and the earthworks are slumped due to erosion," said Fowler. Disappointed by how few details of Fort Edward's structure remain after centuries of erosion and overgrowth, yet intrigued by reports of outbuildings, a garrison cemetery and other facilities on the grounds, he wanted to know more. "As you walk around, you can't really tell it's a fort; it looks like a ditch with a bank," he said. "Unless you're familiar with military architecture, you wouldn't understand it's a star-shaped fortification."

Fowler believed lidar technology could give his students and other archaeologists their first real opportunity to study the impressive layout of the 270-year-old British fort.

Lidar: a new tool for archaeology

Lidar is becoming a popular tool in archaeological studies due to its ability to penetrate vegetative cover and reveal what lies beneath. Even at historic sites

where archaeological research has been approved, removal of bushes, trees and grasses is seldom allowed, or can be prohibitively expensive. Laser scanners, ground penetrating radar (GPR) and geophysical surveys can map the bare earth, and sometimes what is beneath the ground, without disturbing the natural environment.

Parks Canada was interested in Fowler's efforts to bring Fort Edward back to life virtually, but there was no budget to acquire new lidar data. Fortunately, Canadian federal, provincial and municipal governments have made archives of publicly-funded lidar surveys freely available. From Novia Scotia, Fowler obtained airborne lidar data that had been acquired with a Riegl laser scanner over Fort Edward for a nearby hydroelectric project in 2011.

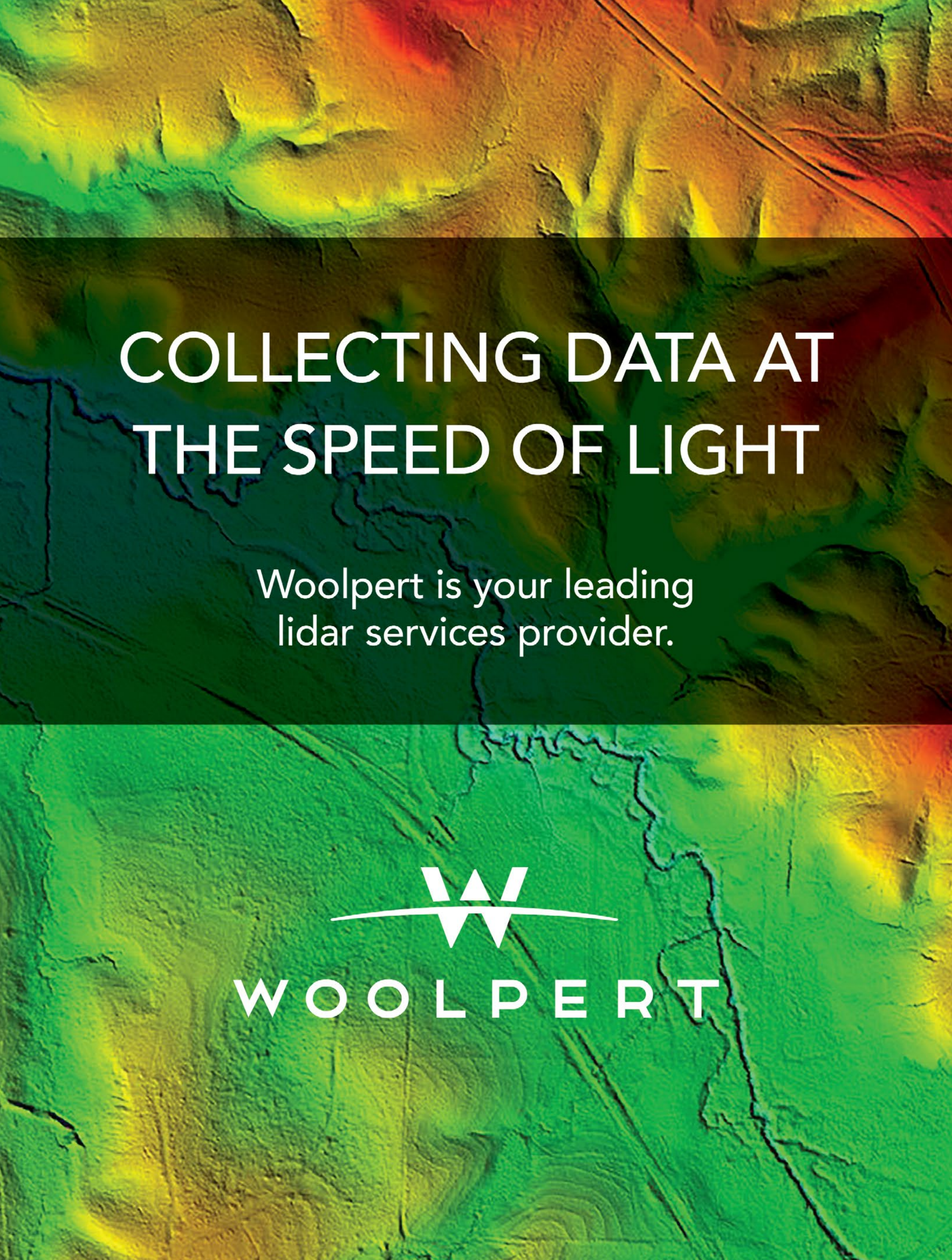
Fowler also obtained a satellite image of the area to establish a baseline of what is visible from overhead at Fort Edward. The image showed a faint outline of the fort with four bastions but few other details. Next, he turned his attention to the lidar point cloud.

Lidar data sets can be intimidating for archaeologists, because the files themselves are enormous, Fowler explained, and the software often used to exploit them can be expensive and difficult to learn. Instead, he opted to employ the Surfer gridding and visualization package from Golden Software[1], which he had been using for over 10 years to create 2D and 3D maps from GPR and handheld magnetic susceptibility surveys. "This package is the workhorse for mapping our geophysical surveys," he said. "You can do so much with it relatively easily." Surfer had recently been upgraded with lidar point cloud processing functionality, and he decided to try it at Fort Edward.

Visualizing Fort Edward

Fowler loaded the lidar file into Surfer. The first processing step was to filter out first-return elevation points, which represent the laser pulses that struck vegetation. This filtering created a bare-earth elevation model. He then

1 www.goldensoftware.com.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Fort Edward National Historic Site of Canada
GoogleEarth basemap (2015), Northeast Archaeological Research, 2019

used the software to densify the remaining points through interpolation so he could generate a granular contour map. He varied the contour intervals until the map expressed the terrain in fine detail. "With the [25-centimeter] contours, the star shape really pops out. You get an immediate sense of the relief," he explained.

The contour map revealed the micro-topography in and around the fort that highlighted structural details typical of the time. For example, Fort Edward was built on top of a small hill surrounded by gently sloping terrain, which gave soldiers on the ramparts unimpeded views of potential attackers. The slope also meant invaders would have to run uphill crossing an open field, leaving themselves exposed to gunfire.

The bare-earth model and contours brought the star-shaped structure into better focus, but the erosion had worn down the dirt ramparts and begun to fill in the ditches. To further enhance their visibility, Fowler generated a hillshade relief map which allowed him to artificially create sun illumination to emphasize terrain. He also purposely exaggerated the Z values in the point cloud to emphasize vertical highs and lows.

Fort Edward suddenly jumped off the computer screen in 3D almost exactly as it appeared in the 1700s. The earthen ramparts and bastions were sharply defined. Outside the earthworks lay ditches that would have further slowed attackers on foot. "The exaggerated elevation values highlighted the micro-topography," said Fowler.

What intrigued the archaeologist about the scene were features he hadn't expected and hadn't noticed on the ground. A depression inside the fort's walls was a cellar for a barracks, still visible on the surface today. But outside and to the east of the ramparts are two rectangular features completely invisible at surface level. Fowler intends to return to the site and investigate whether these could be related to the garrison cemetery or outbuildings known to have existed just outside the battlements.

Another phenomenon that fascinated him was the striations in the earth just east and southeast of the structure. These showed up in the hillshade relief but not in the contour map. Fowler is certain these are micro-terrain remnants of agricultural tilling that took place on the site decades ago, yet long after the fort was abandoned. While not related to the history of the fort, these farming remnants contribute to the overall story.

"This is why micro-topography matters," he said. "Things show up that you don't expect."

What's next for lidar and archaeology?

Fowler is incorporating the use of lidar into his archaeology classes at Saint Mary's University and it is a growing part of his consulting work. In addition, he shared the results with fellow archaeologists as well as Fort Edward researchers at Parks Canada. Mostly unfamiliar with the use of lidar in this type of project, they were impressed with the details revealed in the Surfer visualizations and want to apply lidar technology at other sites.

Fowler hopes lidar will emerge as a primary tool in historic preservation at important locations like Fort Edward across Canada and around the world. The technology provides an unbiased baseline of sites and their condition, against which to judge future observations.

"When you can map features and objects and visualize them at such fine levels of detail, it allows you to inventory cultural and archaeological resources on site," he said. "Once it's mapped with lidar, future point clouds show how a site is evolving over time, so heritage managers can better monitor resources they are charged with preserving."

Kevin Corbley is a business consultant in the geospatial industry. He may be reached at www.corbleycommunications.com.

BY STEWART WALKER

Dr. Joerg Herrmann

Senior Vice President, Special Projects, Capella Space

For this installment of Quick Takes, we discuss the commercialization of synthetic aperture radar (SAR) with Dr. Joerg Herrmann, Senior Vice President, Special Projects, Capella Space[1]. This reflects LIDAR Magazine's interest in technologies that are complementary to lidar in determining elevation and elevation change.

LM: Joerg, you and I first met when you were with Airbus and I was with BAE Systems. Can you please tell us something about yourself and what prompted your move to Capella Space? What is your role in the start-up company? You had to move to San Francisco to fulfill your new role—has that been fun?

JH: Working at one of the world's largest aerospace and defense companies taught me a lot about building space systems and working with the government, but to fully realize my career-long dream of commercializing synthetic aperture radar (SAR), I knew I needed to be at a company that could move quickly and be agile. Silicon Valley is unique in that there is great enthusiasm to apply breakthrough technology to transform major industries using new and unconventional approaches while also generating commercial returns. This creativity gives us an incredible opportunity to build the future of commercial space.

When I met Capella Space CEO Payam Banazadeh a couple of years ago, it was clear he was building something really powerful and that we share the same mission of disrupting how SAR is being used. I saw for the first time a tangible path to achieving what I always believed would be possible with SAR technology.

In the late 1990s, I proposed the commercialization of SAR remote sensing in collaboration with industrial and institutional partners in Europe and North America, which resulted in the TerraSAR program. At that time I served as founding CEO of the TerraSAR-X operating company Infoterra, and to ensure legal security for the service's business case, I requested data security legislation in Germany.

LM: Please tell us about the founding of Capella Space and the other senior leaders in the company. From the website, it is clear that Capella Space is blessed with a hugely talented and experienced leadership team.

JH: When Malaysia Airlines Flight 370 went missing in 2014, Payam was shocked by the lack of visibility into our planet and frustrated that rescue teams couldn't find the plane. Given all of the advanced technologies for monitoring activity on Earth, how could a plane just disappear? This event was the catalyst for Capella Space and inspired him to help people and companies make better decisions through on-demand SAR data.

Capella has assembled a stellar team of industry veterans committed to delivering on the promise of real-time Earth observation. We have deep domain expertise across a wide array of verticals—military, aerospace, geography, computer science, etc.—but we share a common goal of realizing Capella's vision for a world empowered by SAR satellite data.

1 https://www.capellaspace.com

Capella high-resolution SAR imagery of the San Francisco Bay area. The area delineated by the blue box in the left-hand panel is shown enlarged in the right-hand panel. The imagery was acquired in September 2019 using Capella's technology deployed on an aircraft for testing. This image is representative of the imagery customers can expect once Capella's Sequoia satellite is launched into orbit.

LM: How did you decide on the name "Capella"? I'm very excited about this, especially since I attended a concert by Out of the Blue, the world-famous Oxford a capella singers, at the Edinburgh Fringe Festival this summer!

JH: Nothing to do with a cappella, I'm afraid! We took our name from a close, non-eclipsing binary star that is the brightest yellow star in the sky. The star is made up of four components that never block one another when seen from Earth (just like how our SAR constellation will never be "blocked" from seeing the planet by clouds or nightfall). The name Capella means "the little goat" in Latin. In Greek mythology, the star represents the goat whose broken horn became the cornucopia, a horn of plenty which could be filled with anything its owner wished for. We believe that one day soon Capella's information will do the same for many clients.

LM: How is Capella Space funded? Is it venture capital?

JH: Yes, we are venture-financed and recently received additional funding to complete our first operational seven-satellite constellation launch in 2020, with significant backing from multi-billion-dollar funds DCVC (Data Collective) and Spark Capital.

LM: What was the opportunity that you saw when you founded Capella Space? What can you do, using smallsats, that existing providers such as Airbus and Maxar cannot? ICEYE already has satellites in orbit. And we believe that UrtheCast is planning a constellation, for which the first launch comes quite soon. Then there is XpressSAR, i.e. perhaps you are part of a trend towards smallsat SAR. So far, however, the SAR constellations that are actually flying are traditional, large, heavy satellites, whereas your plan is based on small-sats—why do you think that is?

JH: Capella is the first private U.S. company to develop small SAR satellites for the commercial market, and we've made an effort to design a satellite system that is the quickest and most cost-efficient to scale. Our satellites are less than half the size of other SAR small satellites, and thirty times smaller and hundreds of times less expensive than traditional SAR satellites. Capella has optimized the satellite manufacturing for cost and schedule, and will in the next step optimize for output and cadence. Our SAR sensor design abstains from the widely used flat antenna approach, either with slotted wave guide or active phased array, which can be schedule driving, but it capitalizes on high performance components ensuring great image quality. Our supply chain is lined up, and our facilities are extended to reach the capacity for assembly, integration and test of 12 spacecraft per year in 2021. All these strategic decisions and actions mean that we can launch more satellites faster, on far fewer rockets and with significantly less capital than any other company.

Our first wave of operational satellites will set a new technological standard for the industry by featuring sub-0.5 meter very high resolution (VHR) to capture images of unparalleled quality. But not only that—the new constellation will also achieve a high energy efficiency that enables an impressive imaging capacity and flexibility through a collection time of up to 10 minutes every orbit, which is five times better than other small satellite competitors. Combined, the advances mean Capella will deliver more higher-quality images in less time than anyone else in the industry. We are focusing on high image quality paired with a high level of timeliness.

LM: Please tell us about your constellation—the satellites themselves, the SAR sensors, the orbits and the planned schedule of launches? What are the big features of the Capella Space solutions, for example resolution, revisit time, or ease of tasking?

JH: The Capella constellation of 36 satellites will be placed in 12 orbital planes to provide hourly revisits of any point on Earth. All satellite operations, from scheduling to product delivery, will be automated, and the constellation schedule will be constantly updated to support on-demand acquisition requests. In addition, each satellite will be operated under orbit control conditions that meet the needs of good quality interferometric SAR data collection, with an interferometric repeat time as short as 4 hours.

Capella's technology makes it the first company in the industry to capture truly sub-0.5m VHR imagery. What's more, Capella entered into industry-leading agreements with Inmarsat and Amazon Web Services (AWS) to task satellites in real-time and rapidly deliver frequent, timely and flexible SAR data via the AWS Ground Station network. As a result, Capella is the first and only Earth observation company to offer real-time SAR, where we will accept requests, task our satellites in real-time, then deliver imagery to customers within, on average, 30 minutes of collection. Government and commercial markets increasingly demand this type of real-time data, which has driven Capella's customer growth. We recently announced government customer wins—U.S. Air Force and National Reconnaissance Office—and booked contracts with multiple other organizations across key industries.

In early 2020, Capella will launch its first operational satellite, Sequoia, followed by the launch of six additional satellites throughout the year. Sequoia will be deployed from Cape Canaveral into a polar sun-synchronous orbit by Space X. The miniaturized SAR sensor that will fly on Sequoia is a significant upgrade from the radar tested on our previous satellite, Denali, and it has been successfully tested on multiple airborne campaigns. After Sequoia, three more satellites will go up in June on the Indian PSLV launch. Three additional satellites will then be going up in Q3 or Q4 2020, forming the complete Whitney constellation.

With the advance of Capella's innovations in satellite technology, VHR SAR imagery, and on-demand Earth observation data, 2020 will be a momentous year for Capella, its customers, and the commercial space industry.

LM: What are the advantages and complementarities of SAR imagery, with respect to the much more familiar multispectral imagery available from constellations such as DigitalGlobe, Airbus and Planet?

JH: SAR functions independent of weather and sun illumination, which is a precondition for reliable, cloud-free and persistent monitoring. Through hourly revisits over any hotspot on the globe, this ensures excellent insights into patterns of life and any changes that matter to a customer.

Besides that, SAR is able to measure distances with extreme precision and, like lidar, can be used to measure topography and 3D structures. Location accuracy of SAR imagery can be significantly higher than optical camera systems typically achieve. Also, the automated analysis of surface motions with millimeter accuracy is a capability very specific to SAR. Change detection analytics based on SAR measurements have proven to be a reliable tool, and by adding AI, the utility of our monitoring frequency will make hotspot monitoring much more efficient and reliable.

LM: Now the big question for lidar people! Please explain a little about differential InSAR, coherent change detection and all the wonderful things that SAR can do in Z and ΔZ.

JH: SAR can be used to determine digital elevation models, either by radargrammetry (stereo, like photogrammetry) or by interferometry. Across track interferometry may be most comparable to a "stereo view". Repeat pass interferometry implies that you take a second data collection with the same observation geometry next time your satellite flies over the same area. This method is used for coherent change detection, and the changes you can detect correlate to the wavelength of the spectrum being used. In the X-band spectrum that we and many other systems are using, this is in the millimeter range. If the resolution is sub-meter, it is possible to detect a footstep in sand or grass that was not there before. If you build a collection of time series data over an area with expected dynamics, you can measure the "breathing" of the earth's surface over an oil or gas production field or measure even minute-by-minute changes on critical infrastructure such as a bridge, pipeline or dike.

Meanwhile, scientists have also optimized the atmospheric correction in radargrammetry measurements, so that ground control points can be measured from space with geodetic accuracies in the centimeter range.

LM: Your plans are a lot more than a dream, are they not? You already have a pathfinder mission in orbit. Can you please tell us something about that? Also, when I heard you speak at the Pecora 21/ICRSE 38 conference in Baltimore recently, you said that you were integrating a satellite for an imminent launch. How did that go?

JH: We have reached what our engineering experts refer to as a "very high level of compaction" in our design—we have significantly reduced the size of our spacecraft while maximizing performance. In essence, we pack enormous performance into a very small volume. Development risks have been mitigated with our pathfinder mission last year. Our micro-SAR sensor, which capitalizes on insights learned from the Denali mission, is currently being used in airborne campaigns to optimize the processing and calibration of the sensor system. We can launch the next satellite, Sequoia, with confidence early next year, knowing we have a high level of technology readiness on board and on the ground, in addition to validated automation of our mission operations.

> "Capella will accept and task its constellation in real time and deliver imagery to customers within on-average 30 minutes of collection."

LM: When we met during Intergeo in Stuttgart in September, you said that the mission control aspects will be very automated. Could you say a little more about this and explain how this differs from other constellations, please?

JH: Operating a large satellite constellation benefits from a high level of onboard autonomy, as well as automation of the end-to-end operations. While traditional satellite missions often depend on a ground operations team, we have prepared our system to operate autonomously over a wide range of operating scenarios. This is essential for cost-efficient and conflict-free operations of the fleet, and for meeting customer requirements with the real-time capability we are offering.

LM: Moving to the downstream side, could you say more about data download, processing and distribution? What is Capella Space doing in these areas that is particularly exciting?

JH: We recently entered into an exclusive agreement with Addvalue, a one-stop digital, wireless and broadband communications technology products innovator, for use of its Inter-Satellite Data Relay System (IDRS™) via Inmarsat's global L-Band satellite communications network. Inmarsat is the leading global mobile satellite communications provider. The partnership gives Capella a significant market lead as the only SAR provider with real-time tasking capability and positions Capella as the only SAR operator capable of real-time responsiveness. This constant contact with the fleet via Inmarsat's network of communications satellites will reduce the time it takes to order and deliver VHR Earth imagery from hours to minutes. This makes Capella the first and only Earth observation company that can accept and task its satellites in real-time, making it virtually latency-free. Capella will accept and task its constellation in real time and deliver imagery to customers within on-average 30 minutes of collection. As the industry average from order to delivery is typically eight hours and can be as long as several days, Capella will provide satellite imagery more than 16x faster than the industry average.

LM: What products will you make available to end-users?

JH: We will roll out a portfolio of products next year, starting with high resolution, frequent revisit SAR data, and then add data stacks for interferometric and change analysis triangulation and monitoring services.

LM: Is there anything unusual or novel about your business model, in terms of pricing, subscriptions or other payment schemes? What is the platform that you mentioned at Pecora 21/ICRSE 38?

JH: We are giving our customers and partners access to our API via our online platform, the Capella Console. Customers can subscribe to services, and our pricing will be very competitive.

LM: What do you expect to be your main markets? Do you think Capella Space will be a defense contractor, with a few commercial clients as well? Some people have said that it is impossible to make money from spaceborne earth observation without massive defense purchases what do you think?

JH: Defense and intelligence are a key market, of course, but both government and commercial markets are increasingly demanding this type of VHR real-time Earth observation data. We've recently secured major contracts with multiple divisions of the U.S. government, including recent contracts with the U.S. Air Force and the National Reconnaissance Office, and are also working with customers across multiple other use cases, including insurance, disaster management, oil and gas, urban development and maritime. We value our commercial clients and see numerous opportunities to democratize access to SAR outside of defense and intelligence.

LM: As a result of your choices of hardware and software technologies, and the various technical and business innovations that you are accomplishing, do you expect some new customer groups who will use SAR differently from how data from the existing constellations is being used?

JH: Absolutely. Capella is committed to helping provide more people with access to SAR data. We recently launched the Capella User Community, which gives members free access to Capella's SAR data. In exchange for feedback and results of their projects, these users can explore different applications to solve some of our world's greatest problems—from natural disaster response and city planning to illegal fishing monitoring.

We also recently announced a partnership with SpaceNet, a nonprofit organization dedicated to accelerating open source, artificial intelligence (AI) research for geospatial applications.

The goal of these programs is to expand awareness and use of SAR data to encourage experimentation and help uncover new applications for using this technology—we've only scratched the surface of what's possible.

LM: Finally, a couple of very speculative questions. Do you have any thoughts about Capella Space doing a multispectral or hyperspectral constellation once the SAR is up and running? And do you think there is any possibility of spaceborne lidar using smaller satellites like yours?

JH: Space-based lidar is being used to measure wind, cloud and aerosol profiles, and to assess topographic data on the Earth's surface (for example, ICESat-2). These missions are still rather heavy and power-hungry. Multispectral constellations are emerging, while hyperspectral is also coming out of smaller satellites. The next few years will reveal how these remote sensing techniques can find a role in developing the world of microsatellite constellations.

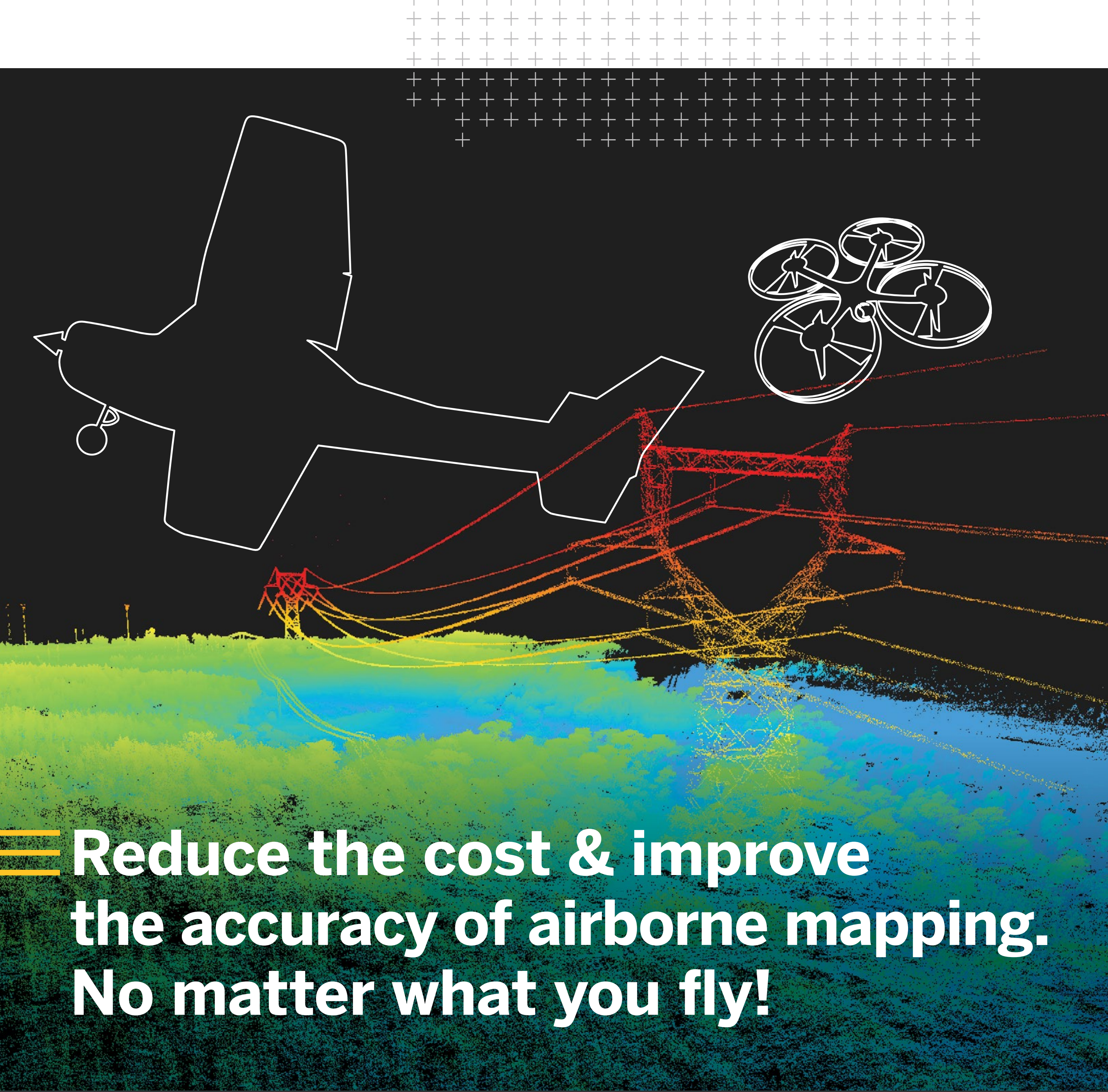
LM: Dr. Herrmann, thank you very much indeed. *LIDAR Magazine* is very grateful to you for taking the time to answer our questions. We look forward to news of your various launches and the forthcoming SAR products.

Joerg F. Herrmann is Senior Vice President of Special Projects at Capella Space Corporation. He previously served as senior business development executive at Airbus Defence and Space. He initiated the commercialization of synthetic-aperture radar (SAR) satellite remote sensing in Germany through the TerraSAR program and served as founding CEO of the TerraSAR-X services entity, Infoterra.

During his more than 30 years in the geospatial and space industries he worked in system engineering and design, program management, marketing and sales, strategy and business development, and general management.

In recent years, he developed strategic partnerships and conducted fund raising for innovative space initiatives involving SAR satellite constellations, and laser communication.

His educational background is in engineering, business administration, and entrepreneurship.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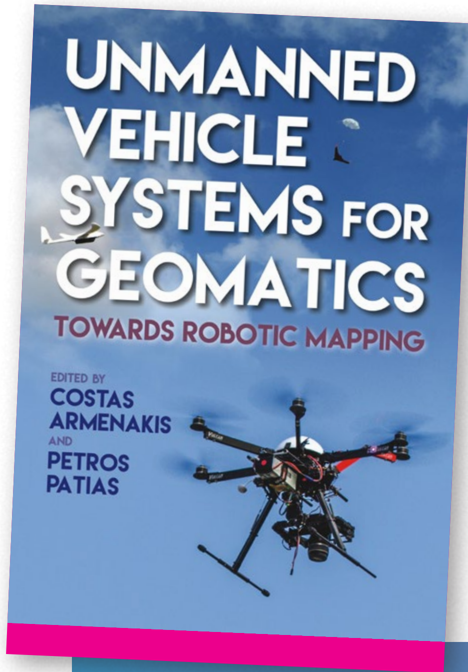
BY STEWART WALKER

Unmanned Vehicle Systems for Geomatics

Towards Robotic Mapping



EDITED BY COSTA ARMENAKIS AND PETROS PATIAS

- Whittles Publishing, Dunbeath, Caithness, UK, 2019.
- 243 x 160 mm, xv + 318 pp, 202 color and black and white illustrations, 31 tables, 3 algorithms, index.
- Hardback, ISBN 978-1-84995-127-2, £85.00. $107.83 Amazon.

UAV-lidar is a hot topic for *LIDAR Magazine* readers, who have noticed the arrival of sensors from the automotive market. How timely it is, therefore, to have a new textbook that gives structure to the technology and applications of mapping with autonomous vehicles. While its long title underlines the focus on geomatic applications, it reveals little about the types of unmanned vehicle systems (UVSs) it covers, but most of the content concerns UAVs, mainly carrying cameras and sometimes lidar sensors. Indeed, the preface congratulates the geomatics community on its felicitous adoption of UAVs, though it fails to describe the audience at which the book is aimed.

The book is a collection of eight essays. The editors, who are also contributors, are well known. After decades in national mapping in Canada, Costas Armenakis changed horses late in his career and is a professor in geomatics engineering at York University. Petros Patias is professor and director of the Laboratory of Photogrammetry & Remote Sensing, University of Thessaloniki. The book began when the former enjoyed a sabbatical at the seat of learning of the latter. The other contributors are mainly academics, at universities in Canada, Germany, Switzerland and US, but two are in government in Germany and Switzerland and three, in the commercial UAV world in Germany and US.

Armenakis himself authors the introductory chapter, starting with MMSs, UVSs and UAVs. His approach is generic and systematic, but his material on classifying UAVs is awkward as several different schema are breathlessly thrown before the reader. We were guilty of similar taxonomic excesses with analog stereoplotters 50 years ago! On page 9, we hit a major weakness, to which your reviewer will return: a hardcover textbook cannot be up-to-date like a white paper, website or blogsite, but the inclusion of out-of-production UAVs is unfortunate. Notwithstanding this, the overview of the field is welcome. Armenakis turns to the value of UAVs for geomatics, with good sections on sensors and their decreasing SWaP profiles. The UAV part concludes with a section on regulatory issues, again somewhat out of date, and the chapter ends with short, informative sections on ground and marine UVSs. All chapters end with long lists of references.

Chapter 2 is likely to be key for many geomatics readers, covering coordinate systems, transformations, mission planning, image and camera measurements, bundle adjustment, georeferencing, dense image matching, structure from motion, SLAM, orthorectification and registration of point clouds. Encompassing all this

in 35 pages is challenging, but there is enough to give a grounding and encourage those interested to look in the many references for more.

Chapter 3, "Unmanned vehicle systems and technologies for sensing and control", begins with UAVs, their characteristics and their classification—is this repetition of material in chapter 1, or a didactic tool? Certainly there is far more detail here on platforms, including several pages on balloons, cameras and lidar, followed by short sections on multispectral, hyperspectral, acoustic, magnetometer and meteorological sensors. The authors are obviously on home turf in the sections on flight controllers, autopilots and communications. These are probably more important to suppliers than end-users—the book will attract both. Again, the chapter is richly furnished with references, but with reference numbers in square brackets, as opposed to alphabetical listing by author. Chapters 3, 4 and 7 prefer the former; the other chapters, the latter.

Andreas Nüchter (University of Würzburg) is the sole author of chapter 4, on position and orientation of sensors for UVSs. This is primarily about pose estimation for UVSs on the ground. More accustomed to airborne vehicles, your reviewer therefore encountered fresh, enjoyable material here as the equations for robotic motion are developed. The chapter has plentiful equations and algorithms and both Bayes and Kalman filters are introduced. SLAM and calibration are covered, followed by real-world mapping applications. The chapter ends with autonomous navigation and obstacle avoidance.

Most readers of this review will feel on safer ground with chapter 5, "Data acquisition and mapping". The authors use the term "small-scale" when they really mean "small-area": with centimeter pixels, you can have a map scale as large as you like! Again there is review material on UAVs, followed by a useful comparison of UAV mapping to other technologies, such as total stations and manned aircraft. This chapter, like the last, is well illustrated with practical examples. Both UAV-photogrammetry and UAV-lidar are covered and there are good discussions of point clouds, orthoimages and accuracy. There is plenty of useful material here and your reviewer would have welcomed even more.

Patias is the sole author of chapter 6, "Applications, case studies and best practices". He provides summaries of many practical projects, from archaeology and heritage, agriculture and forestry, disaster management and emergency response, mapping and monitoring, transportation, and environment, energy and mining. Each case study is well described and illustrated and ends with a handful of references that Patias accurately calls "credits". These are over and above the references at the end of the chapter. Some of the 72 figures in the chapter are rather small, but the generous use of color makes most of them work.

The last two chapters are, respectively, "Emerging trends and technologies" and "Outlook—addressing the challenges". The problem is that, owing to the passing of time, some of the trends and technologies have emerged and some of the challenges have been addressed. Indeed, the way the market has converged, for many applications, on battery-powered multicopters carrying cameras and, in many cases, lidar sensors, was perhaps not foreseen when some of this material was first written. Chapter 7, however, devotes considerable space to system integration—airframe, flight control system, ground control station, data link, fuel, batteries, payload, processor, power systems and software. This is useful and undergirds the value of the book to system and component suppliers as well as users. There is brief discussion of lidar, photogrammetry and other sensors, but much of this material has already been covered. Chapter 8 looks at societal, technological, regulatory and financial challenges. It seems to bring in material from references rather undigested, for example European Community (EC) material on technological issues and both EC and other material on the regulatory environment, which if course is enjoying considerable attention, so is changing too fast for the book to keep up.

> "This is a well produced book, with color on every page, printed on high quality paper. The authors write clearly and their international perspective is appealing."

Incorporating material from commercial and AUVSI reports to provide insight into trends and forecasts is sensible, but the examples chosen were published in 2007 and 2013. It must not be inferred, however, that older material is necessarily incorrect or without value. These two chapters indeed raise important issues.

This is a well produced book, with color on every page, as headings, titles, or graphics, printed on high quality paper. The authors write clearly and their international perspective is appealing. Whittles has been a leading player in geospatial publishing for many years—its location in remote northern Scotland rejuvenates your reviewer's memories! There are acceptably few typos or glaring errors, except that the two pages of authors' biographies seem to have been edited very lightly. Also, throughout the book, the terms "GPS" and "GNSS" are used interchangeably, whereas it would have been more pleasing to the eye and consistent to prefer the latter throughout. The spelling of "lidar", of course, is a topic on its own! There is a glossary of acronyms and initialisms and a four-page index. The book can be enthusiastically recommended, but with a tinge of disappointment: the material needs to be updated: it has very little content and references more recent than 2016. Many of the URLs were last accessed some years ago—did they work the day the book was published? Your reviewer understands that high-end book publishing is far from an instant process, but readers will be distraught that products and technologies they are encountering every day are not mentioned, such as DJI and the leading UAV-lidar integrators. We hope that the second edition provides a thorough update, excises repeated content and combines the last two chapters. Nevertheless, the book sets out a useful framework to understand UVSs in the geomatics world, much of the material is still valuable despite the dated references, and it deserves a place on the shelves of geospatial students, professors, practitioners and suppliers.

Stewart Walker, Managing Editor, *LIDAR Magazine*.

Graham, *continued from page 48*

and Orientation System and fully calibrated. Post-processing software must implement algorithms that can effectively ray trace from each 3D point to the appropriate pixel in the "best" source image. In our example above, the image acquired when the sensor is directly over the tree/paint strip would be the correct one for painting the leaf whereas a non-nadir image that is "peeking" beneath the tree will have to be selected for the road strip 3D point. It's complicated!

Most providers of drone LIDAR that integrates one or more cameras do not implement 3DiS. Instead they have a workflow that creates a digital orthophoto and then recommend a third-party software (Global Mapper, for example) to simply color the LIDAR using a digital orthophoto. If you think about it, this cannot possibly be correct. An orthophoto contains a single color pixel for a particular X, Y location in the scene. If I had a pipe on the ground under a lattice structure under a tree, I would have three points from the LIDAR but only one point from an ortho (most likely the tree point). All three points would be colored the same. This problem is very nicely illustrated in **Figure 1**. These data were produced from a very high-end drone LIDAR/camera system (list price over US $200,000). We can clearly see the vertical bands of color; the signature of the "quick and dirty approach" of colorization from an orthophoto. Not only are these data wrong but downstream processing that relies on correct colorizing will fail.

It should be evident that there is a very big difference between "colorizing" LIDAR data and a true 3DiS data set. If you plan to invest in an sUAS LIDAR system, make certain the scheme is compliant with the requirements of 3DiS. Also be aware that a 3DiS cannot be fully achieved in hardware or software alone; it takes a careful system design of both. Thus if you are acquiring a sensor but part of the workflow software is from a third party, you are probably not getting a true 3DiS. A good example of a well-engineered 3DiS is GeoCue's True View 410!

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

RANDOM **POINTS**

LEWIS **GRAHAM**

What is a 3DiS anyway?

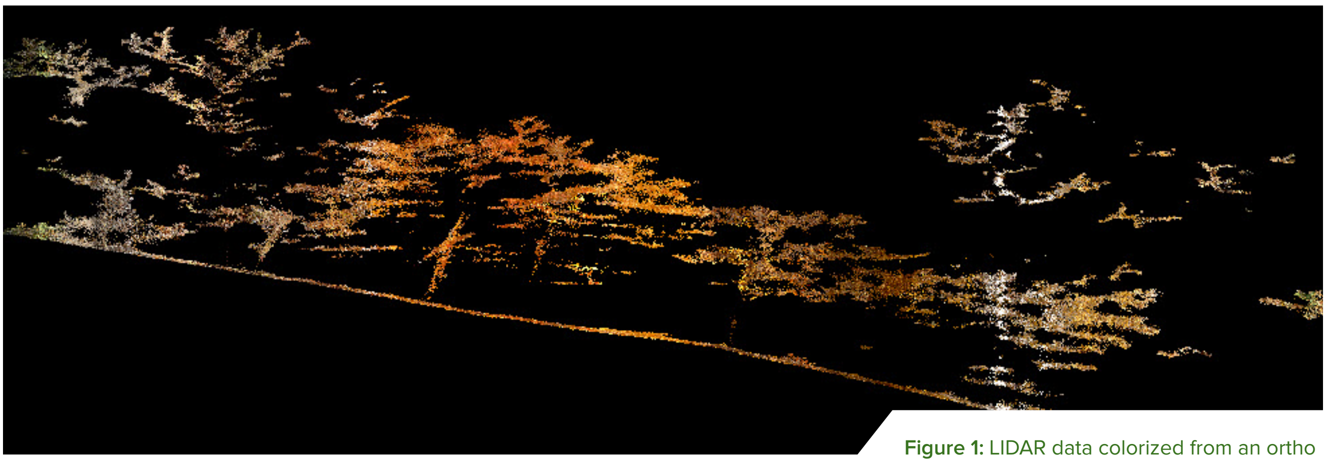


Figure 1: LIDAR data colorized from an ortho

I really think it is time, particularly in the small unmanned aerial systems (sUAS) mapping arena, to make high accuracy *colorized* 3D point clouds the base data standard. I coined the term "3D imaging System" (3DiS) for the systems that can create these data. With that said, what exactly is a 3DiS?

The first part of 3DiS is the 3-Dimensional (3D) bit. A 3DiS must be capable of directly sensing a surface. For now, this means that 3DiS are limited to active sensors: LIDAR, Sonar, Radar. Photogrammetry cannot be the 3D part of a 3DiS because it does not provide accurate range data for many scene types such as vegetated areas, wires, thin vertical objects, poorly lit objects, objects free of texture and so forth. For sUAS mapping, this means the sensor must contain a LIDAR.

The "I" part of a 3DiS is *imagery*. These data are used to "paint" the 3D points obtained from the active sensor part of the 3DiS (again, LIDAR for a drone mapping system). Most commonly, the imagery will be supplied by visible spectrum ("Red-Green-Blue", RGB) cameras flown concurrently with the 3D sensor. However, it could certainly be infrared, multispectral and so forth depending on the requirements of downstream applications. The imagery must be *concurrently* acquired with the 3D data. This rule is in place because objects move. Consider a construction site with a lot of mobile equipment. The 3D data cannot be properly painted with imagery if objects moved between the time of acquisition of the 3D data and the imagery. Thus a first pass with a LIDAR and a second pass with a camera will not quality as a 3DiS.

The third requirement is that the 3D data must be "painted" with the *true* "color" of the object at that point (here we use color loosely—it could be infrared, multispectral and so forth). For example, if a green tree leaf is directly over a yellow paint strip on a road (meaning both points share the same planimetric coordinates), the 3D point corresponding to the leaf must be painted green and the 3D point on the road must be colored yellow. This is a major point (pun intended) for a 3DiS. It means the painting of the 3D points must use the original image data for "colorization", not a derived product such as an orthophoto. While the painting of points can occur in real time on the sensor itself, it more typically occurs in post-processing software. Thus the "S" in a 3DiS can be interpreted as "Sensor" or "System."

This final requirement of painting the 3D point with the correct image pixel adds a high level of complexity to a 3DiS. The cameras must be tied to the Position

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