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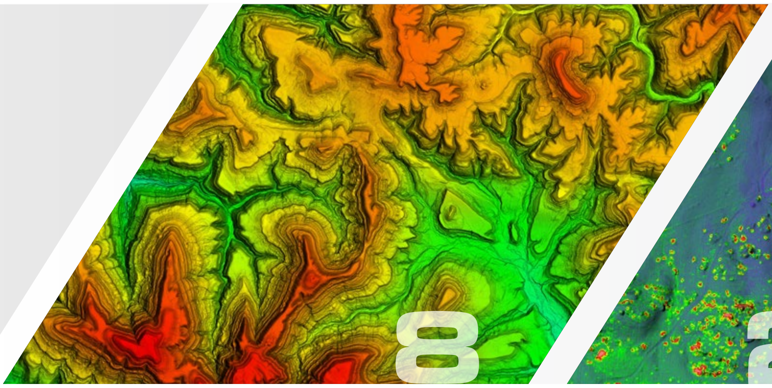

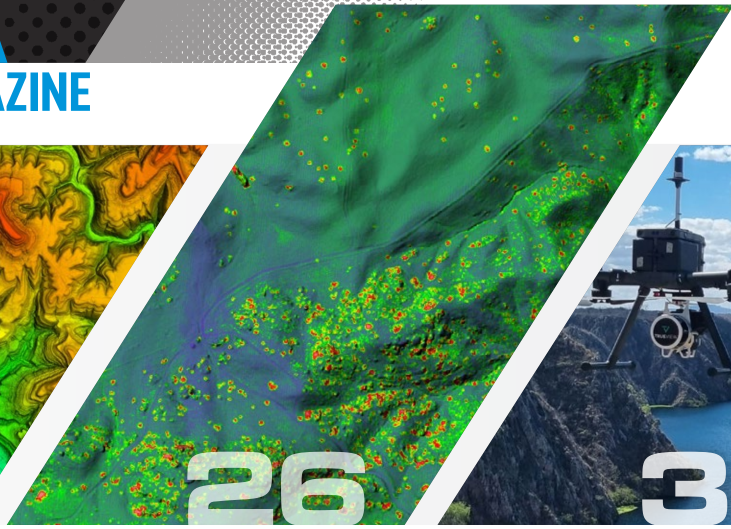

IN THIS ISSUE

COLUMNS

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◀ ON THE COVER

Bluff and river in the eastern hills of Arkansas. I mage courtesy of United States Geological Survey.

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DR. A. STEWART WALKER

Celebrating Lidar Worldwide

This issue was released at the Geo Week conference in Denver on 10–12 February. By no coincidence, this year's event concludes on World Lidar Day. I'd be amiss if I didn't commend the team at Diversified Communications, host of Geo Week, for their efforts leading up to this year's celebration. Senior managers Lora Burns and Carla Lauter went to great lengths over the recent weeks (and months!) to develop promotions, a dedicated panel discussion, special exhibit areas and more. We owe them a debt of gratitude.

World Lidar Day was designed to raise awareness about the value of lidar. Ultimately, the platform is intended to generate discussion and aid discovery about the promise of geospatial technology, something we can all get behind and benefit from. Note that if you or your firm develops or utilizes lidar technology, the founding member organizations encourage you to share a little about how or why it's beneficial on February 12th.

This edition's cover-story highlights another founding member organization that has made great strides in developing the World Lidar Day mission: Woolpert. The feature that begins on page eight highlights their successful lidar collections over Eastern Arkansas as a 3DEP update. Arkansas's GIO, Shelby Johnson, co-authors the piece with Woolpert program manager, Sam Moffat. The two cover not only 3DEP and its refreshment, but also the wide-ranging benefits it brings to the state.

On page 16 you'll find part II of Gottfried Mandlburger's series, *Airborne Lidar: a Tutorial for 2025*. This segment covers how integrated systems, where lidar and camera(s) are combined, are configured and the advantages they bring. Though *LIDAR Magazine* is published in the U.S. and this issue is centered on Geo Week, we must remember that there's a lot going on overseas too. We've already begun the *Elevation for the Nations* series by Ada Perello of EAASI[1], who summarizes the various nationwide lidar programs being conducted in Europe. We can report that PCP2025, the 4th International Workshop Point Cloud Processing[2], held in Stuttgart four days before Geo Week, was fully booked well before the event. More focused, and equally attractive, is 3D Underwater[3]: this 3rd

1 lidarmag.com/2023/10/07/elevations-for-the-nations/ and lidarmag.com/2024/09/22/elevations-for-the-nations-part-ii
2 pcp2025.ifp.uni-stuttgart.de
3 tuwien.at/en/mg/geo/photo/events/3d-underwater

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underwater workshop, to be held at TU Wien on 8-11 July 2025, is organized by Gottfried and his colleagues on behalf of ISPRS Working Group II/7[4], CIPA Heritage Documentation[5] and Deutsche Gesellschaft für Photogrammetrie, Fernerkundung und Geoinformation[6] (DGPF: the German Society for Photogrammetry, Remote Sensing and Geoinformation). 3D Underwater will be a strong meeting and is highly recommended. These and other technical meetings taking place internationally are listed on the ISPRS Calendar[7].

Geo Week marks the 10th anniversary of the founding of the boutique French company, BayesMap Solutions[8]. On page 28, we offer an article by founder and president Dr. André Jalobeanu. He writes as if he is interviewing himself, allowing him to reveal some of the motivation behind the creation and development of his company and explore aspects of the technical side. Those of us who grappled, with varying degrees of success, with Bayesian inference during undergraduate statistics courses, can but admire how this penetrating approach is devastatingly effective when applied to lidar data. Many firms in the U.S. and beyond use BayesMap software for lidar strip alignment, but other major capabilities are also available.

I remember well the podcast conducted with Vivien Hériard-Dubreuil, CEO of Microdrones[9]. On page 34, we are pleased to follow this up with an article from the GeoCue[10] part of Microdrones, in which Bret Burghdurf relates how Terra Brasil[11] uses LP360 software to integrate airborne lidar with bathymetric data to generate the deliverables required by its clients.

On page 40, we have an installment of *USIBD Matters* from John Russo, president and CEO of Architectural Resource Consultants, a firm of architects in Tustin, California. John is also founder and past president of the U.S. Institute of Building Documentation (USIBD). In this capacity, he has submitted a piece about version 3.1 of USIBD's Level of Accuracy specification, which was released just as this issue was going to print[12].

Immediately afterwards, Amar Nayegandhi, now in post and working hard in Woolpert's St. Petersburg office, addresses an important question in the latest installment of his *Full Coverage* column (supported by Al Karlin). We are all excited by the ease with which we can acquire more and more data, but is there a threshold at which diminishing returns set in with respect to lidar density?

Last but not least, on page 48, we are delighted to welcome a new Contributing Writer. John Welter, Division President, Geospatial Content Solutions (GCS) at Hexagon Geosystems, is a well-known figure, both to the Leica Geosystems customers whom he visits round the globe, but also to the wider geospatial community. John and his father Fred ran a thriving geospatial services company, North West Geomatics, in Calgary, Alberta, Canada. This was acquired by Hexagon in 2014 and the result has not only been energetic management of the Leica Geosystems airborne sensors, but also the creation and growth of the content program. The first instalment of his *Content to Serve* column highlights three major trends for 2025: AI, cloud computing, and sustainability. It's intriguing how John complements Gottfried's teaching on the technology of hybrid sensors, by proselytizing their reduced flight times and carbon emissions compared to traditional dual-mission data collection.

As we celebrate World Lidar Day, therefore, we can perceive the contents of this issue as a microcosm of our favorite light detection and ranging technology's success: massive data acquisition for a successful government program and the benefits; hybrid/integrated sensors; the sophistication and reliability of software products that have been many years in the making; the evolution of building documentation and its role as an enabler; AI, the cloud and sustainability; and the question of how much data is enough. Another trend, however, underlies all this like a palimpsest—digital twins, which will attract users and demonstrate successes throughout the year. Thank you for being part of the *LIDAR Magazine* community.

A. Stewart Walker // Managing Editor

4 www2.isprs.org/commissions/comm2/wg7
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6 dgpf.de
7 www.isprs.org/calendar/default.aspx
8 bayesmap.com
9 lidarmag.com/podcast. Podcasts are in preparation with guests Steven Woolven (Trimble Applanix), Josh Novac (Deweberry) and Philippe Simard (SimActive).
10 geocue.com
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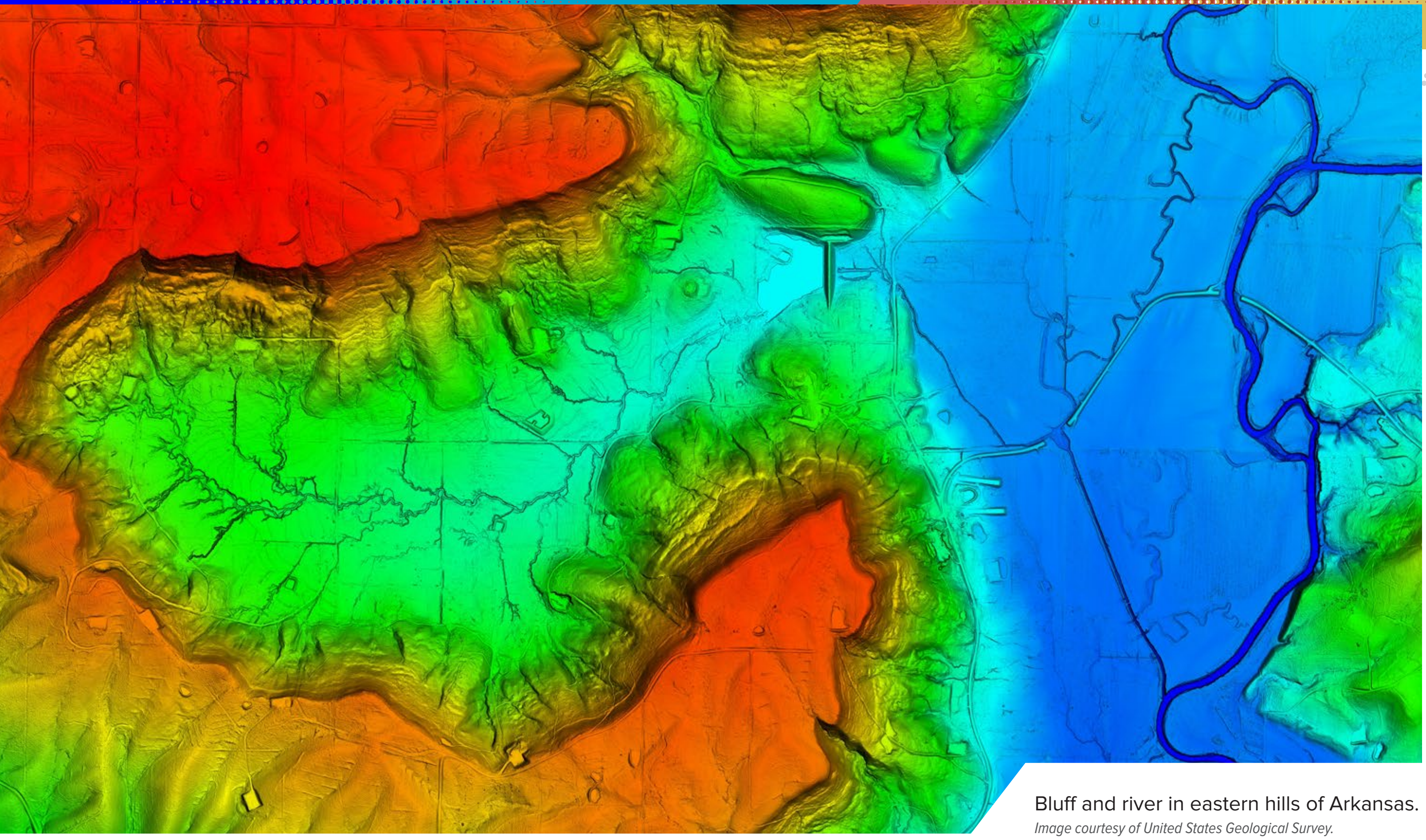

Bluff and river in eastern hills of Arkansas.
Image courtesy of United States Geological Survey.

Refreshing the 3DEP Baseline

Arkansas teams with Woolpert on ambitious lidar acquisition plan

BY SHELBY **JOHNSON** AND SAM **MOFFAT**

The 3D Elevation Program (3DEP) conducted by the U.S. Geological Survey (USGS) has bolstered Arkansas's economic growth and provided its taxpayers with myriad returns on investment. Led by the state's Geographic Information Office (GIO), Arkansas has leveraged baseline 3DEP digital elevation data to reduce costly agricultural water usage, mitigate flood risks, identify dangerous geohazards, and accelerate infrastructure development activities. As a result, Arkansas residents are safer, their farms are more sustainable, and the overall business climate has grown more attractive.

When 3DEP launched its next-generation refresh phase, Arkansas jumped at the opportunity in 2023 to obtain new elevation data to augment the baseline products acquired during the previous eight years. Concurrently, the state saw significant value in increasing its funding share to acquire lidar elevation points at a higher density—8 points per square meter (ppsm) versus 2 ppsm in the baseline collection.

The increased point density of the next generation 3DEP data will result in greater accuracy in projects using that data, while driving an overall positive economic impact for Arkansas, according to the state's GIO. Nationwide, this repeat coverage of higher-quality lidar will support the detection of landscape

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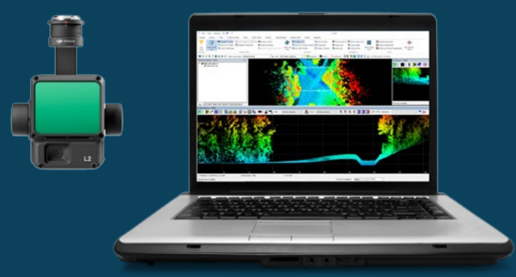

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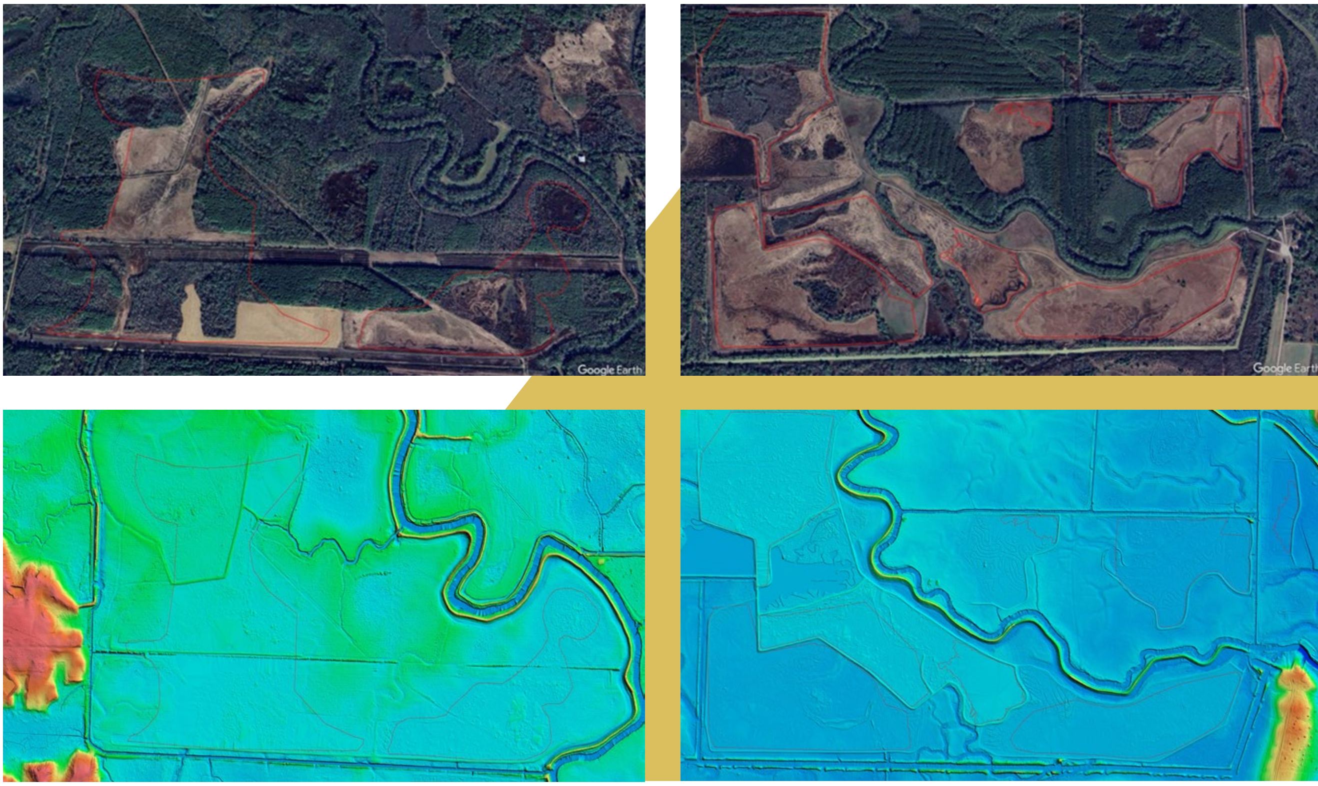

These comparisons for Google Airbus 2024 data (top) and 2024 3DEP (bottom) shows how the 3DEP data is used to help manage rice field flooding. The polygons in the data show the interpolation.

3DEP images courtesy of United States Geological Survey.

changes due to construction, urban growth, landslides, lava flows, surface mining, shoreline erosion, and many other natural and anthropogenic impacts.

Refreshing the baseline 3DEP data

USGS began its first full year of 3DEP production in 2016 with the goal of capturing high-resolution topographic elevation measurements for use in generating baseline datasets of bare earth digital elevation models (DEMs) and 3D point clouds for the nation [see sidebar].

From the outset, a unique aspect of 3DEP has been its shared program funding and coordination among federal, state, tribal, and local government agencies. More than a dozen aerial mapping firms were contracted to perform the acquisitions, using airborne lidar everywhere except for Alaska, where cloud cover necessitated the use of synthetic aperture radar. Baseline lidar specifications called for the capture of Quality Level 2 (QL2) elevation measurements at 10 centimeters vertical accuracy and 2 ppsm density. To date, 98% of the nation has been mapped successfully in the 3DEP baseline phase.

In 2023, USGS made several modifications to 3DEP, most notably the option for states to "buy up" to QL1 data collection at 8 ppsm, i.e. to help fund the upgrade when otherwise the collection would have been at the QL2 level. Thanks to technological advances in airborne lidar systems that have reduced operating costs since 2016, QL1 data has become more affordable for many states.

USGS selected Woolpert, an international architecture, engineering, and geospatial firm with a long history of supporting large-area mapping activities, including 3DEP, to collect new data across Arkansas. The state and the company collaborated to generate an ambitious 3DEP refresh plan to map the entire state in just two flying seasons, the 2023/24 and 2024/25 seasons, to support data consistency.

Mapping Eastern Arkansas

The new acquisition plan divided the state roughly into eastern and western


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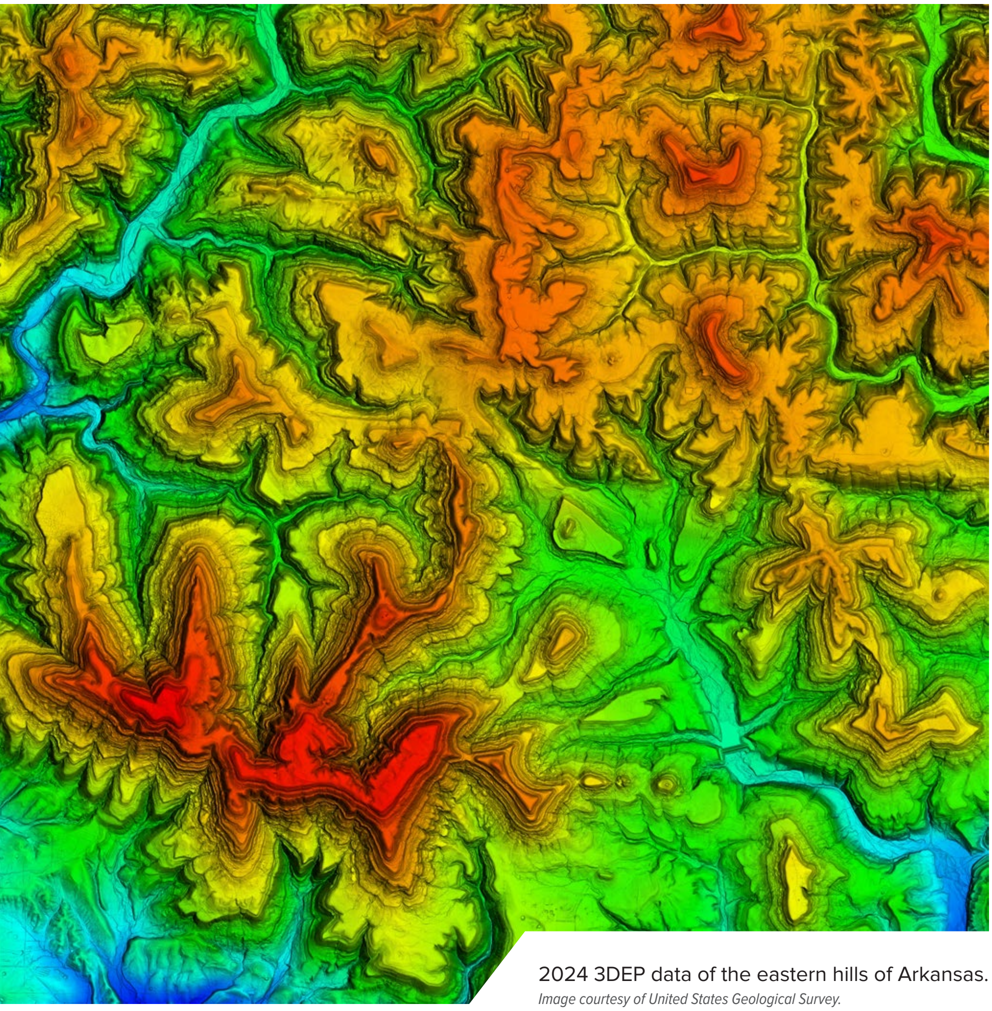


2024 3DEP data of the eastern hills of Arkansas.
Image courtesy of United States Geological Survey.

halves, each to be captured during a leaf-off period from early December to late March. To cover this large area, Woolpert dispatched three of its 13 aircraft to the state, each equipped with powerful Leica TerrainMapper lidar scanners. Flying at 6500 feet above ground level, these sensors collected elevation points as well as four-band imagery used for feature validation.

Starting in December 2023, Woolpert flew the eastern half of the state, moving south to north, because the vegetation would stay leaf-off in the northern part of the state until the end of March 2024. Flight lines were planned in advance, but each day's flying assignments were determined by weather and where the ground was clear and exposed—without snow or seasonal flooding.

During the lidar data acquisition, Woolpert field crews surveyed separate GNSS ground control points and checkpoints. Tied to the local coordinate system with the Continuously Operating Reference System network, the control points were used to relate the lidar measurements to Earth and the flight lines to each other during processing. The checkpoints were used for independent quality assessment.

Woolpert processed the raw lidar data to generate three primary deliverables—a classified point cloud, bare earth DEM, and extracted hydrographic breaklines. The classes included basic categories of vegetation, bare ground, and water bodies. Eastern Arkansas features a unique agricultural land class, known as Green-Tree Reservoirs, which are purposely flooded after the growing season to attract migrating waterfowl for hunting purposes. These temporal water bodies were not present in every farm field but were identified as their own class.

Thanks to the careful, yet flexible, flight planning, Woolpert covered half of the state in a single flying season as requested by Arkansas. This accomplishment improved the overall quality of the data due to acquisitions being conducted under consistent ground and weather conditions.

Following the completion of the eastern Arkansas data collection in March 2024 and subsequent processing, Woolpert delivered the elevation products along with metadata and checkpoints to USGS for quality assessment. Depending on file size, the GIO delivers products via online and hard-drive methods to interested state agencies and private sector engineering firms at no charge. The data is also incorporated into The National Map for use by the general public.

Leveraging 3DEP in Arkansas

The GIO resides within the state's GIS office, which is a division of the Arkansas Department of Transformation and Shared Services. The GIO makes use of 3DEP data for visualization projects while serving as the data warehouse and distribution center. The majority of the derived elevation products are employed in engineering and science applications. In many cases, these projects are performed jointly by state and federal offices and are as diverse as the Arkansas landscape.

One of the most important 3DEP applications that will become even more effective with the availability of the 8 ppsm refresh data is an ongoing initiative called irrigated land leveling. Spearheaded by the U.S. Natural Resources Conservation Service, this process yields dual success by simultaneously conserving precious surface water and reducing irrigation costs for Arkansas rice growers.

Totaling about 1.4 million acres, rice fields are plentiful in the southeastern part of the state near the Mississippi River Delta. This form of agriculture is irrigation-intensive and requires a constant, minimum water coverage for rice production. In fields with uneven or sloping topography, an excessive volume of water is needed to cover all spots, including the high ones, to a minimum depth. Then, low points are often submerged in considerably more water than is needed.

This comparison of Google Airbus 2024 data (top) and 2024 3DEP (bottom) at the top of page 9 shows how the 3DEP data is used to help manage rice field flooding.

The data enables government agencies to identify the fields that have not been leveled, in order to target education, training, and outreach on the benefits of land leveling. This effort is especially impactful on water conservation as the state transitions from aquifers to surface water for agriculture.

The land leveling process involves grading fields with earthmoving equipment to level out the terrain's highs and lows. At an average volume of 27,000 gallons per acre-inch, the potential water savings associated with level fields are staggering. According to a report in the *Arkansas Democrat-Gazette*[1], the typical unleveled Arkansas rice field averages 30 inches of water coverage, while a leveled one only needs 18.

1 arkansasonline.com/news/2023/aug/13/industry-gathers-for-rice-field-day/

As indicated earlier, another agriculture-related application of 3DEP data is Green-Tree Reservoir (GTR) management. The elevation data can be used to identify wooded lowlands often found on agricultural properties that could be converted to GTR if the landowner is interested. Once flooded, GTRs are typically leased out for duck hunting, which adds a significant revenue stream to the owner and the local economy.

Since most flooding is not desired, urban planners and engineers rely on

3DEP Success and Evolution

By any metric, 3DEP has been successful and it keeps improving thanks to continuous evolution in procedures and technologies. In 2012, the program was expected to achieve an annual nationwide return on investment of $690 million for private and public stakeholders. Today, this annual return on investment calculation has soared to $7.6 billion for the next generation of 3DEP if fully implemented.

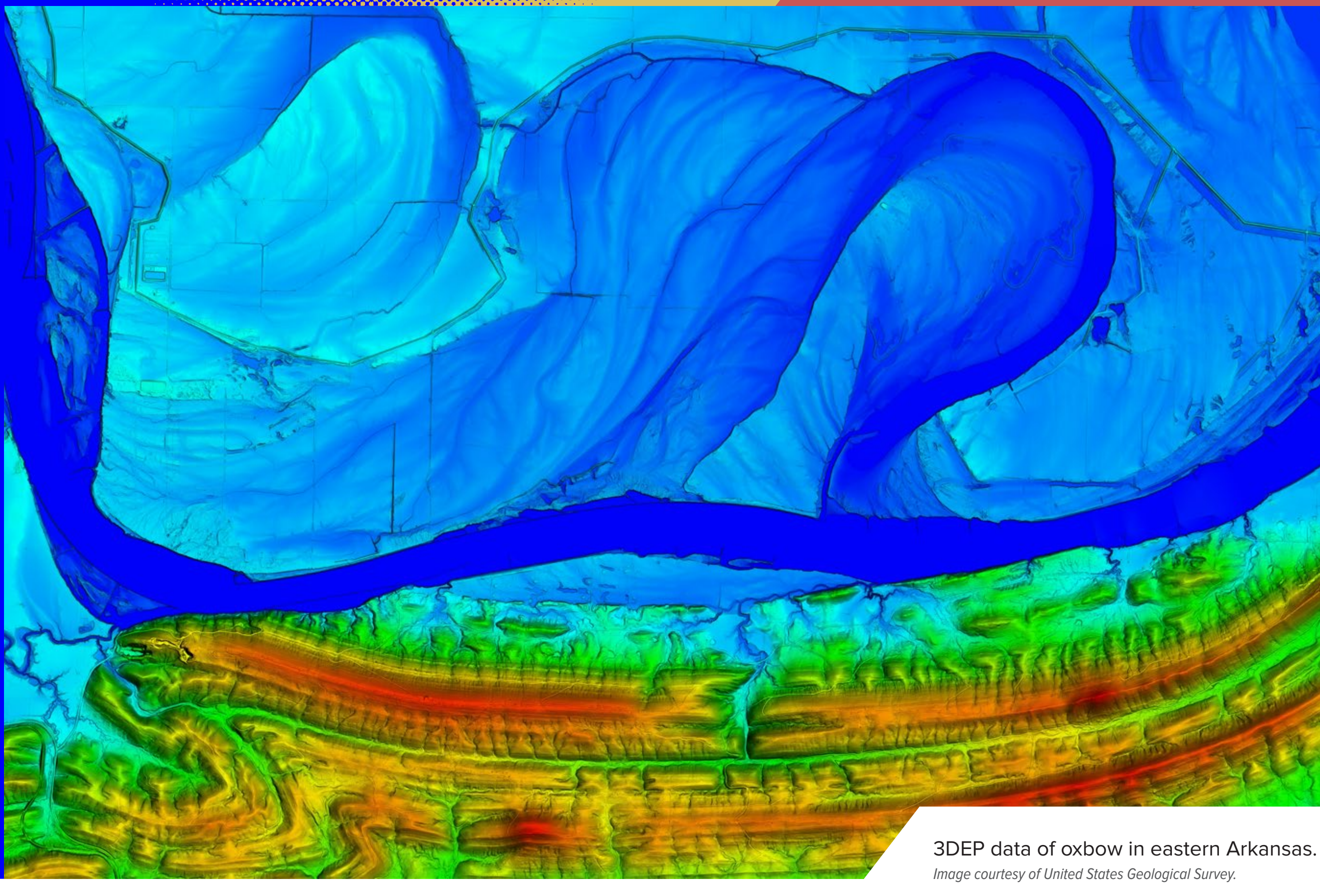
According to USGS, the goal to provide the first-ever national 3DEP baseline has remained consistent since the first full year of 3DEP production in 2016. Goals for the next generation of the program are to provide higher-quality data at an increased frequency and to integrate inland bathymetry data. The 3DEP specification is continually evolving and improving.

Funding for the 3DEP baseline has depended heavily on partnerships, as does the next generation program. 3DEP has amassed over 350 partner organizations over the years, and about 60 to 65% of the overall program cost is funded by partners.

The changes in goals from the baseline to the next generation of 3DEP are driven by documented user needs in the 3D Nation Elevation Requirements and Benefits Study, conducted by USGS in partnership with NOAA. These needs have grown because of improvements in technology and data quality, as well as the increased accessibility of data as 3DEP coverage has expanded.

One of the primary benefits of 3DEP for participating states is the availability of cost sharing through a fair and open process known as the annual Data Collaboration Announcement. USGS funding provides up to 50% of costs, and USGS and other federal funds are often used to expand the footprint of the survey area. States benefit from USGS expertise in contracting for data acquisition, the USGS lidar data validation process to support data meeting 3DEP quality standards, and the public availability of lidar data through The National Map products and services.

This unified approach to data acquisition also benefits USGS and other federal partners by reducing unit costs through pooled funding and economies of scale achieved with larger project sizes. The participation of funding partners in 3DEP also makes lidar datasets publicly available, supporting the mission-critical needs of USGS and other federal agencies.



3DEP data of oxbow in eastern Arkansas.
Image courtesy of United States Geological Survey.

elevation data to perform stormwater flow modeling in the planning of new streets and curbs or any construction project that alters the landscape. This kind of hydrologic mapping also is useful in smaller, microsite engineering projects when a single structure, such as a store or restaurant, is built. These commercial development projects stand to benefit most from the newer 8 ppsm data.

The increased point density will improve the quality and precision of 3DEP applications, each in its own way, but the overall advantage will be experienced in terms of return on investment. Higher-density data enables civil engineers, whether leveling a farm field or preparing a building site, to do more topographic planning and preliminary design in the office before dispatching a survey crew to spot-check plans in the field. Users can enjoy significant savings, in terms of both time and money.

The GIO's strategy is to make the best-quality data freely available to the commercial sector, just as it does for government projects. This promotes development and drives economic growth, earning Arkansas a reputation as a good place to do business, which is in the best interest of the state and its taxpayers.

Shelby Johnson is the Director of the Arkansas Geographic Information Systems (GIS) Office. He has over 30 years of experience in the geospatial disciplines. Under his leadership the State of Arkansas has completed numerous statewide framework data sets that serve as the state's spatial data infrastructure. These include several statewide digital orthoimagery collections, the completion of in an initial Quality Level 2 lidar dataset and a robust set of boundaries, roads, addresses and parcels that are used daily by federal, state, and local governments to make better decisions to improve the lives of Arkansans. Shelby was instrumental in organizing the State GIS Board and is responsible for assisting it in building a coordinated GIS system to meet the needs of people in Arkansas. Shelby is a native of Madison County and attended the University of Arkansas, where he obtained a Bachelor of Arts degree in Geography. He resides in Little Rock with his wife, Belinda, and one son.

Sam Moffat is a Geospatial Project Director at Woolpert, with expertise that encompasses all aspects of the industry, together with specialized knowledge of large-scale state, local government, and federal mapping efforts. He keeps abreast of emerging technologies and the benefits of digital data collection, including aerial imagery and airborne lidar, and has successfully managed five statewide mapping programs. In addition to managing and directing projects, Sam is well-versed in fostering sustainable relationships and assisting organizations to leverage geographic information to drive business value and operational efficiencies.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AIRBORNE LIDAR

A Tutorial for 2025

Part II: Integrated systems

The first part of the tutorial (lidar basics) reviewed the fundamentals of airborne lidar, also referred to as airborne laser scanning (ALS)[1]. We concluded that ALS is a multi-sensor system consisting of a navigation component and a scanning lidar device. The Global Navigation Satellite System (GNSS) antenna/receiver and the Inertial Measurement Unit (IMU) provide precise position and attitude information of the carrier platform. The laser scanner itself is again a multi-sensor system consisting of the scanning and the ranging unit. All these components together comprise the complete ALS system, which delivers dense 3D point clouds of the topography, vegetation, buildings, water bodies, and infrastructure, such as power lines and the like. The outstanding features of ALS are (i) high point density of typically 5-30 points/m^2 (ppsm), (ii) good height accuracy in the range of 5-10 cm, (iii) planimetric resolution of around 20 cm, and (iv) the capability of penetrating vegetation. The last of these has made airborne lidar the prime technique for capturing countrywide digital elevation data as the basis for national and transnational digital terrain models (DTMs). Next to precise geometry, ALS also provides radiometric information for each laser point, as either signal intensity or even calibrated reflectance. The latter is a measure which reflects properties of the illuminated object only, while the former also depends on mission parameters such as measurement range and incidence angle, as well as system and atmospheric parameters.

> “The combination of laser scanners and digital cameras has opened new applications.”

1 Mandlburger G., 2024. Airborne lidar: a tutorial for 2025. Part I: Lidar basics, *LIDAR Magazine*, 14(4): 26-31, December 2024.

ALS sensors as described above have revolutionized large-area elevation data acquisition since around the turn of the century, whereas in earlier years mapping was dominated by aerial photogrammetry based on analogue images. The introduction of digital metric camera systems and the development of efficient photogrammetric computer vision algorithms like Structure-from-Motion (SfM) and Dense Image Matching (DIM), however, has again changed the situation over the last two decades. Especially for the derivation of digital surface models (DSMs), aerial photogrammetry based on multi-view stereo (MVS) nadir and oblique images has proven to be a good choice. As DIM is generally capable of delivering a 3D point for each image pixel, this potentially also increases the spatial resolution of the captured elevation data.

The logical consequence was that manufacturers began to integrate both laser scanners and high-end cameras into comprehensive multi-imaging sensors. This tendency could be observed from both sides, either traditional camera manufacturers integrating laser scanners, or vice versa. Another option

BY GOTTFRIED MANDLBURGER

for enriching the traditional monochromatic ALS sensors is to operate multiple lasers with different laser wavelengths in a single compound system or to operate multiple monochromatic ALS systems simultaneously on the same aircraft. The first is the manufacturers' approach, the second that of the system providers. However implemented, the result is a multispectral laser scanner and, therefore, another example of an integrated senor system. The remainder of this tutorial first compares the basics of airborne lidar and multi-view stereo photogrammetry from a conceptual point of view and then introduces integrated lidar-camera sensors available on the market and their features. In addition, existing multispectral lidar solutions are introduced, including a discussion of their advantages, especially for 3D point-cloud classification.

Airborne lidar vs. aerial photogrammetry

In Part I of the tutorial we have already learned that airborne lidar is an active polar measurement system, which uses short laser pulses for time-of-flight-based ranging. This means that an object can be reconstructed in 3D, if it is measured in a single scan strip. One of the specific strengths of lidar is its multi-target capability, enabling the penetration of vegetation to reveal objects below the canopy and to provide data from the ground for deriving a high-resolution DTM. For a complex scene with trees, buildings, a

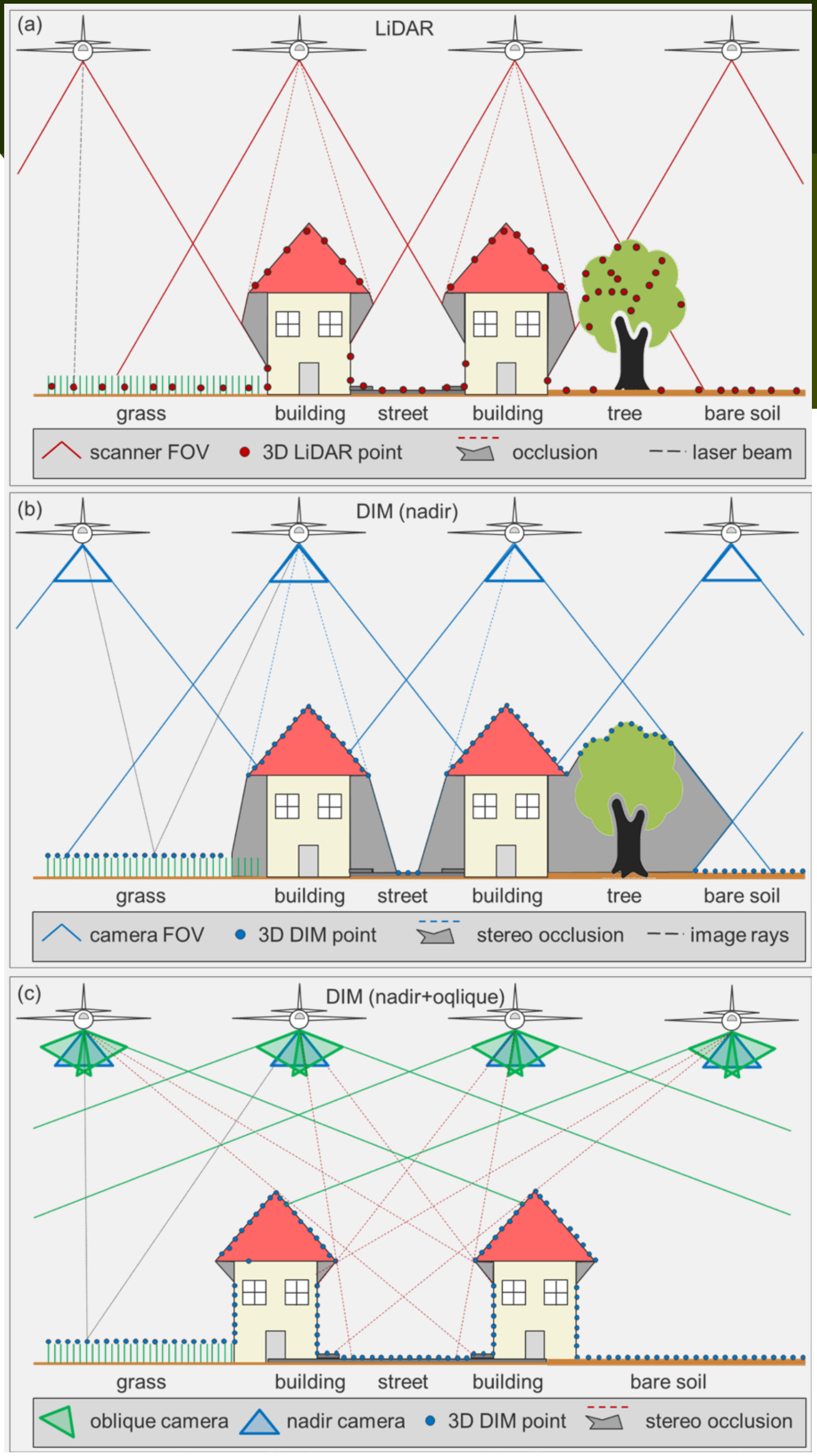

Figure 1: Schematic drawing of data acquisition based on (a) airborne lidar, (b) DIM with nadir images, and (c) DIM with nadir/oblique images.

	Airborne Lidar	Dense Image Matching
data acquisition	GNSS+IMU+scanner	GNSS+camera, IMU optional
light source	active (laser)	passive (solar radiation)
measurement principle	time-of-flight	image ray intersection
measurement rays per point	1 (polar system)	≥2 (multi-view stereo)
target detection	multiple targets per pulse	topmost surface
radiometry	monospectral (@laser wavelength)	multispectral (NIR-R-G-B)
typical point spacing	15-40 cm	5-20 cm
preconditions	(diffuse) object reflectance	texture (image contrast)
typical height precision	2-3 cm	0.5-2 x GSD

Table 1: Features and characteristics of lidar and DIM.

street canyon, and a grass area, this is schematically sketched in **Figure 1(a)**.

Driven by advances in digital camera technology and photogrammetric computer vision algorithms, modern image-based 3D surface reconstruction techniques also provide a high level of precision and robustness. Starting from a set of images and their corresponding camera parameters (i.e. interior and exterior orientation), MVS algorithms first compute so-called disparity maps, applying suitable stereo matching algorithms such as semi-global matching. As a result, stereo correspondences between pixels across image pairs are established, enabling the derivation of dense 3D point clouds via forward intersection. In addition, matching each image against multiple overlapping images generates redundant depth observations. Thus, each single pixel of an image block provides one or more corresponding 3D coordinate triplets. The resulting dense point cloud can subsequently be filtered during DSM generation. If suitable redundancy is available from multiple views, state-of-the-art algorithms can reconstruct surface geometry at a resolution that corresponds to the resolution of the available imagery. Since the size of an image pixel on the ground (ground sampling distance, GSD) is usually smaller than the footprint diameter of an airborne lidar system, DIM potentially delivers a higher point density compared to lidar. As objects can only be reconstructed from images if they are visible in at least two images, however, (stereo) occlusion is generally higher in the case of image-based 3D surface reconstruction. **Figure 1(b)** illustrates this for nadir images, which is the standard case in aerial photogrammetry.

To mitigate stereo occlusion and to enable reconstruction of vertical façades in densely populated city areas, modern image-based sensor systems use oblique cameras in addition to standard nadir cameras. A well-established, multi-camera configuration consists of one nadir camera and four oblique cameras (front, back, left, right) tilted by 45°. **Figure 1(c)** demonstrates the significant reduction

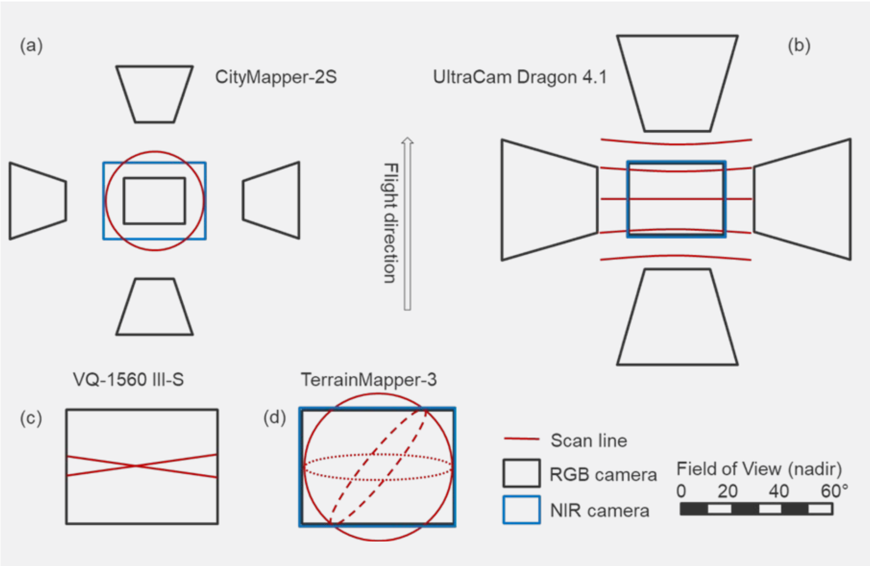

Figure 2: Schematic drawing of the scan and image setup of selected integrated sensor systems.

Sensor	TerrainMapper-3	CityMapper-2S	VQ-1560 III-S	UltraCam Dragon 4.1	Galaxy T2000
Manufacturer	Leica Geosystems	Leica Geosystems	RIEGL LMS	Vexcel Imaging/ RIEGL	Teledyne Op-tech
Laser channel [nm]	1064	1064	1052	1064	1064
Scan rate [kHz]	1x2000	1x2000	2x2200	1x2400	1x2000
Scanner FoV across [°]	60	40	58	60	60
Laser footprint @1000 m agl [cm]	17	23	23	28	23
Camera model	MFC150, 150 MP	MFC150, 150 MP	PhaseOne, 150 MP	Sony IMX411	Optech CS-series (optional)
RGB	1x nadir (RGBN)	1x nadir, 4x oblique	1x nadir	1x nadir, 4x oblique	
NIR	cf above	1x nadir	-	1x nadir	
GSD [cm]	8.3	3.3	7.5	4.7	

Table 2: Setup and specifications of selected integrated lidar-camera sensors; laser footprint and image GSD are reported for a flying altitude of 1000 m agl.

of the stereo occlusion using oblique and nadir images for a schematic scene with two buildings. It is noteworthy here that the joint orientation of nadir and oblique images is more challenging than the nadir-only case due to pronounced scale differences in the oblique images.

To round up this section with theoretical considerations, **Table 1** gives an overview of the features and characteristics of airborne lidar and DIM.

Lidar-camera integrations

As stated in the introduction, airborne sensors for acquisition of 3D elevation data nowadays combine laser scanners and camera systems. **Table 2** provides a selection of state-of-the-art sensor systems from four manufacturers - Hexagon/Leica Geosystems, RIEGL Laser Measurement Systems, Vexcel Imaging, and Teledyne Geospatial.

All the sensors in **Table 2** use an Nd:Yag laser (neodymium-doped yttrium aluminum garnet) at a wavelength of around 1064 nm with a pulse repetition rate (PRR) of 2 MHz or more. They all provide the possibility to integrate one or more digital aerial cameras—either RGB, NIR, or compound RGBN. Most of the systems have the cameras tightly integrated and the scan pattern of the lidar unit is adjusted to match the footprint of aerial images. **Figure 2** shows the scan-image layout for selected sensors.

> “Another option to enrich monochromatic airborne lidar systems is to use multiple laser wavelengths and thus create a multispectral lidar instrument.”

The Leica TerrainMapper-3 integrates a lidar unit and a 150 MP RGBN frame camera. The system features a narrow laser beam with footprint diameter of 17 cm when flying at an altitude of 1000 m above ground level (agl). At this altitude, the image GSD measures 8.3 cm. The scan pattern, produced by a dual-wedge Risley prism, is circular and the diameter covers the full 60° across-FoV of the RGBN images (**Figure 2(d)**).

RIEGL's VQ-1560 III-S is a dual-channel laser system. Each of the two lasers fires with a PRR of 2.4 MHz. Both lasers are deflected by a single four-sided polygonal mirror wheel and form an X-shaped scan pattern on the ground. The two scan lines are inclined by ±14° to optimize the point distribution on the ground and to allow nadir and sideward but also slightly forward and backward looks (**Figure 2(c)**). The lateral FOV of

Figure 3: RGB-colored 3D point cloud of the city center of Munich, Germany. Data acquired with a Leica CityMapper-2.

58° matches the size of the integrated PhaseOne 150 MP RGB camera.

Both the Leica TerrainMapper-3 and the RIEGL VQ-1560 III-S use the integrated cameras primarily for colorization of the 3D laser point cloud, which enhances the interpretability of the laser data. The images can also be used for classical aerial photogrammetry, however, to derive digital orthophotos. However, as both systems only use nadir cameras, the independent derivation of a 3D point cloud via MVS and DIM suffers from stereo occlusion as explained earlier and as can be seen in **Figure 1(b)**. To complement the laser point cloud with a complete and gapless image-based point cloud including points on façades, oblique images are needed.

The Leica CityMapper-2 sensor system is optimized for urban 3D data acquisition and combines a 2 MHz lidar unit with six aerial MFC150 cameras. Two cameras (RGB, NIR) face downwards in the nadir direction and four RGB cameras point obliquely, forward, backward, left, and right. The setup of the lidar unit corresponds to that of the Leica TerrainMapper-3, and, for the Leica CityMapper-2S system shown, the circular scan pattern matches the base area of the NIR nadir image with an across-FOV of 40°. As can be seen in **Figure 2(a)**, the footprint of the RGB image is smaller compared to the NIR image by a factor of 1.6. The setup with nadir and oblique images enables the independent derivation of a comprehensive 3D point cloud from images and scans, respectively. This redundancy can be used to fill eventual gaps in one of the data sources. One disadvantage of the circular scan pattern is the lack of nadir views, which are advantageous for object detection in narrow street canyons. The constant off-nadir angle of the conical scanning mechanism, on the other hand, enables oblique laser beam vectors in all wind directions. Together with a suitable side overlap of 50°, this enables the capture of buildings from all sides in both scans and images.

The basis of Vexcel Imaging's UltraCam Dragon 4.1 sensor system is the well-proven UltraCam camera family. The system consists of two equally


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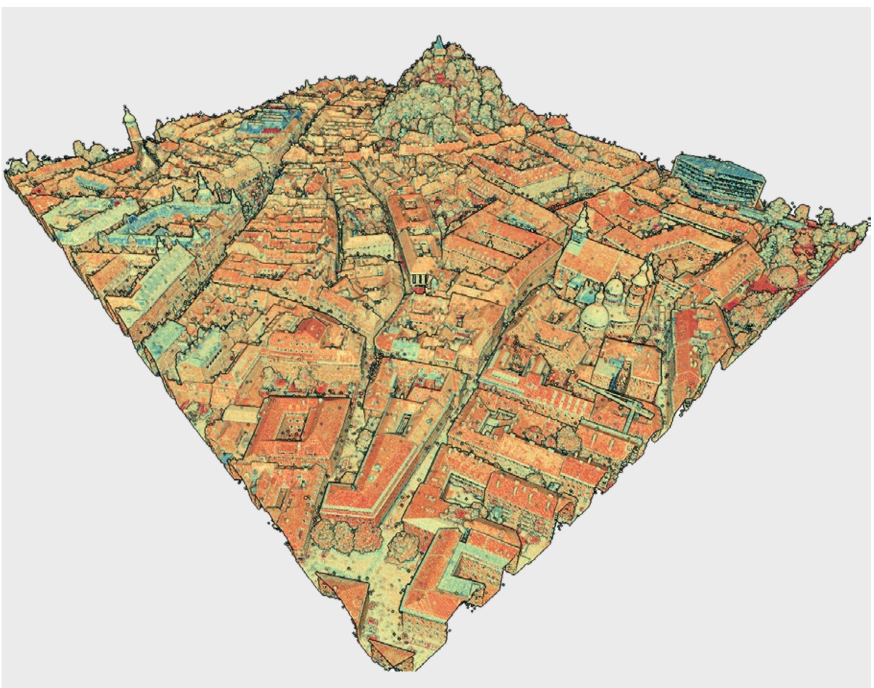

Figure 4: Urban scene in Graz, Austria acquired with the Vexcel Imaging UltraCam Dragon 4.1 — RGB-colored point cloud derived from the nadir and oblique images via DIM (top) and lidar point cloud of the VQ-680-OEM laser scanner colored by intensity (bottom).

sized nadir cameras (RGB, NIR) and four oblique cameras. The system depicted in **Figure 2(b)** uses a 50 mm lens for the nadir camera with a FOV of 36.8° across track and 27.9° along track. The system is complemented with a RIEGL VQ-680 OEM laser scanner operating at a PRR of 2.4 MHz. The scanner uses a five-sided polygonal mirror wheel, where each side is slightly tilted in relation to the next side. The first mirror face deflects the laser beams vertically down and enables nadir looks in the middle of the flight strips. The other four mirror faces are manufactured to deflect the beams 20° and 40° forward and backward, respectively (**Figure 2(b)**). With a lateral scanner FOV of 60°, a full rotation of the mirror wheel results in five scan lines, which fully cover and even extend the nadir images of the UltraCam. Thus, this scan pattern combines the advantages of vertical and oblique scanning, which optimally complements the nadir-oblique camera setting of the system. As in the case of the Leica CityMapper-2, the setup provides an optimal configuration for colorizing the laser point cloud and allows for mutual gap-filling of the lidar- and image-derived point clouds. Such comprehensive data is the ideal basis for city modeling, 3D mesh generation, solar potential studies, analysis of urban green space and the like.

Figure 3 shows an example of an urban scene captured with an integrated lidar-camera system. The scene in downtown Munich (Germany) was captured with the Leica CityMapper-2. The lidar point cloud is RGB-colored based on the nadir and oblique MFC150 images.

Figure 4 shows another example of an urban scene (Graz, Austria) acquired

with the Vexcel Imaging UltraCam Dragon 4.1. The left-hand shows the RGB-colored point cloud derived from the nadir and oblique images via DIM and the lidar point cloud of the VQ-680-OEM laser scanner colored by intensity. All scenes shown in **Figures 3 and 4** feature high completeness including points on façades and in street canyons.

Multispectral lidar

Another option to enrich monochromatic airborne lidar systems is to use multiple laser wavelengths and thus create a multispectral lidar instrument. While precise geometry and vegetation penetration are the most prominent features of airborne lidar, practically all lidar sensors also provide intensity information. Once the raw lidar amplitude/intensity readings are corrected for the dominant range and incidence angle effects (see details in Part I of this tutorial), it is possible to derive a radiometrically calibrated reflectance attribute for each point. Such information is beneficial for semantic labeling of the lidar point cloud, as we will see later in this section.

Constructing a multispectral airborne lidar sensor involves careful planning of the setup with respect to both signal detection (range, signal intensity, pulse shape…) and beam steering. Ideally, a multispectral instrument would rely on a super-continuum laser, also referred to as a white laser, and send out the entire spectrum in a single laser pulse. This means that all wavelengths of the pulse propagate at the same time, in the same direction and with the same beam characteristics (pulse length, beam divergence). On the signal detection side, this means that a wavelength-dependent beam splitter has to split the incoming echo pulse and steer it to individual detectors, which are sensitive to the respective wavelengths. While such concepts are commonly used in microscopy and spectroscopy, in the mapping environment super-continuum lasers have been applied successfully only in terrestrial, close-range applications but not for airborne lidar.

For enabling multispectral information in airborne lidar, multiple monochromatic lasers and corresponding receivers are used. The individual laser pulses are commonly deflected via a single scanning device—a mirror, polygonal wheel, or Risley prism—but typically not at the same time and not in the same direction. In addition, the pulse length and the beam divergence may differ between the individual lasers, mainly because of eye safety considerations, especially when using visible green lasers as part of a multispectral instrument. While concurrent and coaxial pulse emissions of the individual monochromatic lasers would be desirable, the implementation is technically demanding. In practice, multispectral instruments therefore deliver individual 3D point clouds for the individual lidar units. In post-processing, it is then possible to fuse the individual monochromatic point clouds to a joint multispectral point cloud by attaching the missing radiometric information from neighboring points of the remaining channels based on spatial neighborhood queries. A potential problem in such a setup is scan shadows, which may differ from one wavelength laser channel to another due to different viewing geometry. Two instruments implementing this strategy are the Teledyne Optech Titan and the RIEGL VQ-1560 DW. The basic specifications of both instruments are summarized in **Table 3**.

The RIEGL VQ-1560 DW (DW = dual wavelength) is a variant of the VQ-1560 III-S sensor described in the previous section. It provides a NIR and a green laser operating at wavelengths of 1064 nm and 532 nm respectively. The X-shaped scan pattern is the same as depicted in **Figure 2(c)**. The only difference is that one of the two NIR channels is replaced by a green channel. In addition to the two laser channels, the device also has two nadir cameras (RGB, NIR), making it an integrated

Manufacturer	Product	Laser channels [nm]	Scan rate [kHz]	Camera	Type
Teledyne Optech	Titan	532/1064/1550	3 x 300	CM-10000	80 MP, RGB
RIEGL	VQ-1560 DW	532/1064	2 x 1333	PhaseOne	150 MP, RGB+NIR
RIEGL/FGI	HeliALS (VQ-840-G/ miniVUX-3/VUX1)	532/905/1550	200/300/1000	--	--

Table 3: Examples of multispectral airborne lidar sensor systems.

system in two respects. Using the blue and the red channels from the passive imagery, a 3D point cloud with four spectral bands can be derived. In this scenario, the entire geometry would come from the lidar acquisition and the spectral content would be derived either directly from the laser measurements (NIR, green) or from the images (blue, red).

In addition to the two 532 and 1064 nm bands of the VQ-1560 DW, the Teledyne Optech Titan instrument has an additional SWIR channel at a wavelength of 1550 nm. The individual laser pulses are deflected via a single oscillating mirror. The scan planes are vertical for one channel and 7° forward or backward, respectively, for the other two channels. The three monochromatic channels allow the creation of a combined 3D point cloud, where each point features three laser-derived intensities (532/1064/1550 nm), which can be visualized as a false-color composite. An example is shown in **Figure 5**. Researchers have used Teledyne Optech Titan data for various applications, most importantly for improved point cloud classification especially in forested environments, where the multispectral content also helps to identify individual tree species from both the geometric and radiometric content of the data.

Following the initial hype after 2015, when the instruments mentioned above were introduced to the market, the interest in multispectral lidar decreased in the following years. One of the reasons was that the Teledyne Optech Titan sensor is no longer available. Today, however, the scientific community demonstrates an increasing interest, especially as compact sensors are now available, which opens the door for integrating multiple monochromatic sensors on a joint airborne platform (for example, a helicopter). The forestry industry is also the driving force here, due to the strong demand for improved biomass estimates. In the context of climate transition, it is of the utmost importance to monitor the development of the Earth's forests, as wood plays a key role as a building and heating material. Classification of tree species is facilitated by the availability of both precise geometry and radiometry, as certain tree species can be detected based on their geometric shape and a further distinction is possible based on reflectivity or reflectance. **Table 3** also lists a system developed by the Finnish Geodetic Institute (FGI), consisting of three compact RIEGL laser scanners with wavelengths of 532 nm (VQ-840-G, green), 905 nm (miniVUX-3, NIR), and 1550 nm (VUX-1HA, SWIR). Similar systems are also feasible for manned aircraft by combining, for example, a topobathymetric sensor (532/1064 nm) with a second scanner operating at 1550 nm.

The examples shown in **Figures 5 and 6** highlight the benefits of multispectral airborne lidar for improved semantic labeling. The scene around a high-voltage pylon recorded with the

Figure 5: 3D multispectral point composed of Teledyne Optech's three laser channels, false color composite: blue (532 nm), green (1064nm), red (1550 nm).

> "Multispectral systems offer great potential for point cloud classification and enable much finer class granularity with many potential applications."

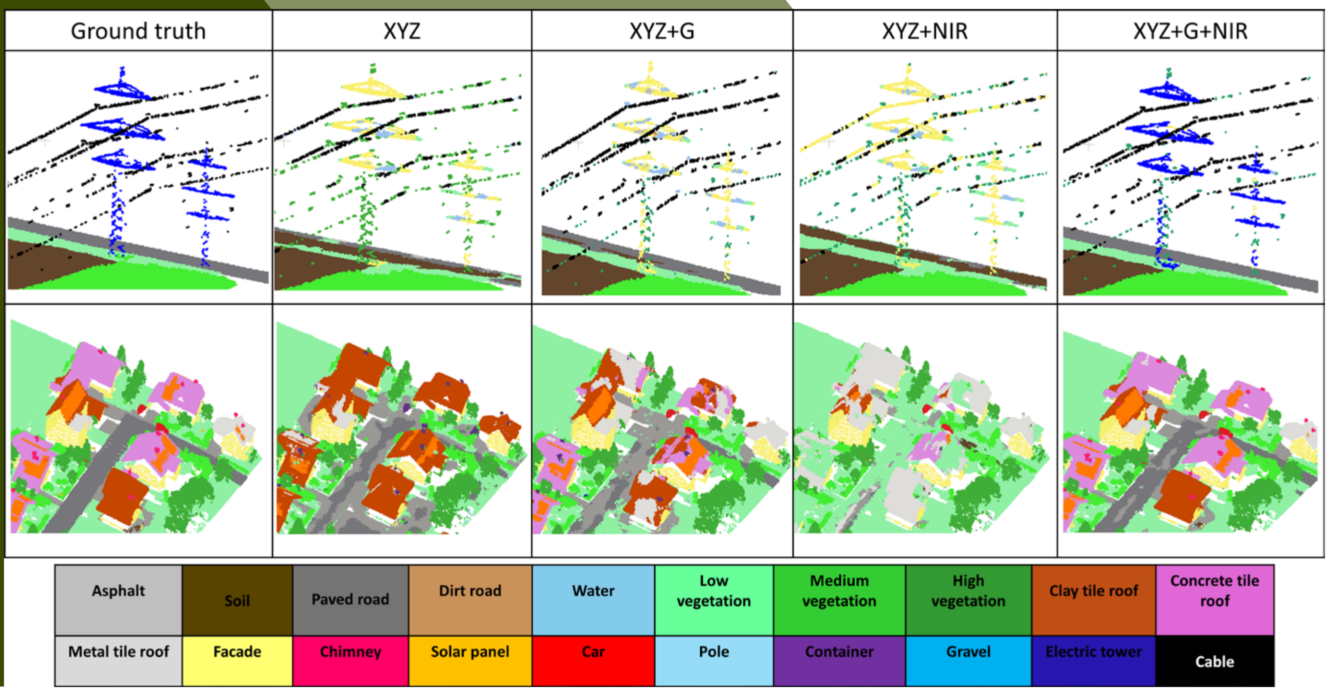

Figure 6: Labeled 3D multispectral point cloud of a high-voltage pylon scene captured with the RIEGL VQ-1560 DW sensor: manually labeled reference (ground truth) and different classification results, based on deep learning, using geometry only (XYZ), geometry + single-band reflectance (XYZ+G, XYZ+NIR), and geometry + multispectral reflectance (XYZ+G+NIR).

RIEGL VQ-1560 DW dual wavelength sensor (Loosdorf, Austria) cannot be correctly classified based on either the 3D geometry (XYZ) alone or with the inclusion of single-band radiometry (XYZ+G, XYZ+NIR). In contrast, the use of the spectral information of both green and NIR laser channels together with the geometry (XYZ+G+NIR) provides an almost perfect separation of cables, pole, ground, paved road, low and medium vegetation. This result was achieved automatically with deep learning (KPConv). **Figure 7** depicts an urban scene with vegetation patches captured with the HeliALS system in Espoonlahti, Finland. The 3D multispectral point cloud is shown as a false color composite (left) and colored by class labels (right). Again, KPConv-based semantic segmentation provides a very good separation of the dense points into the detailed categories façade, roof, asphalt, tree, grass, gravel, and car.

Conclusions

While monochromatic airborne lidar is a proven technology for the acquisition of nationwide terrain elevation data, the combination of laser scanners and digital cameras has opened new applications. Colored point clouds are much easier to interpret for both humans (visualization) and machines (classification). In addition, the combination of lidar and dense image matching creates denser point clouds than are achievable with a single sensor alone. In particular, integrated sensors equipped with nadir and oblique cameras can provide point clouds of façades and narrow street canyons based on both images and laser scans. The redundancy can be used to fill gaps in each other's data sets. The scan mechanism of airborne lidar

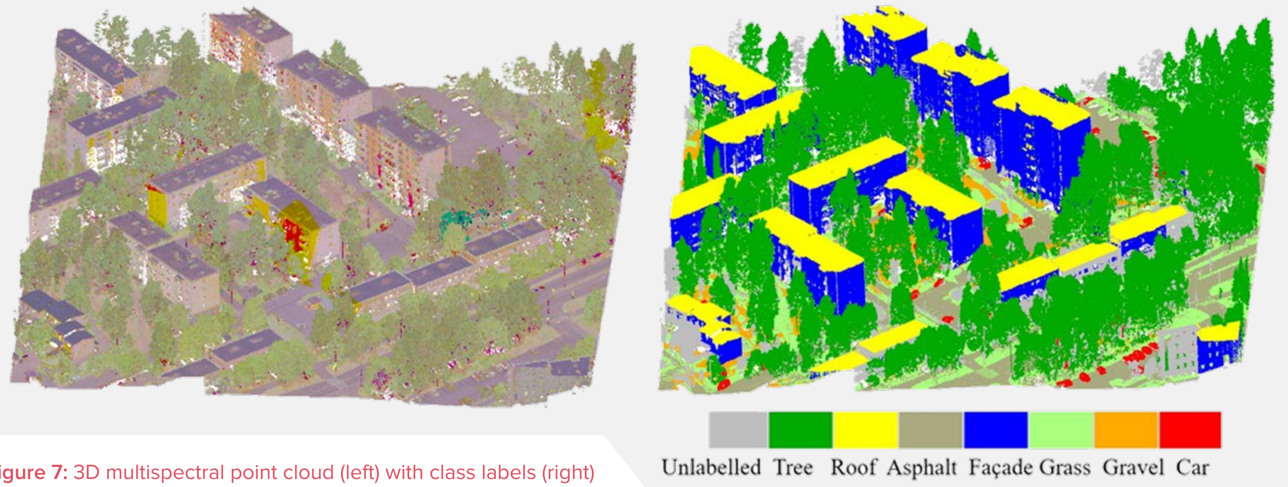

Figure 7: 3D multispectral point cloud (left) with class labels (right) of a scene in Espoonlahti, Finland. Data acquired with the HeliALS sensor system.

sensors, used together with advanced nadir/oblique camera systems, is usually optimized for omnidirectional laser beam deflection. This can be accomplished with either conical (Palmer) scanning or polygonal mirror wheels with differently inclined mirror surfaces providing parallel scan lines with sideward, forward and backward views. Another possible improvement to standard monochromatic lidar is the inclusion of multiple laser wavelengths in a single sensor system. Such multispectral systems offer great potential for point cloud classification and enable much finer class granularity with potential applications in urban mapping, land cover mapping, tree species classification, biomass estimation, and many more. Dual-wavelength multispectral lidar sensors using green and NIR laser radiation are the basis for airborne laser bathymetry, the topic of Part III of this tutorial, which will appear in the next issue of *LIDAR Magazine.*

Dr. Gottfried Mandlburger studied geodesy at TU Wien, where he also received his PhD in 2006 and habilitated in photogrammetry with a thesis on “Bathymetry from active and passive photogrammetry” in 2021. In April 2024 he was appointed University Professor for Optical Bathymetry at TU Wien.

His main research areas are airborne topographic and bathymetric lidar from crewed and uncrewed platforms, multimedia photogrammetry, bathymetry from multispectral images, and scientific software development. Gottfried Mandlburger is chair of the lidar working group of Deutsche Gesellschaft für Photogrammetrie und Fernerkundung, Geoinformation e.V. (DGPF) and Austria’s scientific delegate in EuroSDR. He received best paper awards from ISPRS and ASPRS for publications on bathymetry from active and passive photogrammetry.

Further reading

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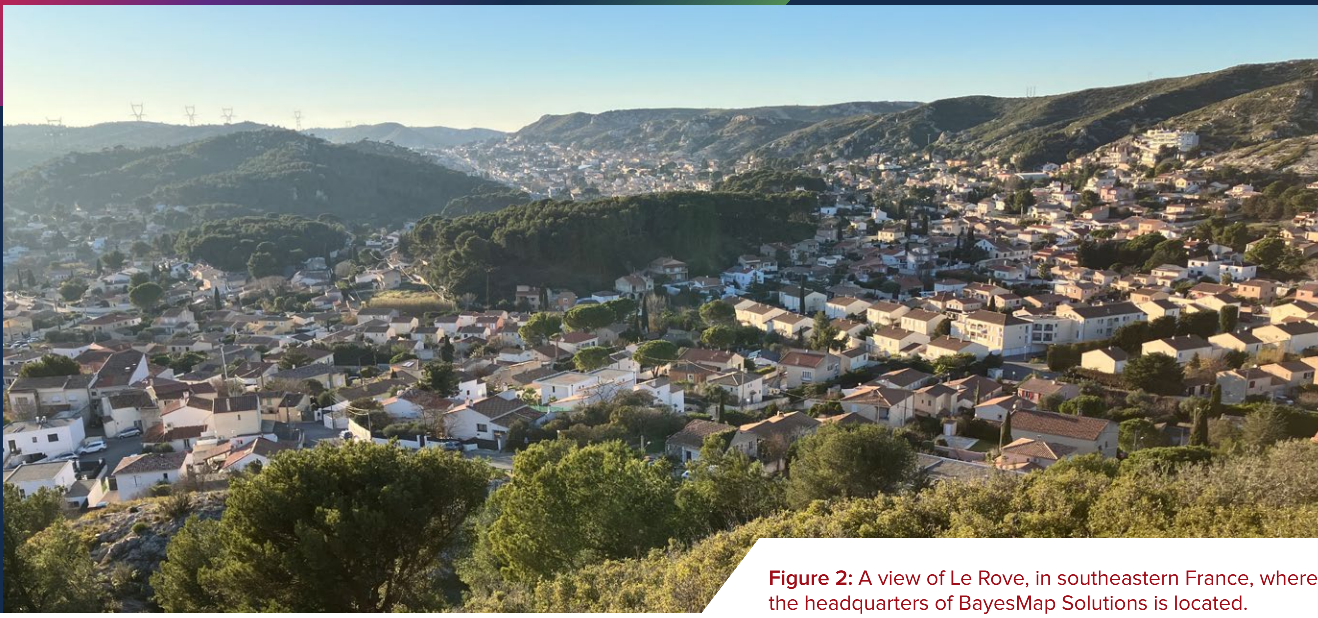

Figure 2: A view of Le Rove, in southeastern France, where the headquarters of BayesMap Solutions is located.

The Magic of Bayes

Niche lidar software supplier celebrates 10th birthday

Figure 1: The author in BayesMap Solutions' first office, between the basement and the backyard of his home in Castro Valley, California.

Figure 3: BayesMap Solutions co-exhibiting with LidarSwiss Solutions at InterGeo 2023.

BY ANDRÉ JALOBEANU

What makes BayesMap Solutions special?

The geospatial community is most rewarded when academic know-how meets engineering realities to provide actionable data that can serve concrete business or societal needs. Yes, we've all heard that before, because that's what we are all looking for. The goal is expressed in the first sentence above through many commendable buzzwords. Let's go over what led to them becoming realities at BayesMap Solutions[1].

The founder is a self-driven/self-taught computer programmer, trained in physics (including that of sensors) and remote sensing, passionate about

1 bayesmap.com

predictive uncertainties. And just as important, he is persistent and not deterred by challenges (so he can tackle unsolved problems on his own even if it takes years to get there). He is rigorous like the academic he was for many years, but at the same time focused on usability (of software, but also of models and theories) and committed to provide the best solution. He built an astronomical image-processing software application while in high-school and later a full star-tracking hardware system complete with automatic control software.

He strongly believes data should be actionable, beyond immediate remote-sensing quality control; his wife is an earth scientist, hence the "so what" is not abstract in their household. And he can communicate. That also started years ago in a non-profit astronomy outreach program, where he improved water-rocket launchers and various material used to teach astronomy and space sciences[2].

BayesMap Solutions is a business partner committed to having a positive impact in the world through: its own practices; helping academic research; encouraging clients to make corporate social responsibility (CSR) and sustainability statements for their company; and rewarding clients who have strong CSR and/or whose missions are related to sustainability, nature monitoring, nature preservation, etc.

Bayes and his theorem

300 years ago, Reverend Thomas Bayes (1702-61) was the first to provide a way of reasoning with uncertainty, deriving what is known as Bayes' theorem (even if its canonical form and first practical applications are due to Laplace, we still refer to this kind of reasoning as Bayesian inference). It allows us to express the probability of a hypothesis given all the available data, also known as posterior probability, by combining the likelihood or the hypothesis (given by experimental measurements) with our prior knowledge.

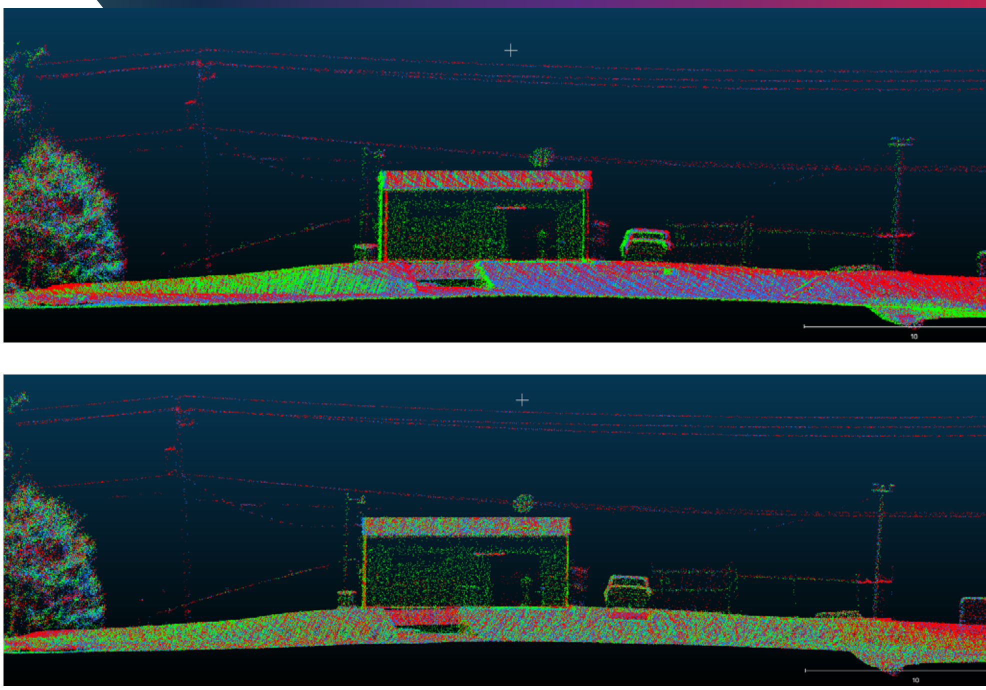

Figure 4: UAV point cloud cross-section showing the misalignment between flight lines (colored by flight line): top—before alignment, bottom—after alignment.

Some history

BayesMap Solutions was founded in September 2014 in Castro Valley, California, a few miles southeast of Oakland (**Figure 1**). The family later moved further east to Pleasanton, and then to Mountain View, close to NASA Ames, in the heart of Silicon Valley. After 10 years in the US, the family moved back to France in 2022. BayesMap Solutions was registered as a French SAS in January 2023 and the home offices are located in the village of Le Rove, near Marseille (**Figure 2**).

The goal has always been to provide unique consulting and software development services for the lidar industry, helping clients extract the maximum information from large, complex data sets. Initially, the focus was on consulting based on the academic experience of the founder. This could be research or development, but also custom data processing. The founder was hoping to be able to use some of his research code developed during past projects (waveform processing, filtering, and change detection) and run the software as a service to process data and deliver it to clients. This way, the developer runs the tools, which simplifies everything: no need for any user interface, manuals, training sessions or customer support!

2 astrorama.net

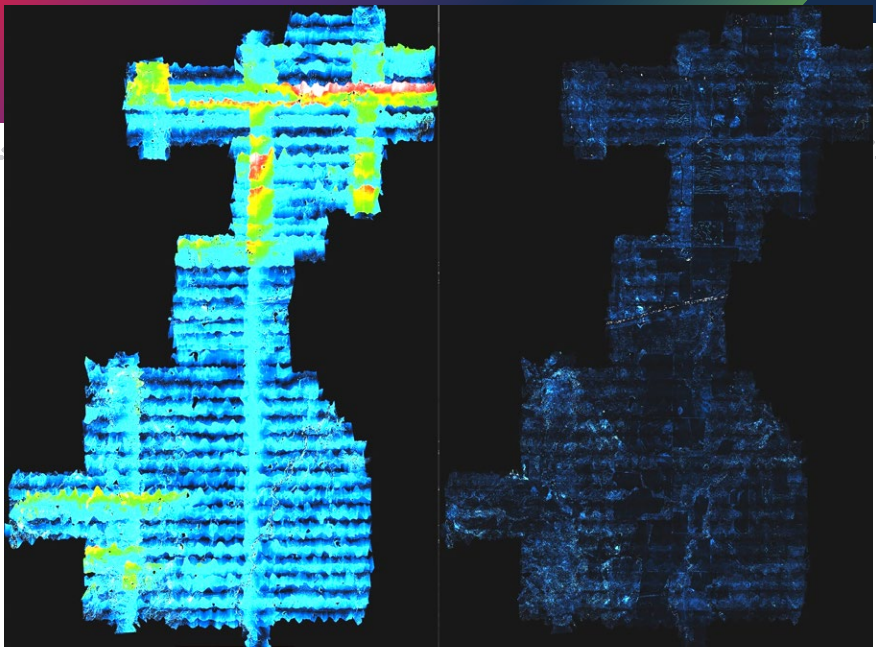

Figure 5: Relative error map (maximum absolute vertical difference between overlapping strips): left - before alignment, right - after alignment. The lack of color in the right-hand image shows that alignment of the strips has all but eliminated the vertical differences.

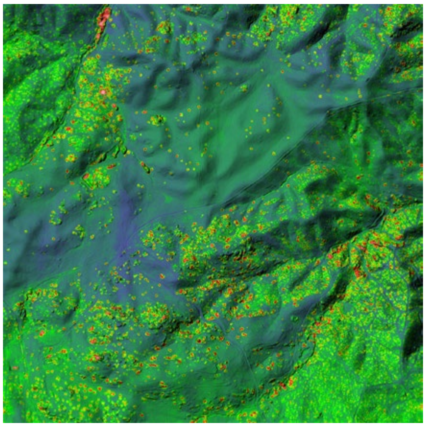

Figure 6: Predictive uncertainty map (spatial distribution of errors) using range uncertainties derived from full-waveform lidar data analysis.

He quickly understood, however, that this type of business model was not going to work. The main reason was the licensing restrictions in California and many other US states – it is necessary to be a licensed land surveyor in order to sell XYZ positions, unless they are in the form of qualitative, low-resolution mapping products. Data transfer issues could be dealt with and software moved to the cloud, but obtaining a license was a different story.

Thus, BayesMap Solutions became a software company. Data collection companies would be the clients, and the production teams would run the software. The problem was to write production-quality code, which is not what most scientists usually do, but it had to be done. A command-line interface was the quickest to develop, and the founder was inspired by Martin Isenburg and the success of LAStools, which was popular in the industry and used as a command-line tool that people were willing to learn.

The WavEx software seemed a good place to start, since some waveform extraction code already existed (Jalobeanu and Gonçalves, 2014a), but soon enough more reverse engineering had to be done to be able to process data from more sensors (Jalobeanu and Gonçalves, 2012). Interestingly, the first academic client was a French university, and the first commercial one was a French company.

Particularly close to the founder's heart is the community that meets every year in Denver at Geo Week. ILFM 2015[3] was a great opportunity for BayesMap Solutions, indeed its first time to exhibit as a company, with a square booth decorated with colorful elevation models, posters of uncertainty maps, proposed software ideas and swag (the iconic DEM lamp proved to be very popular, and the free goodies, beer koozies, calendars and bottle openers were a success) (**Figure 3**). Among all the proposed ideas, lidar strip alignment attracted the most attention. Numerous prospective clients requested an alternative commercial solution to the one well-known software product then on the market, or the software supplied by the sensor manufacturers, and they were willing to buy it if it worked better and faster. That's how StripAlign started (**Figure 4**).

The demand from the industry was motivating, and the next few months were very busy with development, resurrecting some experimental registration algorithms, improving them, and ensuring that they worked on test data. Next, more work was required to put that into production, going from point-cloud registration to actual geometric correction. The effort fell not far short of developing an entire software package from scratch and testing it in a consulting project so the clients wouldn't have to suffer the first bugs. Everything from storage went into the mix—probabilistic modeling, Bayesian inference, robust estimation, fast deterministic inversion and a lot of lidar geometry. Where other developers would have used triangular meshes and points, the founder used his experience in image processing, leading to new and powerful algorithms that were fast.

Thus, the prospects became clients, and they came from all continents—companies large and small, research

3 The International LiDAR Mapping Forum has been subsumed into Geo Week.

institutions and government agencies[4]. They were happy with the improvement of both relative and absolute accuracy of their data. Of course, adjustments were made along the way, but the developer acted quickly, making necessary fixes as well as incorporating various new features suggested by clients. While the first versions of StripAlign were based on simplifying assumptions about flight-line geometry (so a product could be developed fast enough), version 2.0 was critical for the company's success, not only allowing the alignment of cross-strips and complex scans, but also opening the way to alignment of UAV-lidar data, which is collected in a far wilder way than traditional large-scale airborne data[5] (**Figure 5**). A few clients are also using StripAlign to correct sonar (multibeam echo sounder) data – the software simply needs point clouds with a trajectory, as long as elevation increases upwards. WavEx was given a few updates that made it more successful with point clouds, as the waveform market is relatively limited (but still very active in research institutions such as NEON[6], which uses both software products in its workflow).

Switching to a subscription service was a wise decision, and helped differentiate the company from its competitors. BayesMap Solutions offers support directly from the developer, a few hours of training, consulting and testing, and the right to request new features. The company also partnered with various resellers across the globe to develop sales and offer lower prices, especially to small UAV-lidar companies. Some of these, for example GeoCue[7] and Mad Nadir Mapping[8], have integrated StripAlign directly into their software so the user doesn't need to type a command line. The software is also available as a service on the Pointerra 3D[9] and ROCK Robotic's Rock Cloud[10] platforms, which is perfect for occasional users, and easy to use, without learning the commands.

Ten years after its founding, BayesMap has three employees, two support specialists and one computer science student, and the company is likely to expand further. The last two products on the roadmap, accurate gridding and change detection, will be developed within two years, and a graphical user interface should be available in 2025. The two new products will complete the Bayesian toolset, as they rely on uncertainty propagation to generate probabilistic elevation models and help detect statistically significant changes. Starting with WavEx and its ability to provide range error estimates with each point, then StripAlign to correct the geometry, clients will be able to use a fully probabilistic pipeline to derive quantitative results for rigorous scientific applications (**Figure 6**).

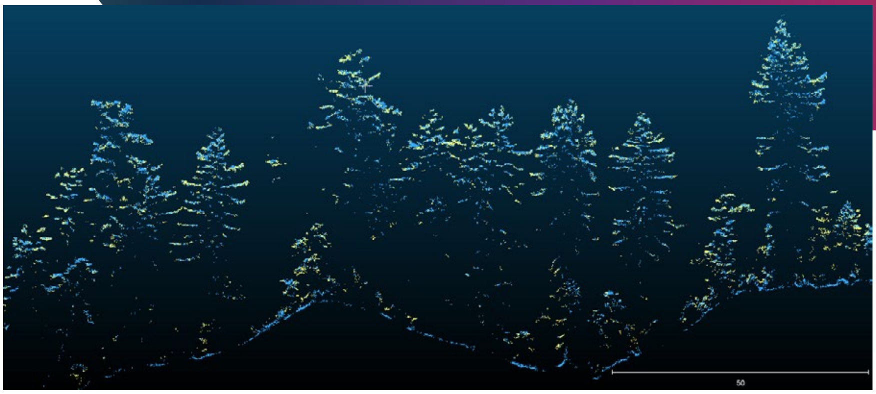

Figure 7: A cross-section of the final point cloud. The data, collected by GEO1/NV5 for the Earth Archive, was processed by BayesMap Solutions using WavEx and StripAlign.

The Bayes in BayesMap Solutions

Bayesian inference may look like magic, but it all comes down to computing the probability density of the unknown variables (which can be 3D points, orientation parameters or gridded elevations), given all the observations and available knowledge (or lack thereof). Models can be quite complex and have many extra parameters, but those are simply eliminated, or mathematically integrated out, to focus on what is really at stake.

To be more precise, a model describing data formation (e.g. sensor geometry and noise) is combined with all available knowledge about the quantity of interest (e.g. digital elevation model smoothness). The goal is to compute the posterior probability density function, using Bayes's rule. This optimally combines data sources and expert knowledge in a consistent way. A probability density encodes both the

4 gim-international.com/content/article/extracting-more-value-from-lidar-data
5 gim-international.com/content/article/pushing-lidar-to-the-limits
6 National Ecological Observatory Network: data.neonscience.org/.
7 geocue.com
8 madnadirmapping.com
9 pointerra.com
10 freelidarprocessing.com

optimal solution and the uncertainty, and Bayesian networks are used to propagate information and uncertainty further down the processing pipeline, all the way to the result, which is a quantity of scientific interest (e.g. snow depth). A spatial distribution of uncertainty on topographic models enables the user to obtain consistent results when deriving physical quantities, for flood analysis or change detection.

Bayesian inference requires an inverse approach, as opposed to direct problem solving in common engineering tasks. The optimal solution it provides actually works, as was shown by LidarSwiss Solutions, a business partner which developed the LSAP system[11] (**Figure 3**). Using StripAlign onboard a UAV made it possible to reach an absolute accuracy upon landing very comparable to what would have been achieved via trajectory post-processing.

In the geospatial field, Bayesian processing has been successful for the past 10 years, and now clients worldwide are using WavEx and StripAlign every day. By way of examples, let us mention the Muir Woods project (GEO1/NV5[12] and the Earth Archive[13]), where both software products were used (**Figure 7**); bathymetric data alignment by Airborne Research Australia[14]; UAV alignment by the Khmer Geographic Institute[15] for Angkor Wat; alignment for the Klinaklini glacier topography change mapping by UNBC and Hakai Institute[16]; and NEON[17] using both software regularly to process large-scale data and publish both aligned points and waveforms for environmental research.

11 lidarswiss.com/technology/lsap
12 nv5.com/geospatial/solutions/geo1-1/; GEO1 was acquired by NV5 in 2022.
13 theeartharchive.com
14 gim-international.com/content/article/pushing-lidar-to-the-limits
15 kgi.xyz

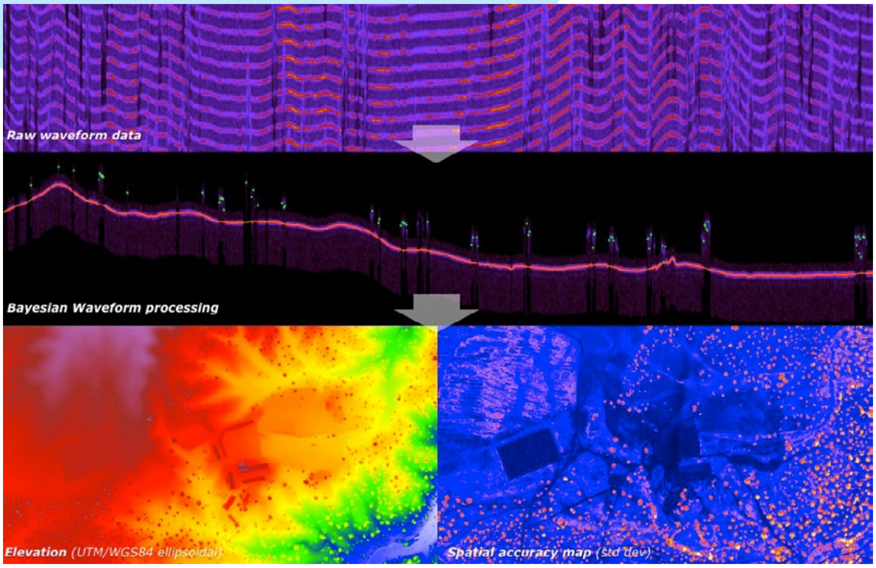

Figure 8: Starting from raw waveform data, Bayesian inference provides robust range information with error estimation, which can be used to derive probabilistic DEMs (elevation and predictive uncertainty for each height of the model).

Testimonial

Sometimes a heartwarming email arrives from a customer acknowledging that the products are working well. Matt Bethel, Director of Operations and Technology with Merrick & Company, Denver, Colorado, wrote: "I wanted to let you know that I got things running properly with your most recent advice/instructions and my test results look amazing. I am blown away by how well v2.0 is working. Thank you very much for the hard work you put in over the last year to get this to where it is now... especially handling the Optech Galaxy sensor. You have accomplished something that no-one else in the industry has been able to do. You should be very proud of your work!"

16 universityaffairs.ca/news/unbc-supercomputer-reveals-acceleration-of-global-glacier-loss
17 neonscience.org/data-collection/lidar

The founder of BayesMap Solutions

André Jalobeanu has been doing research in data processing and analysis (images, signals, time series, point clouds) for more than 20 years. The methods he develops use Bayesian inference, with an emphasis on automation and uncertainty estimation.

He received his Ph.D. in engineering and image processing from the University of Nice-Sophia Antipolis in France in 2001. This included developing new image deblurring algorithms in remote sensing using probabilistic inference.

After three years as a postdoc at NASA Ames in California, where he worked on rendering and 3D reconstruction from imagery, he returned to France and obtained a permanent research scientist position with CNRS near Strasbourg in 2004. He continued to do research on stereo vision and uncertainty propagation but this time from a data fusion perspective.

He moved to Portugal with his family after a few years and pursued more Bayesian stereo research until he concluded that lidar was more appropriate when it comes to computing elevation models with uncertainties in a rigorous way (Jalobeanu and Gonçalves, 2014b). He received a grant for a research project on probabilistic terrain models, which helped pay for full-waveform lidar acquisition in a nearby area and also a few students who helped with surveying. Little did he know that the data he purchased, collected with a RIEGL LMS-Q680 airborne scanner and flown by the French company IMAO, was delivered in a binary proprietary format that could not be read. But after a few months of reverse engineering (and with the help of a collaborator from Coimbra, Portugal) he was able to figure out the format and read the data, and they published the specifications (Jalobeanu and Gonçalves, 2012). Whether RIEGL was happy about that or not, he would not know until years later (**Figure 8**).

He moved again, this time all the way to California, in the Bay Area but across the bay from NASA Ames. Networking during shows like ILMF helped find a senior postdoc position at the Naval Postgraduate School in Monterey, in the Remote Sensing Group, which was interested in his waveform and filtering research. He joined a DHS-funded Earthquake Response project where he contributed to change detection using point clouds (Jalobeanu, Kim, Runyon and Olsen, 2014). The team built mock-ups and scanned them with terrestrial sensors after they were punched and deformed to simulate damage. But he found that the main challenge was first to align the data, which at that time required a lot of manual, tedious work. That's when he started thinking about new ways of registering point clouds. What started as a simple experiment on some troublesome archived data would become the inspiration for the best-selling software StripAlign, years later.

Figure 9: The founder of BayesMap walking in the hills near Le Rove, to find inspiration.

Federal funding eventually ran out, and he started looking for a new place in the Bay Area where he could pursue his research in lidar. Local companies were mostly interested in self-driving cars and city mapping for navigation, not so much in scientific data processing and error propagation. So he decided to start his own company.

Inspiration for new algorithms comes while hiking in the hills, running on the beach or sipping coffee poolside (**Figure 9**).

The BayesMap Solutions logo's fuzzy lines represent the uncertainty in a probabilistic elevation model.

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Jalobeanu, A., A. Kim, S.C. Runyon and R.C. Olsen, 2014. Uncertainty assessment and probabilistic change detection using terrestrial and airborne LiDAR, *Proceedings of SPIE—The International Society for Optical Engineering*, 9080: 19 pp, June 2014[21]. DOI:10.1117/12.2049611.

18 For full text, visitresearchgate.net/publication/267556394_The_full-waveform_LiDAR_Riegl_LMS-Q680I_From_reverse_engineering_to_sensor_modeling.

19 For full text, visit researchgate.net/publication/259621590_Robust_Ground_Peak_Extraction_With_Range_Error_Estimation_Using_Full-Waveform_LiDAR.

20 For full text, visit researchgate.net/publication/268447030_The_Unknown_Spatial_Quality_of_Dense_Point_Clouds_Derived_From_Stereo_Images.

21 For full text, visit researchgate.net/publication/261723452_Uncertainty_assessment_and_probabilistic_change_detection_using_terrestrial_and_airborne_LiDAR.

From Water to Air: Terra Brasil Integrates Lidar and Bathymetry Technology

Comparing airborne lidar with bathymetric data: how Terra Brasil uses LP360 for merging, QA/QC, and deliverables

Figure 1: Oblique view of Pedra Reservoir.

Since its establishment in 2009, Terra Brasil has set a high standard of excellence in the fields of topography, bathymetry, and hydrometry in Brazil. Starting with conventional techniques such as total station surveys and traditional bathymetry, the company has evolved, embracing technological advances to enhance its service offerings. In 2020, Terra Brasil expanded its portfolio to include aerial photogrammetric applications and hydrometry using Acoustic Doppler Current Profilers (ADCPs). The year 2023 marked another significant milestone as the company integrated lidar technologies and advanced modeling software into its operations.

Leading the way is CEO and civil engineer Thadeu Ribas Lugarini, who has been instrumental in steering Terra Brasil towards innovation and technological integration. “We were making technical advancements in the company, and the aerial survey market in topography grew significantly with the advent of aerial photogrammetry,” says Thadeu. “So, we decided to incorporate TrueView aerial lidar, from GeoCue, as we already had extensive expertise in GNSS systems, drone-based surveys, and cartography.”

BY BRET BURGHDURF

Adopting GeoCue’s TrueView lidar and LP360 software

Terra Brasil’s quest for a reliable and efficient lidar solution led it to GeoCue. “We were looking for a lidar solution,” recalls Thadeu. “We liked GeoCue for its customer service and the lidar’s capability to produce realistic and accurate points. Additionally, LP360 provided us with a lot of confidence as it’s software that both generates and processes the point cloud. This allowed us to use a single software for generating and managing the lidar point cloud.”

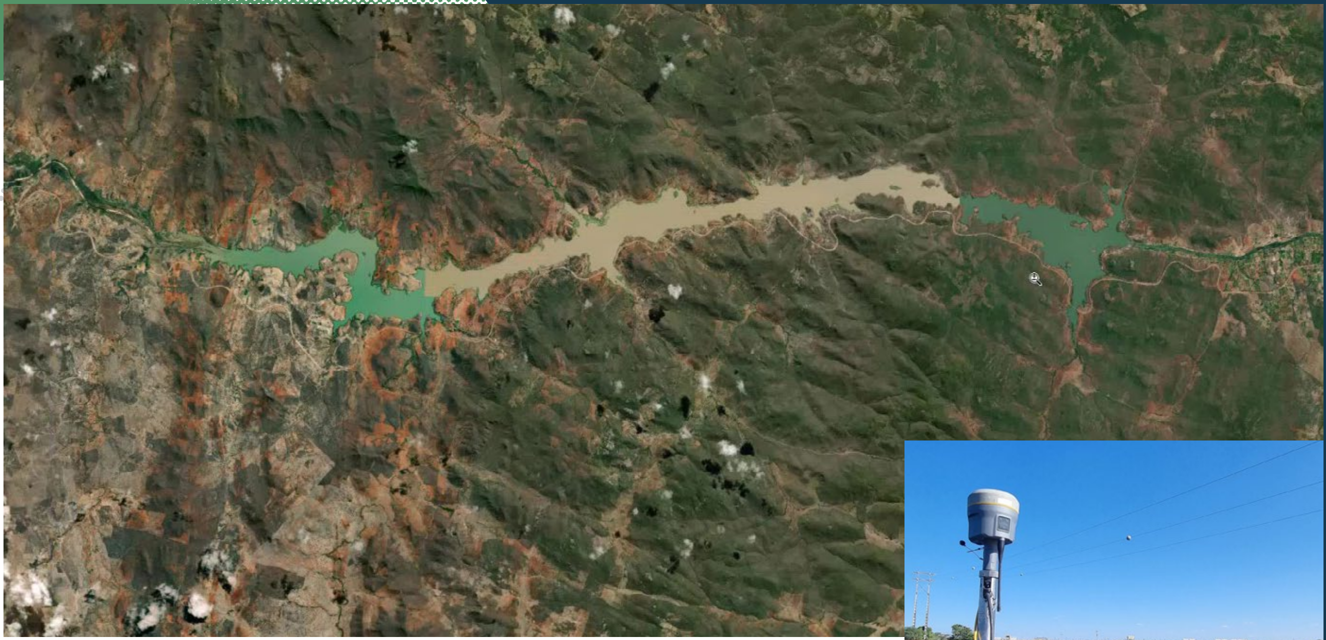


Figure 2: The Pedra Reservoir.

Figure 3: Trimble R12 equipment in use during bathymetric survey.

The integration of TrueView lidar systems with LP360 software updated Terra Brasil's workflow. "The LP360 system enabled the generation of the lidar point cloud and the digital terrain model in a single package," explains Thadeu. "But the most satisfying aspect was working with a model that updates automatically after point classification. Easy export, import, and point cloud merging—all these factors contribute to making LP360 a comprehensive software solution."

One of the key features of LP360 that stood out for Terra Brasil was its ability to integrate lidar point clouds with bathymetric data seamlessly. "This involves integrating the lidar point cloud with a point cloud imported from a TXT table containing elevation and planimetric data from bathymetry," says Thadeu. "Once merged, all that remains is to work with the digital terrain model."

To highlight the impact of LP360 on Terra Brasil's operations, Thadeu shared three of its significant hydroelectric projects. These demonstrate how the company integrates airborne lidar data with bathymetric measurements from lakes and dams using LP360. By leveraging the software's advanced capabilities, Terra Brasil ensures rigorous QA/QC processes, producing highly accurate models and volume analyses essential for critical infrastructure management. These ventures not only underscore Terra Brasil's technical expertise but also showcase the remarkable results achievable through cutting-edge geospatial technology.

Project 1: Pedra Reservoir

The Pedra Reservoir project (**Figures 1 and 2**) was a significant undertaking that showcased the capabilities of LP360, even independently of GeoCue equipment. "In the case of Pedra, we did not conduct drone lidar topography," notes Thadeu. "So, I used LP360 entirely independently of GeoCue equipment, demonstrating that the software can be used for cartographic data generation."

The process involved integrating bathymetric data with topographic data provided by Eletrobras CHESF. "First, I received contour lines of the dry area from Eletrobras as the data was provided," explains Thadeu. "I converted the contours into points spaced every one meter using GIS software. Then, I imported the tabulated points as LAS using LP360's import system. I applied the same method for the bathymetric points."

Conducting bathymetry over a 42 km^2 area presented several difficulties (**Figure 3**). "The challenge was executing lines every 30 meters while maintaining the linearity of the projected line diagonally and following the same standards despite strong waves and winds in the region," recalls Thadeu. "All these factors complicated navigation and brought significant challenges to our team. But with a lot of effort, we managed to complete the bathymetry after five months in the field to accomplish the entire service."

The ability to generate a 3D model and extract volume and area data was invaluable for Eletrobras's reservoir operations. "The information regarding volume and area data from the 3D model allows for

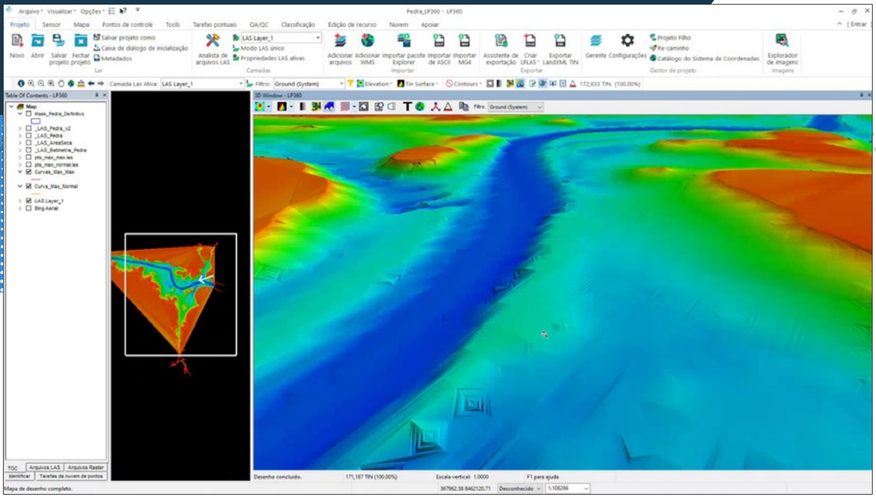


Figure 4: Analyzing the bathymetric data in LP360.

the analysis of volume and area at each elevation of the reservoir," says Thadeu. "This information is crucial for maintaining the hydrological management of the sluice gates and for energy generation at the hydroelectric plant."

The final deliverable was comprehensive (**Figure 4**). "The final deliverable is the digital terrain model in raster format for the entire reservoir of the hydroelectric plant, with elevation information every five meters, which corresponds to the raster pixel, along with the area-volume curve table, which indicates the volume and area for each elevation of the reservoir at every 10 centimeters," explains Thadeu. "This includes information on the reservoir's volume at the maximum elevation (the highest level the reservoir can reach), the normal maximum elevation (the maximum level at which the reservoir is maintained without spilling water), and the normal minimum elevation (the dead volume level)."

Project 2: Hydroelectric plants in Paraná

In another significant project, Terra Brasil utilized the TrueView 540 lidar system and LP360 software for hydroelectric plants in Paraná (**Figure 5**). "In Paraná, we used the TrueView 540 to map the edges of the reservoirs at the Fundão and Santa Clara power plants, which are part of the Elejor hydroelectric plants on the Jordão River," says Thadeu.

Similar to the Pedra project, bathymetry was conducted using a single-beam echosounder. "We conducted bathymetry with points spaced every two meters along the survey line and 40-meter spacing between lines," explains Thadeu. "We used lidar to map the dry area of the reservoir, and then the 3D model was generated by integrating LAS files from both the bathymetry and the topographic area of the dry land."

The data provided to the National Water Agency (ANA) was critical for regulatory compliance and operational efficiency. "The National Water Agency regulates the operation of hydroelectric plants in Brazil through norms and guidelines designed to ensure the correct functioning and operational quality of these plants," explains Thadeu. "One of the controls required by the National Water Agency is the updating of the area-volume curve for these plants so that they can present their data on volume, area, and elevation for operations at maximum maximum elevation, normal maximum elevation, and normal minimum elevation, which are also related to useful volume."

LP360 facilitated this process seamlessly (**Figure 6**). "All this data is extracted from the 3D model of the reservoir generated in LP360," says Thadeu. "Before using this software, I had to work with multiple GIS software to arrive at the digital terrain model. Now, it is possible to work with the generation of the lidar point cloud, integration of bathymetric and topographic data, generate the terrain model, and adjust that model all within the same software, LP360."

The final deliverables were comprehensive and met all regulatory requirements. "The data is shared through the delivery of the digital terrain model, the cartographic products that generated the model, as well as geodetic benchmarks, quality control through control and check points, a local geoidal model that adjusted ellipsoidal altitude

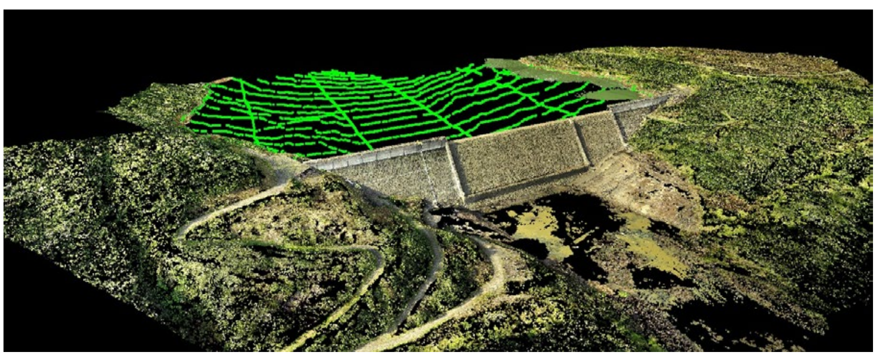


Figure 5: Terra Brasil integrated lidar data from the TV540 with bathymetric data for two hydroelectric plants in the state of Paraná.

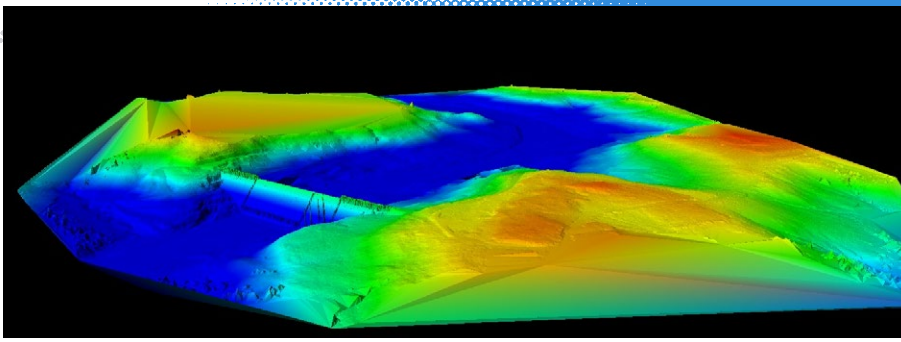


Figure 6: 3D model of the area created with LP360.

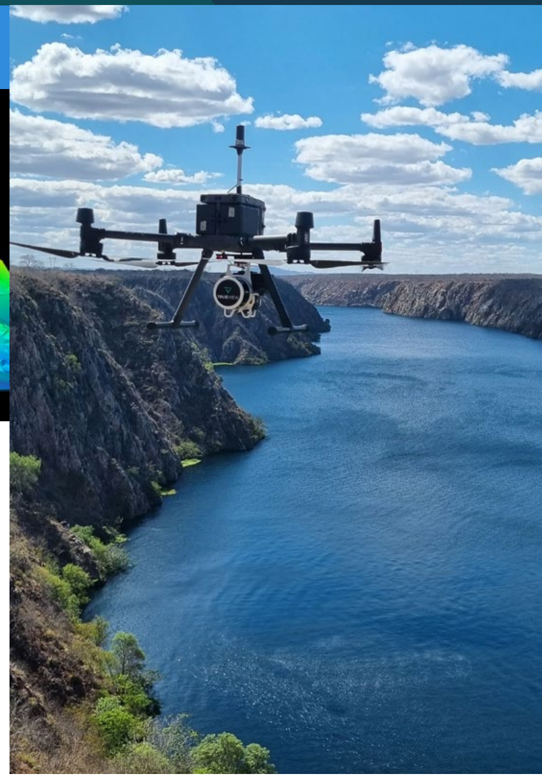


Figure 7: GeoCue TrueView 515 system on DJI Matric 300 UAV flying over reservoir in Rio Grande do Sul.

to orthometric altitude, bathymetric points, and finally, the spreadsheet with the data for the elevation x area x volume curve, which details the area and volume for each elevation of the reservoir," describes Thadeu.

Project 3: Companhia Siderúrgica Nacional (CSN)

The projects with Companhia Siderúrgica Nacional (CSN) in Rio Grande do Sul were particularly significant, especially considering the recent catastrophic flooding in the region. "The projects with CSN in Rio Grande do Sul started before the flooding," notes Thadeu. "We updated seven reservoirs for CSN in the state, all of which were completed before the floods occurred."

After the flooding, Terra Brasil returned to one of the plants for additional mapping. "After the event, we returned to the Canastra plant as it had dried up due to repairs that will be carried out because of the damage caused by the flooding," says Thadeu. "We conducted mapping of the dry plant using TrueView 540, whereas we had previously mapped the dry area with the TrueView 515."

Using both the TV515 and TV540 systems allowed for comprehensive mapping before and after the reservoir dried out (**Figures 7, 8 and 9**). "In both cases, we used lidar mounted on the DJI Matrice 300, supported by GNSS from Trimble," explains Thadeu. "The flights were conducted at an average altitude of 70 meters, with an average speed of five meters per second."

The key findings from the topographic comparison are pending, but they are expected to provide valuable insights. "We have not yet conducted the comparison, but the volume of both models will indeed be compared, and the accuracy of the bathymetry can be evaluated, as compared to the drone lidar," says Thadeu.

The final results included updated reports and comprehensive data sets. "We created reports updating the area-volume curves for the seven reservoirs, containing cartographic information on the topography of the dry area, bathymetry, geodetic benchmarks, control sections for sediment monitoring, and digital terrain models for each hydroelectric project," says Thadeu.

Technical insights and challenges

Integrating bathymetric data with lidar topography presents several technical challenges. "The biggest challenges were integrating data with varying point densities," explains Thadeu. "Lidar provides thousands of points per square meter, while bathymetry with a single-beam echosounder offers points spaced every two meters, with bathymetric lines spaced up to 200 meters apart, resulting in a rich TIN model in the dry topography area and a triangulated model in the wet area."

LP360 plays a crucial role in performing quality assurance/quality control (QA/QC) on the acquired data. "Control points are very useful for analyzing the accuracy of the survey," says Thadeu. "We executed as many control points as possible, while also surveying cross-sections along the edges of the reservoir using a total station to assess the accuracy of the lidar."

He adds, "If possible, it is beneficial for the check points to be identifiable on the ground so that any error can be identified. Quality control is generated from the export of the report on the check points, measuring all errors and the average error of the survey."

The accuracies achieved with GeoCue's TrueView have been impressive. "The accuracies achieved so far have been very good, with all point clouds exhibiting errors ranging from one to ten centimeters, depending on the flight parameters," notes Thadeu.

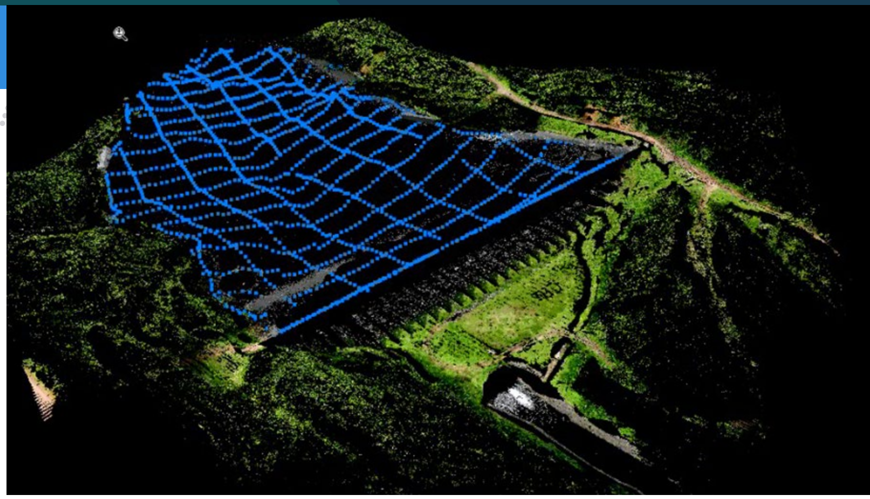


Figure 8: The point cloud of the reservoir with data collected from the TrueView 515, before the collapse.

Describing the process of TIN interpolation of lidar and bathymetry data within LP360, Thadeu says, “The TIN interpolation process is one of the oldest interpolation methods in surface generation programming. In LP360, I have always had good experiences with TIN, and the export function allows for the creation of a lightweight file that is easy to handle in GIS software.”

He emphasizes the efficiency of LP360 in manipulating point clouds. “As mentioned, LP360 greatly benefits from its ability to manipulate the point cloud through classification and simultaneous surface updates, where the final loading is only done during export,” says Thadeu. “This practice significantly saves time when generating a terrain model.”

Advice and recommendations

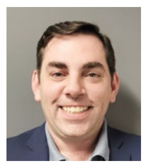
For professionals looking to integrate bathymetric and lidar data, Thadeu offers valuable counsel. “My advice is to look for software that is efficient for data integration, such as LP360, and always use the same planimetric and altimetric reference so that both pieces of information can be integrated without causing breaks in the model,” he says.

He also shares best practices developed while working with LP360 and TrueView systems. “My practice is always to work with the altimetric reference on the ellipsoid, as I mentioned, because it aligns with the reference of the standard GNSS system, since most GNSS devices operate with ellipsoidal data,” explains Thadeu. “Regarding TrueView, I always recommend maximum organization when working with point clouds, as each flight cycle generates a point-cloud package. In extensive projects, maintaining organization is crucial to ensure that no flight or cycle is missing from the project.”

Using the right technology

GeoCue’s TrueView technology has allowed Terra Brasil to undertake larger and more challenging projects. “GeoCue has enabled us to undertake significant projects with lidar, and I would like to thank the team for their partnership and support,” says Thadeu. “We are now considering purchasing the TrueView GO, which would be our third acquisition from GeoCue, and it will undoubtedly allow us to execute many more great projects.”

By using GeoCue’s TrueView lidar systems and LP360 software, Terra Brasil has boosted its abilities, delivering precise and detailed data for important infrastructure projects. The company’s story inspires others to embrace lidar technology to improve efficiency, accuracy, and the impact of their own work.



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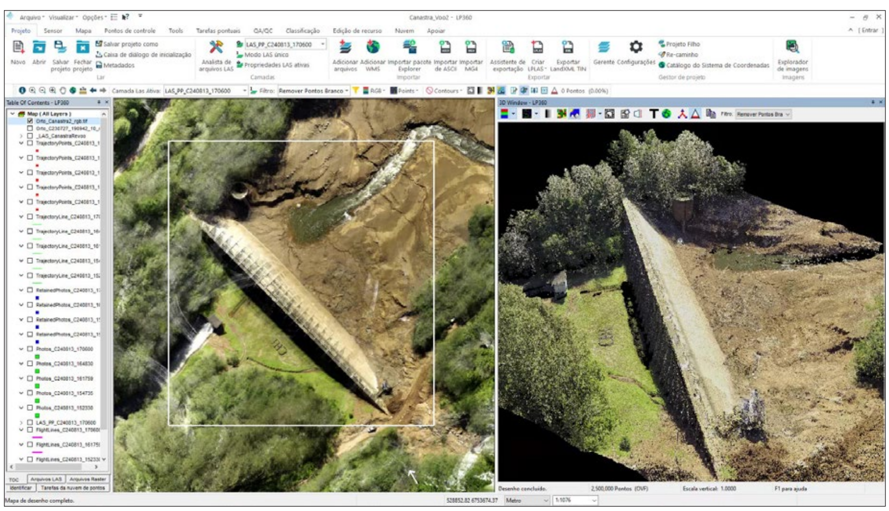


Figure 9: Point cloud taken with the TrueView 540, after the water had drained from the reservoir.

JOHN M. RUSSO

USIBD: A New Chapter for 2025

The Evolution of the Level of Accuracy (LOA) Specification

The Level of Accuracy (LOA) Specification, developed by the U.S. Institute of Building Documentation (USIBD), has become an indispensable tool for building documentation. Since its inception, the LOA has addressed a critical gap: the lack of a recognized standard for specifying accuracy in building documentation. With the upcoming release of Version 3.1 in January 2025 (**Figure 1**), the LOA continues to evolve, incorporating minor but meaningful enhancements to meet the ever-growing demands of the architecture, engineering, construction, operations (AECO), and historic preservation industries.

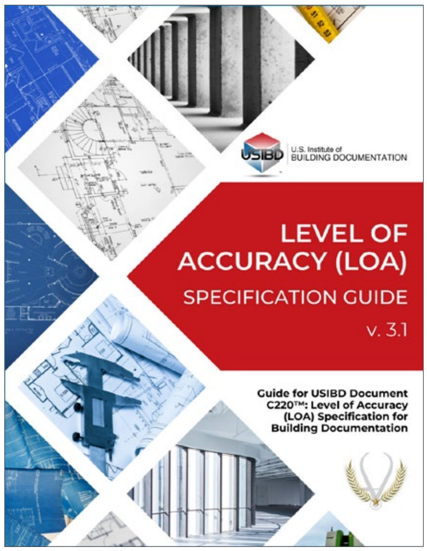


Figure 1: Cover of the LOA v3.1 *Specification Guide*

A brief history of the LOA

The LOA has a storied history, dating back to the release of Version 1.0 in 2014. At the time, there was no universally accepted framework for defining the accuracy of measurements and representations in building documentation. Recognizing this gap, the USIBD formed the LOA Subcommittee under its Standards Committee to address the industry's needs.

Drawing inspiration from recognized standards such as the AIA/BIM Forum's Level of Development (LOD) Specification, CSI's UniFormat™, and the German Institute for Standardization's DIN 18710, the LOA was designed to promote interoperability between existing frameworks, filling a critical void. While the LOD focuses on defining the development level of a Building Information Model (BIM), it does not address the accuracy of the data underlying that model. The LOA bridges this gap, ensuring both measured accuracy and represented accuracy are explicitly defined and met.

The LOA Specification has seen global acceptance, with professionals from diverse industry sectors contributing to its development. It remains the most downloaded document on the USIBD website, reflecting its widespread adoption and utility.

What makes the LOA unique?

The LOA is built around the philosophy that "Intent Defines Process," a guiding principle articulated by USIBD. This emphasizes that accuracy is not just a technical requirement, but a deliberate decision tied to the project's goals. By defining the intent of a project, practitioners can identify the means and methods to achieve the required accuracy.

The LOA framework incorporates five levels of accuracy: LOA10, LOA20, LOA30, LOA40, and LOA50 (**Figure 2**). These levels correspond to increasingly stringent ranges of tolerance, inspired by the five tolerance ranges defined in the DIN 18710 standard. The LOA also introduces the dual concepts of Measured Accuracy (accuracy of the data collected) and Represented Accuracy (accuracy of the models or drawings derived from the data).

This dual approach acknowledges the additional errors introduced during data representation.

Structured using the Metric System (with imperial conversions), the LOA ensures compatibility with global practices while accommodating the needs of the U.S. market. The *Specification Guide* and accompanying *Specification Framework* spreadsheet provide practitioners with practical tools to define and document accuracy requirements for their projects.

What's new in LOA Version 3.1?

The release of LOA Version 3.1 in early 2025 marks a minor upgrade to Version 3.0, which was introduced in 2019. While the changes may be subtle, they

Level of Accuracy (2 σ std dev)					
15cm	5cm	15mm	5mm	1mm	Upper Range (Metric)
5cm	15mm	5mm	1mm	0	Lower Range (Metric)
USIBD LOA's					
LOA10	LOA20	LOA30	LOA40	LOA50	

Level of Accuracy (2 σ std dev)					
6"	2"	5/8"	1/4"	1/16"	Upper Range (Imperial)
2"	5/8"	1/4"	1/16"	0"	Lower Range (Imperial)
USIBD LOA's					
LOA10	LOA20	LOA30	LOA40	LOA50	

Figure 2: Level of Accuracy ranges in metric and imperial units.

are designed to enhance usability and clarity. There are four key enhancements.

1. **Graphical updates**: Improved visual elements throughout the document enhance readability and comprehension, such as those in **Figures 3 and 4**.
2. **Simplified tolerance computation**: Previous versions included detailed narratives on relative measurement tolerances (e.g., squared vs. linear approaches). These have been replaced with a practical method for converting between tolerance and standard deviation. This change aligns the LOA with common field measurement practices and ensures compatibility with fabrication standards, which often require tolerances.
3. **Improved readability**: Copy edits have been made throughout the document to clarify technical language and improve understanding for a broader audience.
4. **Practical guidance for professionals**: The new method for converting between tolerance and standard deviation ensures professionals can confidently meet accuracy requirements, regardless of whether a project specifies tolerances or standard deviations.

These changes reflect USIBD's commitment to making the LOA a living document, one that evolves to meet the needs of practitioners while maintaining its foundational principles.

USIBD's new Education Center

In addition to the updated LOA, the USIBD is proud to unveil its new Education Center, a milestone initiative aimed at fostering professional growth and standardizing best practices in the building documentation industry. The Education Center will offer on-demand training and certification programs, starting with a course and certification focused on the LOA.

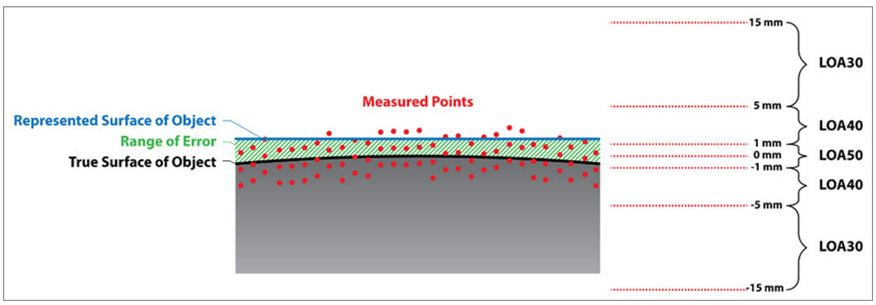


Figure 3: Precision, correctness and accuracy.

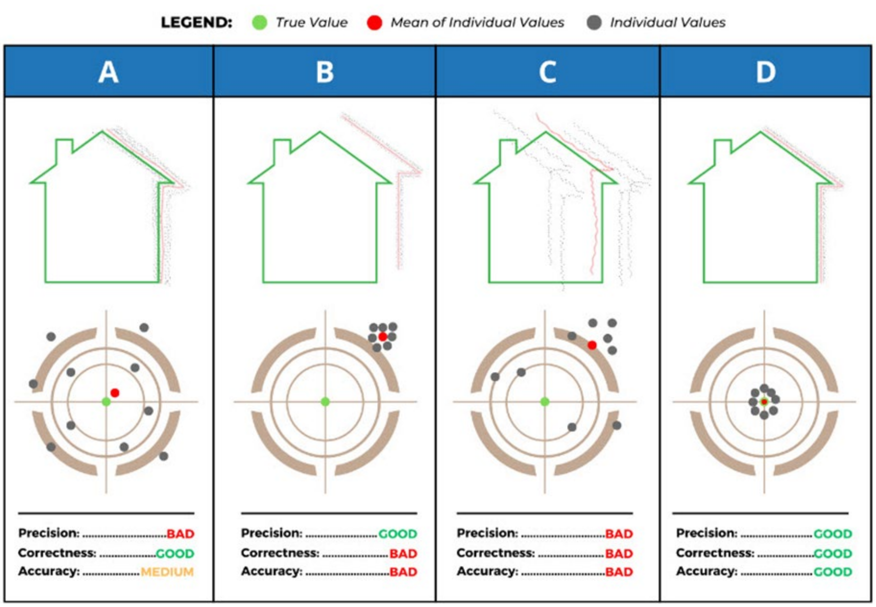


Figure 4: Measured and Represented Accuracy with LOA Levels.

In addition to LOA training and certification, USIBD's Education Center will serve as a dynamic platform for ongoing professional development. The introduction of the LOA training is just the beginning. The Education Center will continually expand its library of coursework, building a comprehensive foundation that will support the eventual rollout of Building Documentation Professional (BDP) and Building Documentation Technologist (BDT) certifications.

These certifications represent USIBD's commitment to establishing a structured pathway for industry practitioners to achieve recognition for their expertise. As new courses are added, they will address key areas of building documentation, from advanced measurement techniques to best practices in data management and integration with BIM workflows. This evolving curriculum is designed to equip professionals with the skills and knowledge necessary to meet the challenges of a rapidly advancing industry.

The BDP and BDT certifications will be pivotal milestones in the professionalization of building documentation, offering practitioners a way to demonstrate their qualifications and stand out in a competitive market. By laying the groundwork now, USIBD is creating a future where excellence in building documentation is both measurable and recognized.

Why the LOA matters

The LOA continues to fill a critical role in the industry. As building documentation technologies evolve, so too must the standards that govern them. The LOA's integration with complementary frameworks such as the LOD Specification and CSI's UniFormat™ ensures its relevance and utility. Moreover, the LOA's commitment to interoperability and practicality makes it a trusted resource for professionals worldwide.

While other guidelines may attempt to define accuracy schemas, the LOA remains the most widely recognized and accepted standard for building documentation. By incorporating input from industry professionals and aligning with global practices, USIBD has created a standard that is not only technically sound but also universally applicable.

Get involved with USIBD

USIBD's success is rooted in the dedication of its members and the collaborative spirit of the building documentation community. As the LOA and the Education Center continue to evolve, USIBD invites professionals to join its committees and contribute to the development of industry standards.

USIBD U.S. Institute of BUILDING DOCUMENTATION

Membership in USIBD offers opportunities to shape the future of building documentation, network with industry leaders, and access valuable resources, including the free download of the LOA.

Conclusion

The upcoming release of LOA Version 3.1 and the launch of the USIBD Education Center represent significant milestones for the building documentation industry. These initiatives underscore USIBD's commitment to advancing standards, fostering professional growth, and supporting the building documentation community.

Whether you are a seasoned professional or new to building documentation, the LOA provides a framework for achieving accuracy and precision in your projects. Download the LOA Specification for free from the USIBD website and explore the new Education Center to take your expertise to the next level. Together, we can continue to shape the future of building documentation.

John M. Russo is the visionary founder of Architectural Resource Consultants (ARC), a pioneering firm specializing in professional building documentation services since 1997. With a career dating back to 1984, Mr. Russo's passion for precise as-built documentation and facility life-cycle solutions has driven ARC to become an award-winning industry leader.

In 2011, he founded the U.S. Institute of Building Documentation (USIBD), a non-profit committed to advancing excellence in building documentation, and served on the Board of Directors and as President for twelve years. Currently, he holds an advisory role as Board Member Emeritus. He is also a member of the BIM Forum Working Group Advisory Board.

Mr. Russo delivers keynote addresses and is a featured speaker at major shows and conferences. He has published widely in many journals and newsletters.

Mr. Russo holds a BA in business administration from California State University, Fullerton, and an AA in Architecture from Orange Coast College. As a registered architect in California, his wealth of experience and unwavering commitment to excellence continue to shape and elevate the building documentation industry under his leadership.

AMAR NAYEGANDHI
FEATURING AL KARLIN

The case for high point density lidar

Does the economic law of diminishing marginal returns apply to lidar point density?

Economics 101 teaches us the law (or principle) of diminishing marginal returns, which states that beyond a certain point of optimal capacity, the addition of another factor of production will result in smaller increases in output. All businesses abide by this classic economic principle, as it relates to decisions made in investing, marketing, and enterprise resource planning. For example, a restaurant owner will hire additional waiters to support the number of customers he expects to visit his restaurant; his profit and customer satisfaction rating will likely increase even though he is paying an additional salary for each subsequent waiter. However, given the limited size of the restaurant seating area and how quickly his chef can prepare the items in the kitchen, he will begin to see a decrease in his profit after a certain level of increased patrons. Until he can increase these other factors (such as seating area size, efficiency in the kitchen, number of chefs), he won't need to hire more waiters. The restaurant owner's 'point of optimal capacity' is defined by the maximum output (profit and customer satisfaction) per unit of input (number of waiters).

Does this principle also apply to the density of a lidar return point cloud? It certainly does, but we will address the point of optimal capacity in a point cloud and the factors that could be changed that will help us maximize output beyond the point of optimal capacity as defined today.

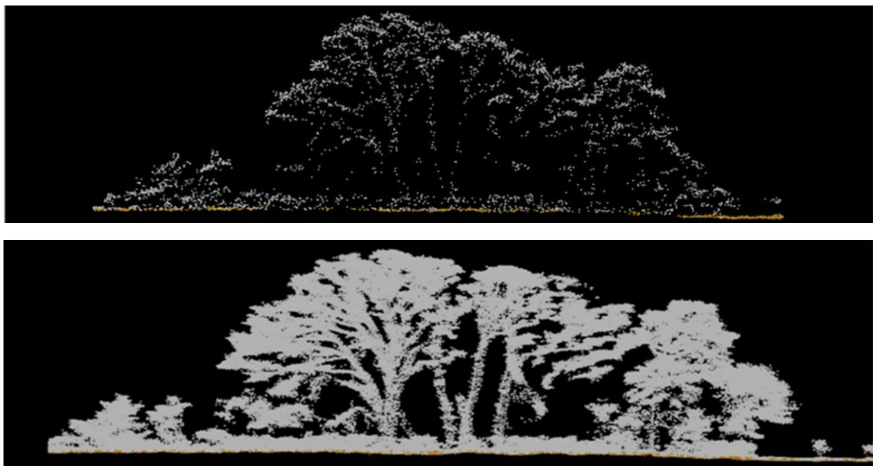


Figure 1: A profile across a canopy tree structure illustrates the level of detail in an 8 ppsm data set (above) and a 200 ppsm data set (below).
Image courtesy of Dewberry.

Is there an optimal lidar point cloud density?

A lidar point cloud is a set of spatially referenced 3D points captured by a lidar sensor. The density of a point cloud is typically defined as the number of "first returns" captured per unit area and represented as points per square meter (ppsm). While we recognize that this definition of "density" may not be ideal, the focus of this discussion, number of points, is independent of how the density is measured (as described in *ASPRS Guidelines for Quantifying Horizontal Density of Aerial Lidar Point Cloud Data, Edition 1, Version 1.0,* November 2024[1]).

Several factors determine the usability of the data produced by a lidar sensor for a given application, including, but not limited to, spatial density, horizontal and vertical accuracy, classification of ground and above-ground features, and consistency in point distribution. The data usability is also based on the ability to characterize the desired amount of detail for the intended feature being mapped, such as the structure of a vegetated canopy, the slope of a terrain, or the modeling of a building rooftop. The key aspect of what is considered 'optimal' depends on the intended

1 tinyurl.com/466zasxr

application. A flat parking lot can be modeled accurately with a point density of 2-4 ppsm, but if we want to model the vehicles in the parking lot, we will need 8-16 ppsm. Alternatively, if the intent is to train an AI algorithm to identify the make and model of those vehicles, we may need a higher density point cloud to accurately represent details of the vehicle's shape. In another scenario, where we need to determine how water will flow in the parking lot in case of a flood event, 2-4 ppsm density will be sufficient. but we will need to achieve an absolute vertical accuracy of better than 10 cm RMSE. Less accurate point cloud data can still be used to train an AI model as long as the density to identify the type of vehicle is sufficient.

A canopy structure can be modeled with a "first return" point density of 2-4 ppsm, which could produce 6-12 returns within the canopy using a multiple return or waveform-resolving linear-mode lidar sensor. However, identifying individual tree stands in a canopy will require a much higher point density, and, depending on the canopy density, we may need upwards of 40 ppsm to accurately measure the tree canopy. For example, in a 525-acre tree assessment study conducted by Dewberry for a local developer within the Tampa Bay area in Florida, a very high point density dataset was acquired using the RIEGL VQ-1560 II sensor flown at 2000 ft AGL with 200% overlap using a cross-hatched flight pattern. The resulting dataset, which produced 200 ppsm for all returns (which is a density of ~50 ppsm for first returns), was used to measure the location of individual tree trunks, identify the tree type, and measure the diameter at breast height (DBH). When compared to a data set of 8 ppsm (**Figure 1**) over the same area, it is evident that for this specific application, the higher-density dataset was needed. This example illustrated that we need sufficient data density to penetrate through gaps in the top layers of the canopy to characterize the tree trunks and understory vegetation. The multiple look angles into the canopy through the cross-hatched flight pattern also enables better characterization of the canopy structure.

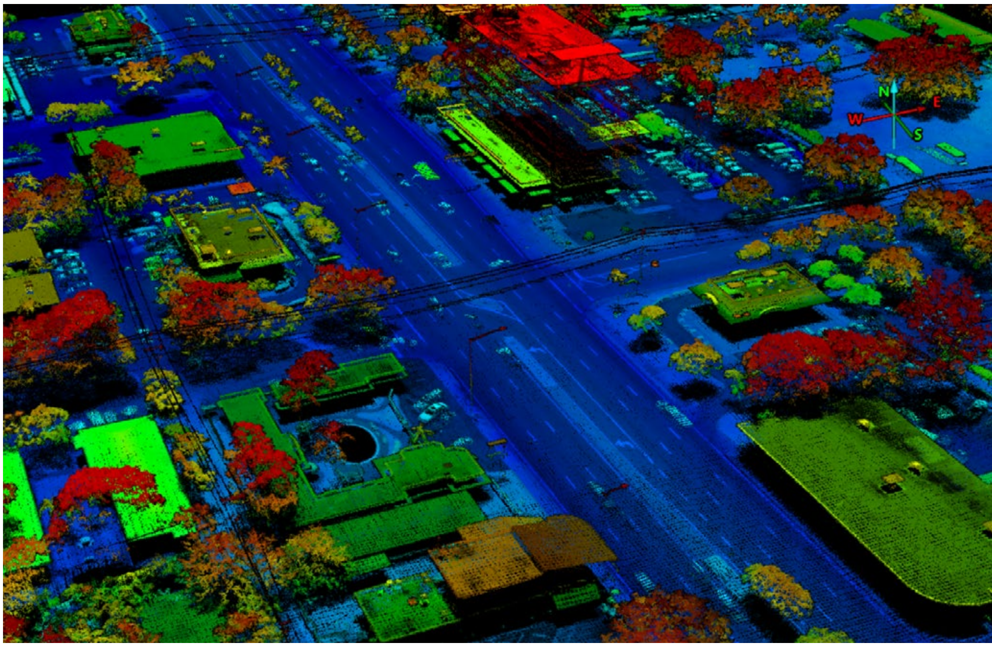


Figure 2: A high-density (100 ppsm) lidar dataset acquired for FDOT in 2017 illustrates the characterization of above-ground features (power lines, light poles, etc.) in very great detail.
Image courtesy of Woolpert.

Accurate mapping for the utilities industry and the electric grid also requires high point density. Managing the transmission and distribution network requires detailed mapping of assets such as power lines, poles, and substation infrastructure, enabling accurate analysis of their condition, locations, and potential issues like vegetation encroachment. Most utility mapping surveys are conducted using airborne lidar mounted on an aircraft or helicopter, flying low and slow above the power lines to achieve 35+ ppsm density. These surveys are used for transmission networks and characterizing substations. Would a higher point density enable accurate mapping of the overhead distribution network?

The Florida Department of Transportation (FDOT) tasked Woolpert in 2017 to conduct a 100 ppsm density survey in a 25 square-mile urban area in Fort Lauderdale, Broward County, Florida. Two airborne survey missions were flown using the Leica ALS80 sensor at 3500 ft AGL with 30% sidelap to produce the required point density. The resulting data set enabled mapping of above ground features such as power lines, light poles, vehicles, and building rooftops with significant detail (**Figure 2**). This dataset was acquired for FDOT to assess the benefits of a high point density for various applications.

These examples suggest that an increased point cloud density does support additional applications, and that higher point density produces an output that has greater value. However, there does come a point when generating more data density may not add more value. It does depend on the application, but, even for the most demanding applications, point densities in excess of 50 ppsm (equivalent to 14 cm point spacing on the ground) may not provide any greater value, which is typically when laser footprint size exceeds the sample spacing for linear-mode airborne lidar sensors. So, should we consider recommending 50 ppsm as the optimal lidar point cloud data density for first returns with the potential to capture >200 ppsm in dense canopies?

> “The opportunities for a high point density lidar are endless, and, with recent advances in technology, the principle of diminishing marginal returns will continue to see a new point of optimal capacity for lidar density.”

50 ppsm density is fantastic, but what about the cost??

We can all benefit from higher point density, but there are budgets and financial considerations that can and should play a big role in decision making. Several studies have been conducted to assess the benefits of lidar data on a national scale. The 3D Nation Elevation Requirements and Benefits Study conducted by Dewberry is being used to plan for the next generation of the US Geological Survey (USGS) 3D Elevation Program (3DEP), following the completion of the nationwide coverage based on a similar study conducted in 2012. Due to a combination of technological advances, the increased need for higher-resolution data to support various applications, and the need to assess landscape change at a finer resolution in areas where natural disasters often occur, USGS is already supporting the collection of 8 ppsm density over large areas on a national scale. Advances in lidar technology have enabled the cost for an 8 ppsm collect to be lower than a 2 ppsm collect from a decade ago. However, a 50 ppsm collect using traditional linear-mode lidar technology will be considerably more expensive than 8 ppsm, as it must be flown at lower altitude with significant overlap.

What if we can reduce the cost by flying higher to cover more area and increase collection efficiency while also increasing point density? What if we can imagine a lidar sensor as an imager similar to an aerial 4-band imagery sensor that captures 6-inch (15 cm) photography at over 10,000 ft AGL? What if we can co-collect lidar and imagery in a single flight to further reduce cost? The lidar imager concept based on photon-counting/Geiger-mode technology is not new, but it has suffered in the past decade from early adoption without a focus on accuracy and reliability. What if we can co-collect linear- and Geiger-mode lidar and 4-band imagery in a single flight at 10,000 ft AGL to produce >50 ppsm ground density Geiger-mode lidar with the accuracy and reliability enabled by integrating linear-mode data, combined with 4-band imagery? The opportunities for a high point density lidar are endless, and, with recent advances in technology, the principle of diminishing marginal returns will continue to see a new point of optimal capacity for lidar density, just like the restaurant owner who has the opportunity to increase those other factors (seating area, kitchen efficiency, chefs) to hire additional waiters and continue to increase customer satisfaction and profitability.

Amar Nayegandhi, CP, CMS, GISP is global head of technology and innovation at Woolpert. He is responsible for aligning, optimizing, integrating, and expanding Woolpert’s technology portfolio across its globally integrated architecture, engineering, and geospatial platform. Amar is an ASPRS Fellow and was the director of the ASPRS Lidar Division. He co-edited the ASPRS DEM Users Manual, 3rd Edition and authored the chapters on airborne topographic lidar and airborne lidar bathymetry. Before joining Woolpert, Amar served as senior vice president at Dewberry, where he led the firm’s geospatial and technology services operating unit. Prior to that, he managed federal coastal science and resource management contracts at Jacobs, where he developed algorithms and post-flight data processing software for government-owned topographic and bathymetric airborne lidar sensors used in research.

Al Karlin, Senior Geospatial Scientist, Dewberry, serves as a consultant on Florida-related lidar, topography, hydrology, and imagery projects.

Welter, *continued from page 48*
resources. This heavily outweighs the environmental impact of flying an airplane or helicopter for data capture, but it doesn't negate it.

In 2025, we'll see the industry pushing for airborne data capture methods that minimize carbon emissions and increase efficiency. Hybrid sensors, which combine multiple data collection capabilities such as imagery and lidar in a single flight, are an emerging solution. These sensors reduce flight times and cut carbon emissions significantly, as recently demonstrated in a project in Nottingham, UK. The city council collaborated with Bluesky International, a leading aerial surveying company in the UK, to develop a 3D digital twin of Nottingham city[1]. This approach lowered emissions while advancing sustainable, data-driven urban planning.

Sustainable data capture is increasingly important as airborne mapping is used in more environmental and sustainability projects globally. For example, with rainforests depleting at an alarming rate, more frequent geospatial surveys are incerasingly critical. However, challenging weather conditions in these ecosystems limit when pilots can safely fly. Hence more businesses are assessing technologies that can perform aerial surveys in a single flight.

One project in Costa Rica[2] saw researchers deploy a hybrid sensor for this very reason. With the data the collected, they are creating a 3D digital twin of the rainforest to monitor biodiversity, providing a model for similar conservation efforts elsewhere

> "The geospatial industry in 2025 will be defined by its ability to adapt and innovate. From harnessing AI to pioneering sustainable mapping and using the cloud for scalability, the industry needs new technology to meet the demands of a changing world."

We will continue to see more projects like these in 2025, potentially using hybrid sensors that integrate additional data types, further optimising efficiency and environmental outcomes.

Cloud computing is scaling geospatial solutions

While end-users demand more and faster data processing, traditional on-premise computing capacity has been a constraint for many businesses. Today, cloud platforms such as AWS and Azure make it easier and quicker to analyse and share geospatial data at scale, even for smaller geospatial companies.

The power of cloud computing became clear during the devastating bushfires that swept through Eastern Australia in 2019 and 2020. Emergency responders needed high-resolution geospatial data updated at regular intervals to coordinate their relief efforts effectively.

We were able to deploy an AWS cloud solution for the New South Wales Department of Customer Service that rapidly processed imagery and elevation data, delivering detailed maps to emergency services within 24 hours. This rapid access to high-resolution imagery and elevation data proved invaluable for guiding relief efforts, and earned an award for innovative emergency response.

There are multiple ways for geospatial companies to use the cloud in the future to support disaster resilience, for example, flood-mapping or even identifying areas of building rubble where somebody may be trapped.

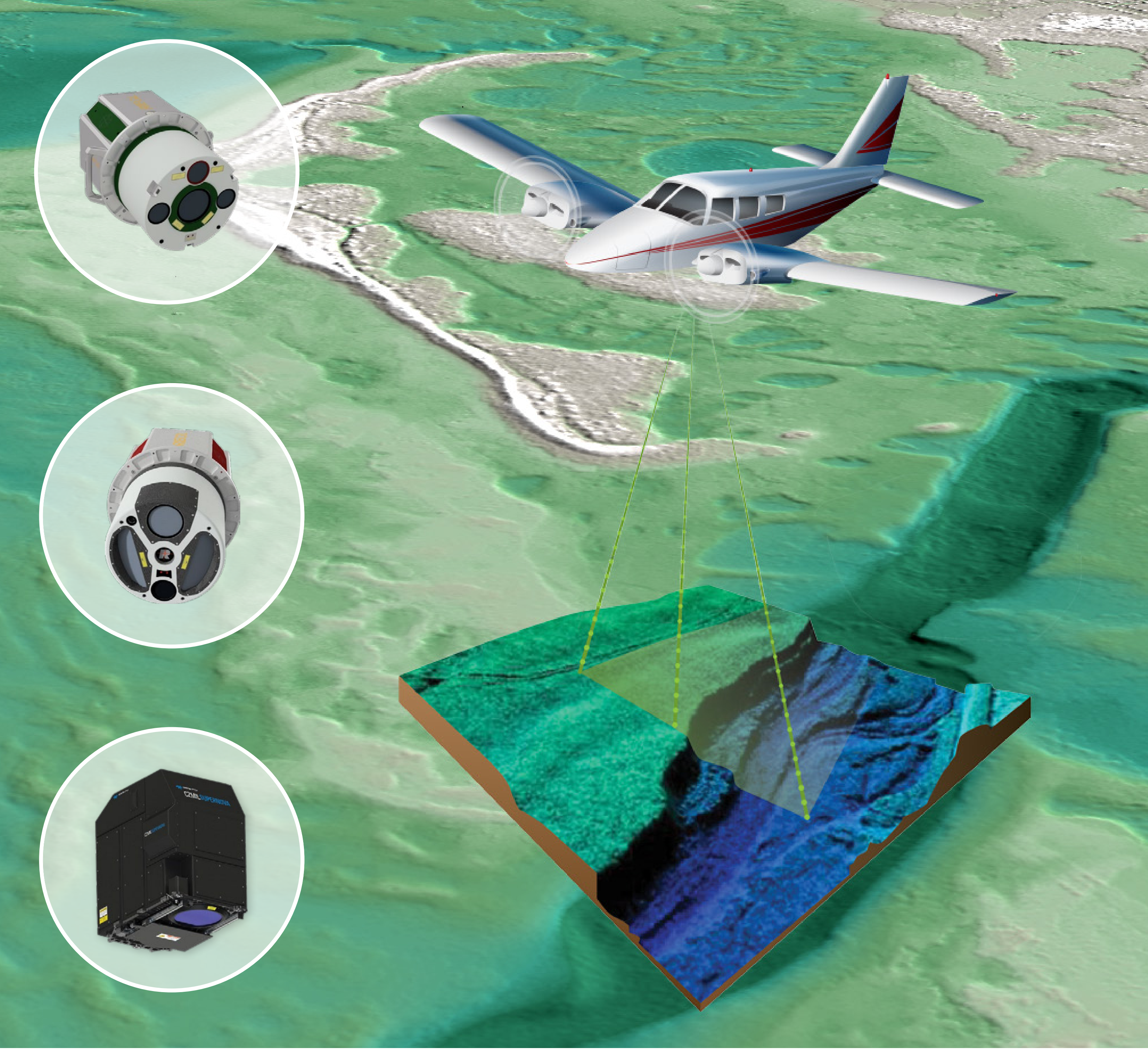
Looking and staying ahead

The geospatial industry in 2025 will be defined by its ability to adapt and innovate. Successful businesses are adopting new technologies and tools to stay ahead of both competition and customer expectations. From harnessing AI for predictive insights to pioneering sustainable mapping and using the cloud for scalability, the industry needs new technology to meet the demands of a changing world.

John Welter is president of geospatial content solutions at Hexagon's Geosystems division. Based in Northern Arizona, USA, he has three decades of extensive and demonstrated experience in the information technology and services industry. He is an expert on topics including geospatial services, airborne mapping technology, big data concepts and IT strategy.

1 Gillespie, A. and L. Hobbs, 2024. A digital twin for Nottingham, *LIDAR Magazine*, 14(3): 26-30, Fall 2024.

2 Kerr, A., 2024. Digital twins open up new possibilities for rainforest conservation, *LIDAR Magazine*, 14(2): 22-25, Spring 2024.



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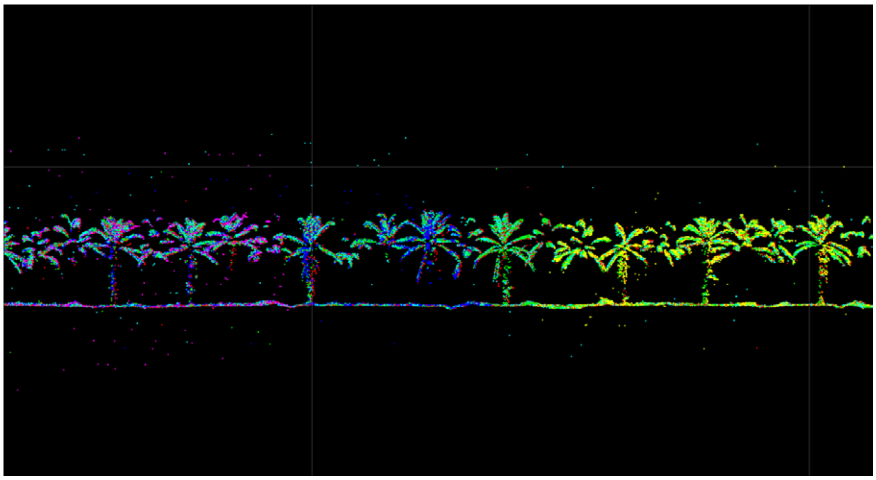
JOHN WELTER

Three key trends influencing the geospatial sector in 2025

AI, cloud computing, and sustainability will redefine how we map and safeguard our planet. We take a first look at each.



This beautiful point cloud of the biodiverse ecosystem of the La Gamba biological corridor, Costa Rica, has been constructed from airborne data and can be combined with data captured on the ground with the Leica BLK2GO handheld terrestrial lidar sensor.

The geospatial industry is entering a new era of demand. Organizations want to understand and manage what's around them better, and technology is evolving to meet these needs, delivering geospatial solutions that provide higher-resolution data with faster refresh rates. So, what trends and innovations will shape the year ahead and beyond?

AI solutions that drive business value

AI is at the forefront of everyone's mind. More importantly, businesses are starting to look deeper into which AI solutions drive meaningful returns. The most innovative and successful applications of AI are those that are taking large quantities of complex geospatial data and simplifying it to drive decision-making for both experts and non-experts.

In the past, once new geospatial data was collected, any earlier datasets were typically set aside and rarely used. Organisations looked at them only after a disaster or during big environmental changes. Now, AI enables real-time data analysis to uncover trends and risks before they materialize.

AI algorithms can process vast volumes of geospatial data to identify changes in the environment, such as forests or water bodies, alerting experts to potential deforestation or flood risks. In Hexagon's Content Program, for example, we map areas of the US every one to three years. We then use AI to quickly compare the new dataset against the old one and 'spot the differences.' This helps identify and predict environmental changes, such as 'this forest is changing faster than we thought' or 'the water is coming inland where not anticipated, which could lead to flooding.' By comparing pre- and post-event data, experts can quantify damage and justify investments in preventative measures, such as flood control infrastructure. In this way, AI is helping us make decisions faster.

Another innovative way AI is used is to analyse complex data to create simple outputs. For example, one of our teams at Hexagon is taking geospatial data of cities and using AI to highlight levels of smog or noise in certain areas with a simple traffic-light dashboard system—a red, amber, or green alert. This provides quick, digestible information for urban planners and the general population to make decisions, for example about where to build a new house.

Sustainability is top of the agenda

Airborne mapping plays a crucial role in protecting the environment by helping us monitor and manage the planet's

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