VOLUME 11 ISSUE 2

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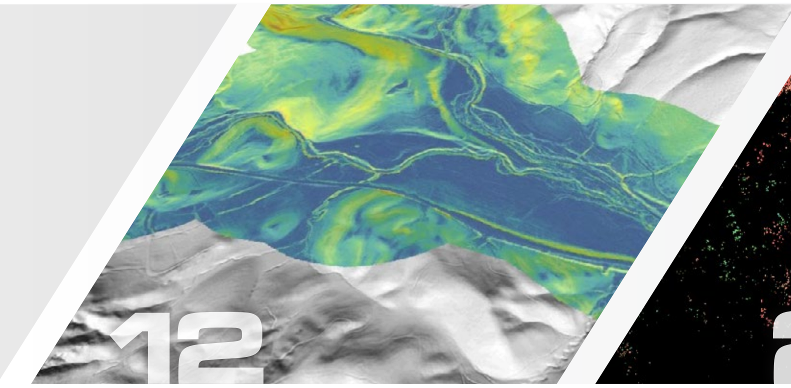

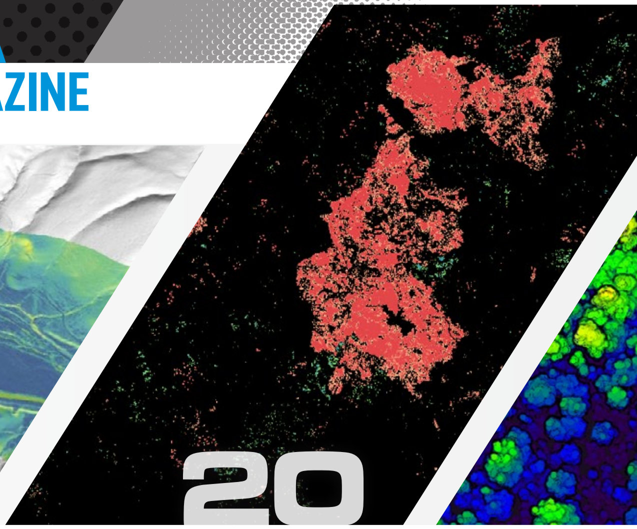

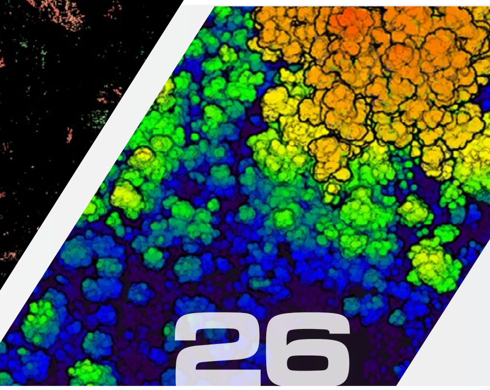

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COLUMNS

◀ ON THE COVER

The Pacific Ocean reaches the coastline at Big Sur, California, known locally as "the greatest meeting of land and sea".

Photo credit: Adam Kazmierski

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DR. A. STEWART WALKER

An Abundance of Caution

"They changed their minds, flew off, and into strange vagaries fell..." Guided by Milton's words from *Paradise Lost*, we're gently resuming travel—but it's a strange feeling and there's an abundance of caution. I discovered that NV5 has an office close to my home and this became my first business trip for almost 15 months. I will write this up for you, because the facility is the focus of NV5's UAV mapping operations, which have a substantial lidar content. With both internal clients from across NV5 (which goes way beyond NV5 Geospatial) and a growing external customer-base, the services of this unit are in demand. NV5 is never idle when it comes to acquisitions and its recent purchase of Geodynamics, headquartered in Newport, North Carolina, constitutes an instant expansion of NV5's hydrographic and coastal science capabilities. Intriguingly, I met NV5's chief synergy officer, Scott Kvandal, whose role is to ensure that all these acquisitions work. Thereby hangs a tale. Back in the twentieth century, when I was working for Leica Geosystems, skilled CEO Hans Hess was fond of the phrase "leveraging synergies". Those were my pre-MBA days and I didn't really comprehend. I fully appreciate now that the success of an acquisition is dependent on effective integration into the culture and operations of the acquirer. If two plus two doesn't equal a lot more than four, then the acquisition is just squandered sweat. NV5 is facing this challenge sensibly.

After the excitement of the last issue, supersized with articles about Florida, we bring to you a more typical offering. The tide of Florida lidar talent has not ebbed, however, and we have a very practical contribution by Ben Wilkinson and Andrew Lassiter of the University of Florida about targets for use in lidar surveys. We have a follow-up from Florida lidar guru Al Karlin to his earlier Puerto Rico piece. Then we fly west to California, where Kass Green, well known Berkeley consultant and author, reports on how consortia of public-sector organizations in or near the Bay Area have contracted for lidar data so that they can have access to very detailed, accurate topographic and vegetation maps in order to manage wildfire risk and many other challenges. There are two further, stylish contributions from the Golden State. Christopher Anderson of Bay Area start-up Salo Sciences talks about his firm's application of complex analytics, rich in artificial intelligence (AI), to satellite imagery and lidar for monitoring wildfire risk. We enter the Pacific with an account by Jennifer Wozencraft of the Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX) of the mapping of the California coast by the US Army Corps of Engineers (USACE) and its federal and private-sector partners. These articles draw from airborne lidar, mainly from manned aircraft, but no issue

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of *LIDAR Magazine* these days would be complete without something equally exciting from the automotive side. So we continued west, across the ocean, for an interview with HanBin Lee, founder and CEO of Seoul Robotics, a Korean start-up that supplies hardware, firmware and perception software which works with a lidar sensors from many suppliers. The issue ends with "LAS Exchange" and "Random Points" by our regular contributors, Lewis Graham and Evon Silvia.

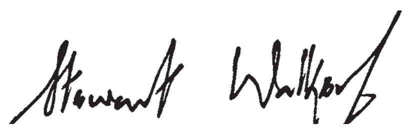
The contents of this issue, therefore, are fine reading, but also link well to what we have in store. In the next issue, we have a companion paper about another USACE geography—mapping the shorelines of the Great Lakes. Global warming, changing water levels and human activities in this vast, critical part of the US merit the best geographic information, of which USACE is a key provider. This article is based on a presentation at a virtual meeting of the ASPRS Eastern Great Lakes Region last year and will be prefaced by a short piece from region president Shawana Johnson.

I have dwelt in these pages on the benefits the geospatial world has enjoyed as a result of automotive-grade lidar sensors finding their way on to UAVs and road vehicles, resulting in economical mapping systems that offer impressive performance. As automotive suppliers pursue the goal of autonomous vehicles, not only driverless cars, but robotaxis, vehicles for moving containers around ports, etc., sensors and the related firmware and software are crucial. The suppliers are busy not only innovating but also chasing the funds they need to grow. The use of special-purpose acquisition companies, which we covered with respect to Velodyne Lidar[1], has become popular—many other sensor supplies have followed this path, including AEye, Innoviz, Luminar and Ouster. We have interviews with two of these in preparation, and another with Neural Propulsion Systems, as well as technology articles from Lumotive and Quanergy Systems. The market is complex: some of the suppliers make sensors and, perhaps, an accompanying SDK, whereas others provide sophisticated software based on AI approaches such as deep learning. Some use their own lidar sensors; some, third-party products. We will try to help you sort this out.

For all this automotive excitement, we must not forget the suppliers that introduced airborne and terrestrial lidar and thus transformed the mapping activity. Teledyne Optech, for example, has recently mounted strong webinars and we are seeking articles on their sensors, such as the Optech CZMIL Nova. Meanwhile, our next issue will contain an article by multiple authors from USGS and other federal agencies about the efficacy of a sensor from Leica Geosystems for both 3DEP and NAIP. The interview with James Van Rens of Riegl USA in the last issue further underlines the strength and vibrancy of these market-leaders. They are cornerstones in the commercial world that provides the means to collect geographic information and is in constant flux: the acquisition by Teledyne Technologies of FLIR Systems, which itself acquired UAV manufacturer Altavian, makes the point!

As I've observed on our website, ASPRS recently held its annual conference, again virtually, and we are approaching a number presenters as prospective contributors. That brings us full circle—back to traveling. ASPRS is planning its participation in the Commercial UAV Expo Americas event in Las Vegas on 7-9 September 2021, which seems almost certain to go ahead live. The ASPRS workshops are likely to focus on what the Society does best—certification, calibration, standards and guidelines. Indeed, I wonder whether its range of publications should be expanded with a manual of UAV-photogrammetry and UAV-lidar. Readers with thoughts on this are welcome to write in!

Let's peer a little further out. Researchers at three UK universities are using lidar to construct high-definition holograms that can be projected on to a car's windshield to allow drivers to "see through" objects, alerting them to potential hazards. It's early days yet and so far they're experimenting with TLS data sets, but the concept is fresh in the sense that it's in the ADAS rather than AV world[2]. Finally, please take time to view a beautiful, mainly photographic history, in flipbook form, entitled *100 Years Innovation Heerbrugg*[3]. The jubilee celebrations were hard hit by the pandemic, but this is one result and it's superb!

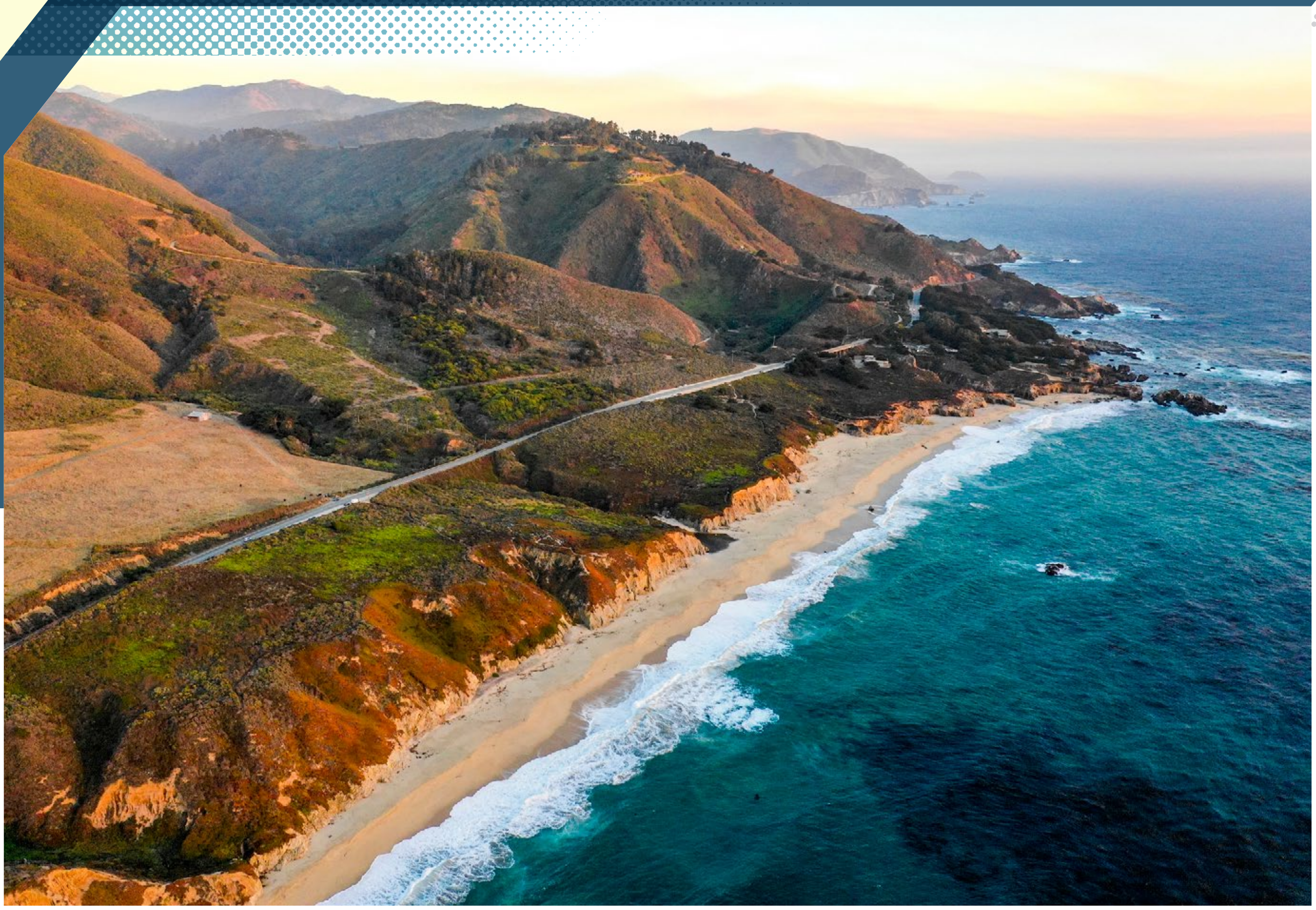


A. Stewart Walker // Managing Editor

1 https://lidarmag.com/wp-content/uploads/PDF/LIDARMagazine_Walker-Velodyne_Vol10No4.pdf.

2 There's a short article at https://eandt.theiet.org/content/articles/2021/04/head-up-display-uses-lidar-to-alert-drivers-of-upcoming-hazards/ and the deeper paper is: Jana Skirnewskaja, J., Y. Montelongo, P. Wilkes and T.D. Wilkinson, 2021, LiDAR-derived digital holograms for automotive head-up displays, *Optics Express*, 29(9): 13681-13695, https://www.osapublishing.org/oe/fulltext.cfm?uri=oe-29-9-13681&id=450306.

3 https://www.flipsnack.com/hexagongeo/100-years-innovation-heerbrugg-hexagon-anniversary-book/full-view.html.



Mapping Coastal California

USACE partners with federal and private organizations to optimize data collection and use on the Pacific coast

BY JENNIFER M. WOZENCRAFT

California's 1352 kilometers of coastline present varied and challenging mapping environments. These range from the sandy beaches of Malibu to the rocky coasts of Northern California and from small creeks and rivers like the Santa Ana to large bays and harbors, such as those in San Francisco and Los Angeles/Long Beach. They flow from dense kelp beds near Catalina to the formidable coastal bluffs at La Jolla and extend from the natural panoramas on the sand dunes at Inglenook to the highly developed coastal communities at Oxnard.

Mapping these diverse conditions is well suited for airborne topographic and bathymetric lidar with high-resolution aerial photography (**Figure 1**) and hyperspectral imagery. This topobathymetric lidar-imagery combination produces highly dense and accurate three-dimensional elevations, centimeter-resolution resolution imagery, and spectral characteristics of land and water. These are used as individual mapping products and combined into derived or fusion products that significantly expand measurement and monitoring of the

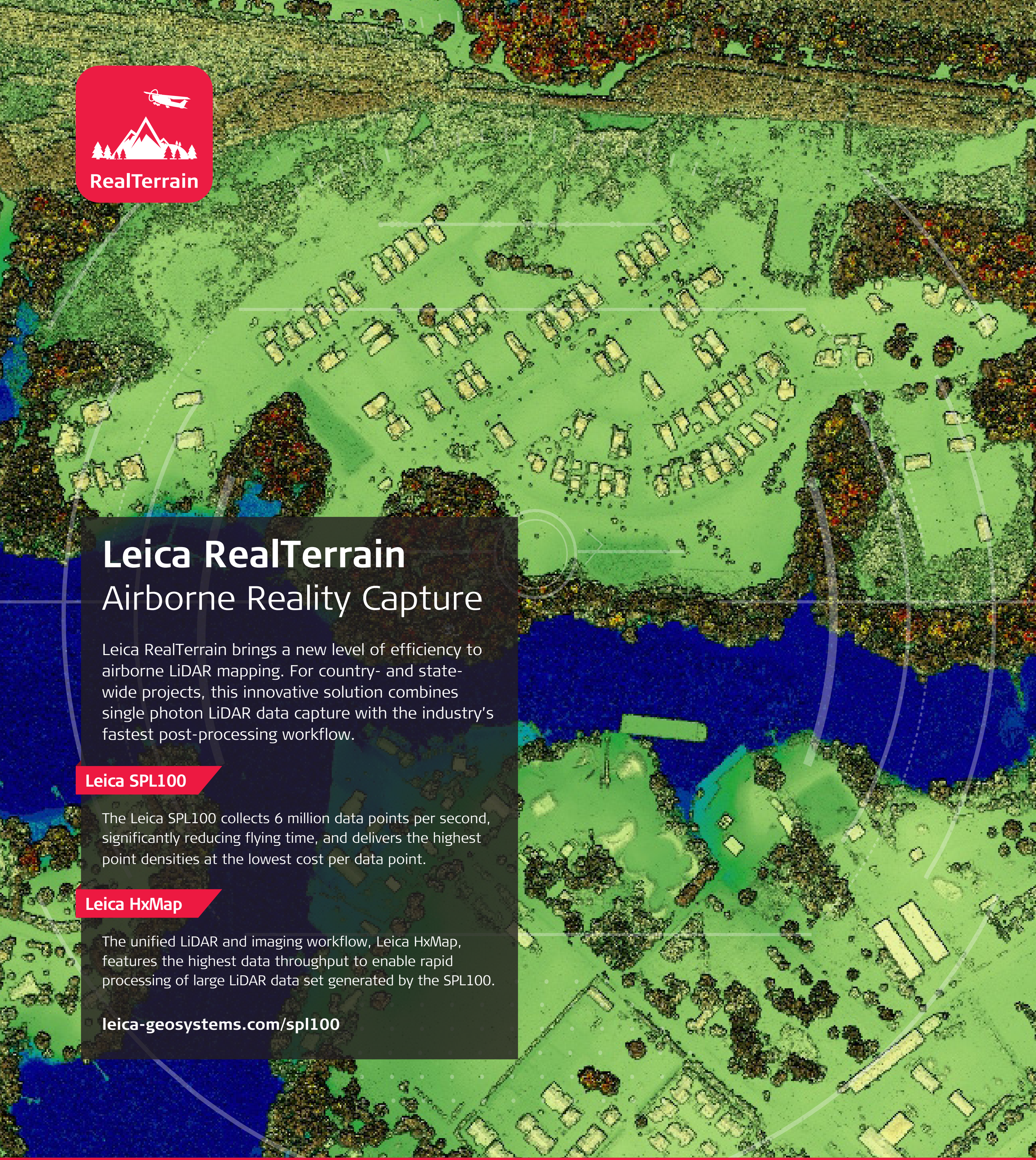


Figure 1: Oceanside, California, is in northern San Diego County.
Photo by Getty Images.

coastal region. During the summer of 2021, large portions of the California coastline are being mapped by the National Coastal Mapping Program (NCMP) of the U.S. Army Corps of Engineers (USACE).

National Coastal Mapping Program

NCMP was established in 2004 to map the U.S. coast on a five-year recurring schedule. It supports the USACE Civil Works mission regarding navigation, flood-risk management, ecosystem restoration, emergency response and regional sediment management. It is the only federal coastal mapping program with a recurring national schedule, and this will be the third time since 2010 that NCMP has mapped the California coast. NCMP flies airborne topobathymetric lidar with a high-resolution camera and a spectral imager to collect data along the coast in the most active zone for sediment movement, 500 meters landward of the waterline to 1000 meters offshore. This nearly mile-wide zone is where currents, waves and storm surge move sand; where the oceans meet the shoreline, bays, inlets, ecosystems and communities; and where change occurs most rapidly. USACE uses the data to monitor and inform decisions on sediment management, coastal studies, beach and dune restoration, remote inspection of coastal structures, and threatened and endangered species and habitats, among other coastal applications. In addition, these data and related mapping products are available to the public through NCMP, local USACE district offices, and the Digital Coast website of the National Oceanic and Atmospheric Administration (NOAA).

NCMP has partnered with the U.S. Naval Oceanographic Office (NAVOCEANO) to develop and share topobathymetric lidar sensors and operational capabilities and with NOAA and the U.S. Geological Survey (USGS) to combine research and develop new products that characterize the coastal zone for the agencies and public. This leveraging of knowledge and expertise is formally called the Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX). It was established in 1998 and is located at Stennis International Airport, Kiln, Mississippi, which is adjacent to NAVOCEANO and USACE. USACE/NCMP and NAVOCEANO have four JALBTCX-developed Coastal Zone Mapping and Imaging Lidar (CZMIL) sensors that are government-owned and contractor-operated. They share the CZMIL sensors to meet their coastal mapping and nautical charting requirements, respectively. The current JALBTCX contractor is WMR-532, a joint venture between Woolpert, headquartered in Dayton, Ohio, and Optimal GEO, headquartered in Athens, Alabama. The CZMIL sensors are operated worldwide to meet both agencies' requirements.

The JALBTCX partnership is a government success story, accomplishing much more working together than these programs could have alone. Partners have each matured their programs and capabilities by coordinating their efforts. The knowledge developed from working together through JALBTCX has been complied in a publication, *Airborne Laser Hydrography II*[1], often referred to as *Airborne Laser Hydrography II (Blue Book II)*, which shares the knowledge gleaned from 30 years of advances and,

1 Philpot, W. (ed.), 2019. *Airborne Laser Hydrography II*, Cornell eCommons. 279 pp. https://doi.org/10.7298/jxm9-g971.

most importantly, from thousands of hours of operational experience. This book includes information from additional international teams and systems, imparting the knowledge gained over a wide range of applications and environmental conditions.

California dreamin'

Before NCMP maps large portions of the California coast this summer, it will coordinate mapping in Texas, finish small sections remaining of Washington and Oregon from last summer's survey flights, and map projects in Alaska under a new requirement to support the Alaska Coastal Mapping Strategy. In all these locations, NCMP begins with a point of contact in each USACE district office to identify requirements and priority areas. The planning process also includes discussions with district stakeholders from other federal, state and local government agencies to make sure as many identified needs are included in the mapping plan as possible.

In addition to direct outreach through the USACE districts, NCMP also works with the Federal Interagency Working Group on Ocean and Coastal Mapping (IWG-OCM), which is a working group of the National Science and Technology Council Subcommittee on Ocean Science and Technology. According to the National Ocean and Coastal Mapping Strategic Action Plan of 2009, IWG-OCM came into existence in 2006 to "facilitate the coordination of ocean and coastal mapping activities and avoid duplicating mapping activities across the federal sector as well as with state, industry, academic and non-governmental mapping interests." IWG-OCM was established into law by the Ocean and Coastal Mapping Integration Act of 2009. To help coordinate coastal mapping programs and priorities, IWG-OCM maintains the Seasketch website (**Figure 2**) for U.S. Mapping Coordination[2].

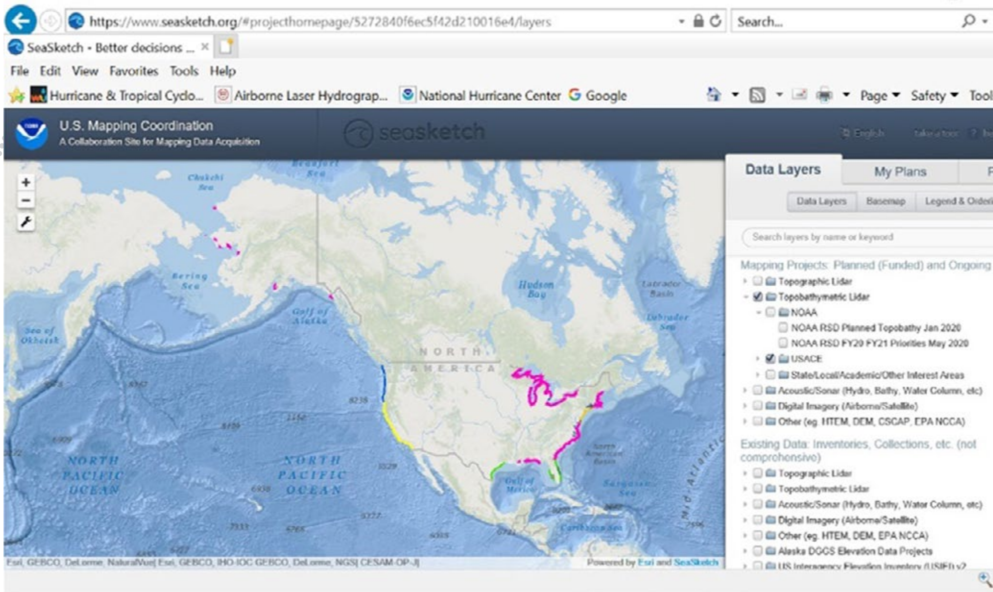


Figure 2: IWG-OCM National Planning Tool.
Image from Seasketch website

California mapping requirements are being developed as this article is being written and because of the flexibility of the planning tools and daily operations, new requirements may be added throughout the flying mission. If areas extend beyond the priorities identified by USACE districts, costs may be covered by federal, state or local agencies under agreements with USACE to transfer funding. This has proved to be very efficient and economical over the years, without requiring new contracting or mobilization expenses, while resulting in more area coverage. For example, it has led to mapping the Niagara River and Green Bay, during the mapping of the Great Lakes. Also, this year two inland California dams will be flown to support research and development efforts, including the development of digital twins to support these flood control structures.

2 https://www.seasketch.org/#projecthomepage/5272840f6ec5f42d210016e4.

Mapping the California coast

NCMP mapped the California coast in 2009-2010 and again in 2014-2015, so it is familiar with and understands the regions and their variations. **Figure 3** shows topobathymetric lidar collected in 2014 at Oceanside, California. Coverage was complete and very thorough. For example, the 2015 California survey flew 1113 flight lines over 93 days, conducting 104 survey flights and covering over 2700 square kilometers along central and southern California. NCMP contributed to an interagency data collection of the California coast in 2016 following an El Niño year wracked by severe storms. It is often the case that NCMP's recurring surveys provide the pre-storm conditions that are used with post-storm surveys to calculate storm damage and coastal impact, helping design more resilient repairs and project adaptions, as was the case with the 2016 El Niño surveys. Additionally, the flight lines from these previous missions form an excellent first cut for planning the 2021 mission, which include USACE navigation projects with channels, jetties and breakwaters; coastal flood risk management projects with beaches and dunes; and ecosystem projects to look at overall condition and measure change.

Comparing elevations from the 2009 and 2014 NCMP surveys immediately demonstrates the value of these repeat datasets (**Figure 4**). The nearshore bar has clearly migrated between the two time periods, with most of the other areas relatively stable. Quantifying these changes lets coastal managers know what is changing and how fast change is happening. It informs decisions on where to focus resources to reduce future damages and increase coastal resilience. Similar comparisons may be made using NCMP imagery and spectral information. USACE uses the imagery to look at jetties and breakwaters to quantify movement of armor stone or indications of internal erosion of the structures and analyzes the spectral data to map land use and ecosystem health changes, such as those caused by invasive species.

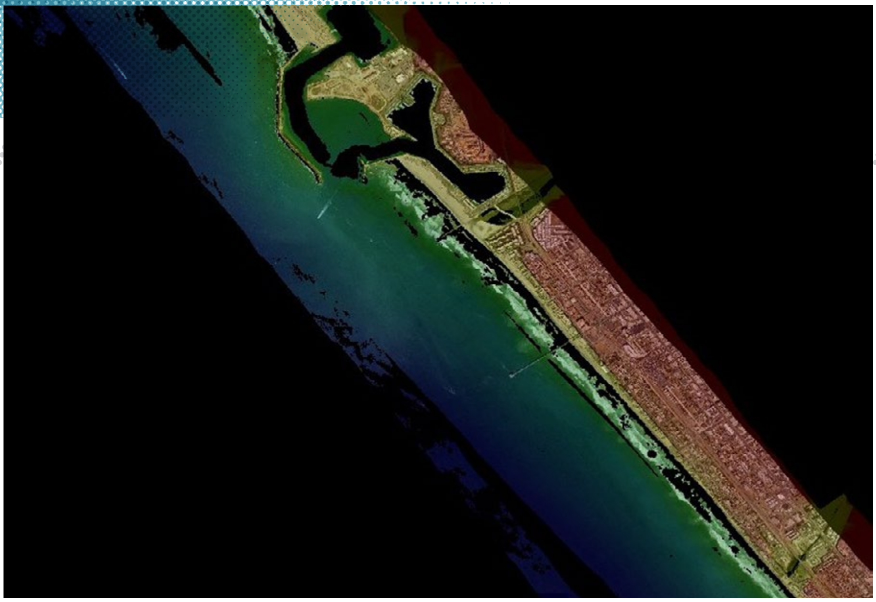


Figure 3: Oceanside, California, topobathymetric lidar collected in 2014.
Image courtesy of USACE/JALBTCX.

Mapping products

The basic products that will result from the coastal California surveys are combined topobathymetric elevations, or point clouds, in LAS format, digital surface models (DSMs), digital elevation models (DEMs), air photo mosaics, hyperspectral image mosaics, a zero contour, all with accompanying metadata compliant with Federal Geographic Data Committee standards. These products have been developed over the years to facilitate ease of use of NCMP data and images by USACE, other agencies, coastal engineers and managers, as well as the public.

DEMs and DSMs are often used in numerical coastal process models that calculate wave runup and storm surge or compare pre-storm and post-storm surveys to calculate volumes of sediment erosion or accretion and, after extreme storms, to determine where buildings were damaged or destroyed. Comparison of zero contours provides a quick indication of what has changed since the last survey. Where change is extensive, the coastal engineer or manager may want to conduct high-resolution 3D change analyses of the beach and nearshore zone to determine the quantity and possibly cause of change.

Image mosaics provide a simple visual record of the condition of coastal jetties and breakwaters and aid inspections by identifying displaced or damaged stones. With centimeter-resolution images, even identifying cracks in rubble mound armor stone or fabricated concrete armor units like the dolos on the Crescent City, California, breakwater is possible. Hyperspectral images are used in combination with lidar elevation data to produce land cover and seabed classifications. Classification of specific vegetation species can aid in the mapping of and design of effective management strategies for invasive species, such as giant reed on the Santa Ana River adjacent to Newport Beach, California. When compared to previous collections, it is possible to calculate landscape changes, such as how much green space has become developed or change in area of seagrass beds.

Emerging tools and capabilities

NCMP has developed a set of geospatial analysis tools that standardize production of key coastal information. The USACE Volume Change Toolbox standardizes computation of beach and nearshore volume change from 3D coastal datasets for sediment budgets and post-storm impact assessments. NCMP initially developed the Toolbox to systematically compute volumes along long stretches of coast for development of regional sediment budgets. USACE Volume Change Toolbox outputs link to the USACE Sediment Budget Analysis System through web services for faster regional sediment budget development. USACE researchers have used the Toolbox extensively to compute regional beach elevation change, shoreline change, and volume change after hurricanes Sandy, Matthew, Irma, Maria, Michael and Sally, and after a strong winter storm season in New York in 2020. The USACE Volume Change Toolbox is a set of Python scripts

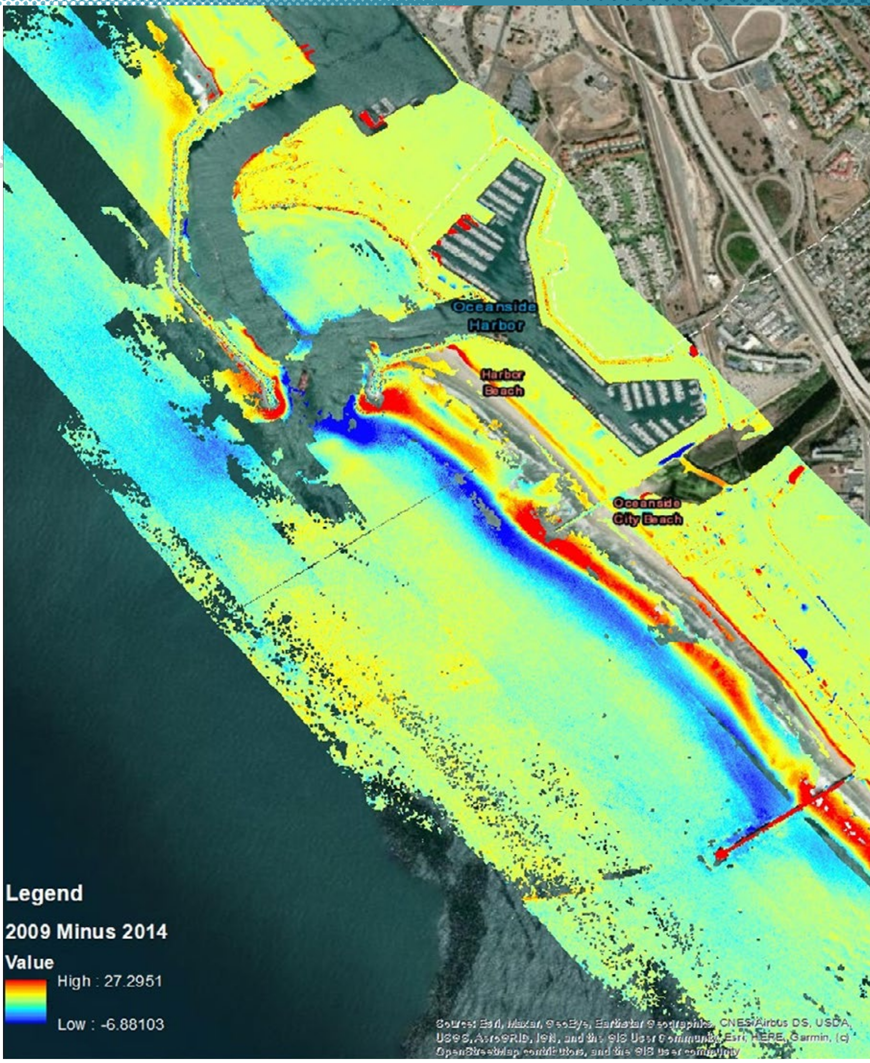


Figure 4: Change analysis at Oceanside, California, from 2009 and 2014.
Data courtesy of USACE/JALBTCX, analysis courtesy of Bowhead.

that guide a user through all the steps needed to compute elevation change, shoreline change and volume change in a systematic way for long stretches of coast (hundreds of miles). The Toolbox operates in an ArcGIS environment and is semi-automated, which means that once a user has set up each step, it runs automatically through the input datasets to produce a result.

The USACE Coastal Geomorphology Metrics Toolbox automates the extraction of coastal metrics such as dune crest location and height, dune toe location and height, bluff crest location and height, bluff toe location and height, beach width, beach slope, and sandbar location and depth. Algorithms for metric extraction were developed in collaboration with scientists in the USGS Coastal and Marine Geology Program. These metrics are used in multiple applications, such as the generation of a barrier island breachability index for the state of Texas, and the computation of bluff recession rates for sediment budget development in the Great Lakes. The Coastal Engineering Resilience Index Tool uses a number of these metrics along with wave, water level, and sediment models and data to estimate the relative resilience of the coast from an engineering perspective. The USACE Volume Change and Coastal Geomorphology Metrics Toolboxes are currently being converted to Python 3 for use in the ArcGIS Pro Environment.

The USACE Dune Vegetation Metrics Toolbox combines dune geomorphology with NCMP imagery to compute several vegetation metrics relevant to coastal studies. The presence of vegetation on a dune stabilizes the dune and increases its protective benefit in the event of a high wave or water level event. The custom toolbox was designed with the Python programming language and integrates ArcGIS Pro geoprocessing tools with ENVI image analysis software capabilities to enhance spatial analytics and spectral-band math algorithms used to derive the metrics.

The USACE Coastal Geomorphology and Dune Vegetation Metrics toolboxes are currently being validated by field data and tested for differing environments around the U.S. coastline.

Summary

Since 2004, there have been over 45,000 separate downloads of NCMP data from the Digital Coast website, amounting to over 10,500,000 MB of data. This is a key performance indicator of the value of the NCMP data and resulting products. This summer, coastal California will be mapped, data will be processed, and standard products will be created and sent to USACE districts in California. They will also be loaded into the Digital Coast for easy public discovery and access. In no time, coastal engineers, scientists and managers will be using this data with results from 2010 and 2015 to inform decisions and target investments that protect the public and raise coastal resilience.

Jennifer M. Wozencraft is the U.S. Army Corps of Engineers National Coastal Mapping Program Manager; Director, Joint Airborne Lidar Bathymetry Technical Center of Expertise.

Combating California Crises with Maps

Bay Area consortia leverage lidar to generate critical detailed mapping

San Francisco Bay Area land managers and stewards have the responsibility of caring for one of the most populated, but also most ecologically rich and beloved places in the United States, if not the world. Home to 7.7 million people and 1.4 million of acres of protected open space, the area's wild and working lands provide residents and visitors with water, varied recreation opportunities, scenic vistas, wildlife habitat, and vital refuges for many threatened, endangered, and special status species. Conversely, the Bay Area also experiences dramatic natural disasters from floods to earthquakes, and, most recently, intensifying wildfires.

To effectively care for the Bay Area's ecosystems and infrastructure and prepare for natural disasters, citizens, landowners, politicians, managers and government agencies must know the location and distribution of resources across the landscape over time. Managing and monitoring carbon stocks, fire and flood hazards, critical habitat and climate resiliency require up-to-date, fine-scale maps and databases of the area's vegetation and topography. Without accurate maps, there is no

BY KASS GREEN

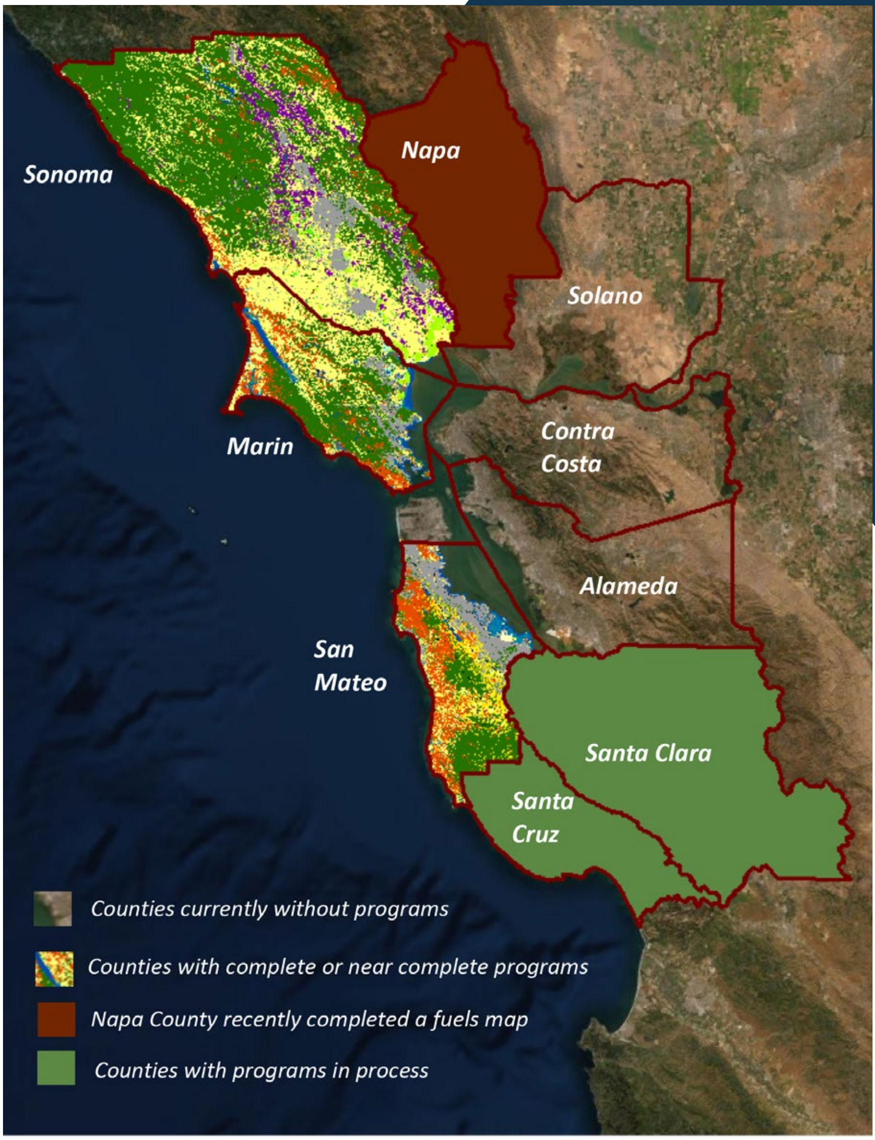


Figure 1: San Francisco Bay Area counties with fine-scale vegetation and landscape data programs.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Area	Program Management	Acres
Sonoma County	Sonoma Ag + Open Space District	1,132,000
Marin & San Mateo Counties	Golden Gate National Parks Conservancy	565,000
Santa Cruz & Santa Clara Counties	Santa Cruz Mountains Stewardship Network	1,233,000

Table 1: Fine-scale vegetation and landscape database programs in the San Francisco Bay area.

way to plan for and comprehensively measure and monitor the impact of human decisions and natural disasters on Bay Area landscapes over time.

Until recently there have been serious gaps in knowledge about the landscapes of the Bay Area. Existing vegetation maps were piecemeal, out of date, or at a statewide scale incapable of supporting local decision-making. Topographic data was coarse or non-existent. As a result, managers and decision-makers labored with maps that were severely out of date, crude, and often incorrect. Over the last seven years, however, numerous organizations in the Bay Area have banded together to create consortia for funding fine-scale vegetation and landscape data sets for much of the region, including Sonoma, Marin, San Mateo, Santa Clara, and Santa Cruz counties (**Table 1** and **Figure 1**). Each of these programs includes the collection of QL1 lidar data to support a variety of applications ranging from vineyard management, to wildfire risk mitigation and response, flood planning, conservation easement prioritization, tax assessment, wetland restoration, endangered species habitat protection, and engineering. This article summarizes the evolution of these programs, focusses on innovative uses of the programs' lidar data, and highlights the factors which led to the programs' success.

Product	Product Requires Lidar Data?
Lidar point cloud	yes
6-inch orthoimagery	no
Enhanced lifeform and land use map (20+ classes)	yes
Wildland fuels (5 m resolution)	yes
Ladder fuels	yes
Topographic layers (slope, aspect, elevation, shaded relief, etc.)	yes
Wildland Fire Risk Index	yes
Canopy cover, height, base height, bulk density	yes
Multi-class impervious/pervious surfaces mapping	yes
Fine-scale vegetation classification: field data acquisition, vegetation descriptions and keys	no
Functional riparian corridors	yes
Hydrological system mapping	yes
Fine-scale vegetation map and accuracy assessment (1/4-1 acre mmu, 100+ classes)	yes
Data access portals	no

Table 2: Products created for the San Francisco Bay Area fine-scale vegetation mapping and landscape database programs. Products delivered vary by county.

Program evolution

When Sonoma's Ag + Open Space District[1] conceived of the first Bay Area vegetation and landscape program, it was initially focused on vegetation mapping only, and the District did not include lidar data because of its expense and the perception that lidar data could add little to the program. Through a series of fortunate events, however, the District was simultaneously included in a successful proposal to NASA's Carbon Monitoring System by Ralph Dubayah and George Hurtt of the University of Maryland (grant NNX13AP69G). Upon award of the NASA grant, plus additional funding from USGS's 3DEP program, the District contracted with Quantum Spatial[2] to capture QL1 lidar for all of Sonoma County along with the 6-inch resolution, 4-band imagery already slated to be collected to support the mapping program. Upon delivery, the value of the lidar data was instantaneously recognized. As stated by Karen Gaffney, conservation planning manager at Sonoma County Ag + Open Space, "It was a revelation. We immediately understood the value of the lidar data for guiding our land conservation investments, and then there was a rapid emergence of multiple uses and applications. Not only did the lidar data improve the quality of the vegetation maps, it also supported climate change action, public safety,

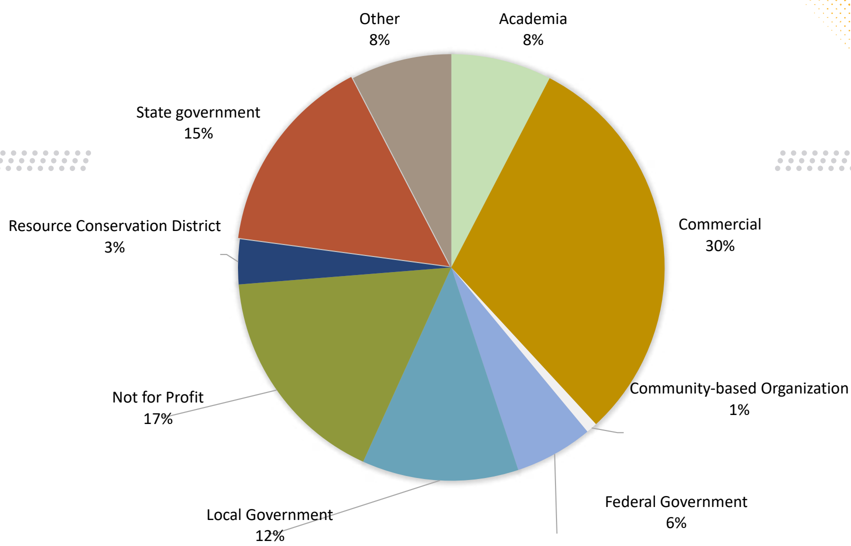


Figure 2: The broad base of users of Sonoma Ag + Open Space program products.
Source: Sonoma County Ag + Open Space Lidar and Veg Map User Survey (2019).

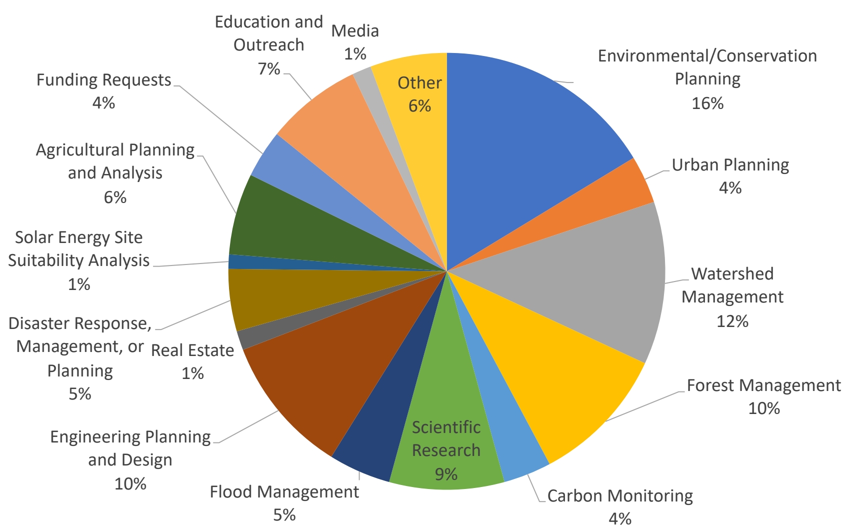


Figure 3: Wide-ranging applications of Sonoma Ag + Open Space program products.
Source: Sonoma County Ag + Open Space Lidar and Veg Map User Survey (2019).

biodiversity protection, agricultural conservation, and watershed health. There was an amplified impact—it felt like 1 + 1 equaled 1000."

Shortly after the ground-breaking Sonoma County fine-scale vegetation map and landscape database products were made public in 2017, One Tam[3] decided to move forward with a similar project, which was initially scoped to include only Marin Municipal Watershed District, National Park Service lands, and county and state park lands in Marin County. However, awareness of the project grew quickly and before long the consortium raised enough funding to map the entire county, with the program managed by the Golden Gate National Parks Conservancy[4]. Soon, interest spread to organizations in San Mateo County, and funds were raised to expand the program to include all of San Mateo County. To date most of the products for this program have been delivered, with the final product—the fine-scale vegetation maps—scheduled for completion in May 2021 for Marin County, and in January 2022 for San Mateo County.

Primarily because of the usefulness of the Sonoma fine-scale data in understanding the behavior of the Sonoma 2017 Complex wildfires, another consortium, the Santa Cruz Mountains Stewardship Network (SCMSN)[5], expressed interest in creating similar fine-scale products for Santa Clara and Santa Cruz Counties. Funding has been raised and that program is well underway.

Lidar data is critical to the creation of most of the fine-scale products being created across the five-county area (**Table 2**). Danny Franco, project manager at the Golden Gate National Parks Conservancy, recently expressed the value of the lidar data to these programs, "Lidar has become a foundational component for planning climate adaptation strategies and environmental conservation at the regional scale because with lidar we can measure, locate, and quantify landscape variables essential to prioritizing and designing projects, as well as tracking change over time. Lidar data and derivative products are the cornerstone of our landscape level strategic planning efforts."

Example applications

Figures 2 and 3 display the results of a survey of users conducted by the Sonoma Ag + Open Space District in 2019 that shows the diversity of users and applications of Sonoma's data sets. This diversity in use and application of program products has extended to the other four counties. Applications of the lidar data in the five-county area include vegetation and wildland fuels mapping, pre-construction site assessments, modelling of flood inundation (**Figure 4**), forest health assessments, landslide and debris

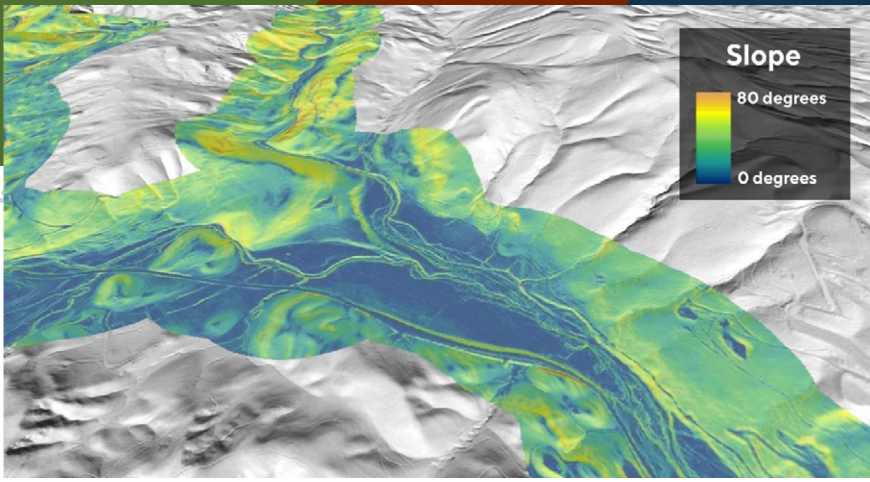


Figure 4: Lidar-derived slope in riparian corridors is used in flood hazard assessments.
Source: Tukman Geospatial.

flow risk analysis, functional riparian corridor mapping (**Figure 5**), bird density modelling, impervious/pervious mapping, prioritizing and planning field work and site assessments, improving the National Hydrological Dataset, wildlife habitat gap analysis, and identification of late seral forest habitats. This section focuses on two applications, vegetation mapping and wildfire risk assessment and response.

Vegetation mapping

Remote sensing analysts make maps by exploiting the relationships between variation on the ground and variation in the data being used to create the map (e.g., imagery, slope, aspect, elevation). Common data elements relied upon include tone/color, shape, size, pattern, shadow, texture, location, context, date, and height. Until the advent of lidar, fine-scale measures of vegetation height were unavailable, or very expensively obtained from stereo imagery. Lidar data provides not only fine-scale measures of vegetation height, but also measures of crown shape, crown density, and canopy base height. Additionally, lidar data can provide high-resolution riparian corridor delineation, and measures of slope, slope position, aspect and elevation—all critical variables that affect vegetation species distribution, and are, therefore, useful in creating a vegetation map. As a result, lidar data supports increased map detail, while also reducing costs and improving map accuracies. "Lidar data allows us to see underneath the canopy and measure the structure of the vegetation and the geomorphology of the landscape," said Mark Tukman of Tukman Geospatial[1], the mapping contractor for the Bay Area programs. "When used to develop independent variables for machine learning, mapping accuracies improve because so many of the lidar variables are significant predictors of vegetation type. In essence, lidar brings the landscape into focus".

1 www.tukmangeospatial.com

Wildfire risk assessment and emergency response

In the late evening hours of October 8, 2017, six separate wildfire events ignited almost simultaneously in California's counties of Sonoma, Mendocino, and Napa. Collectively known as the Wine Country Fires, they were driven by raging northeasterly winds and consumed all types of fuel in their pathways, ranging from cozy suburban enclaves to urban businesses and schools, vineyards, ecological preserves, parks, ranchlands, and forests. When finally contained 20 days later, the fires left 43 people dead, at least 6625 structures destroyed, 90,000 residents displaced and a total of over 198,800 acres burned (**Figure 6**).

Soon after the fires were extinguished, Sonoma Ag + Open Space successfully submitted a proposal for Rapid Response funding from NASA to immediately analyze the impact of the fires on the landscape, and to fully identify the landscape characteristics

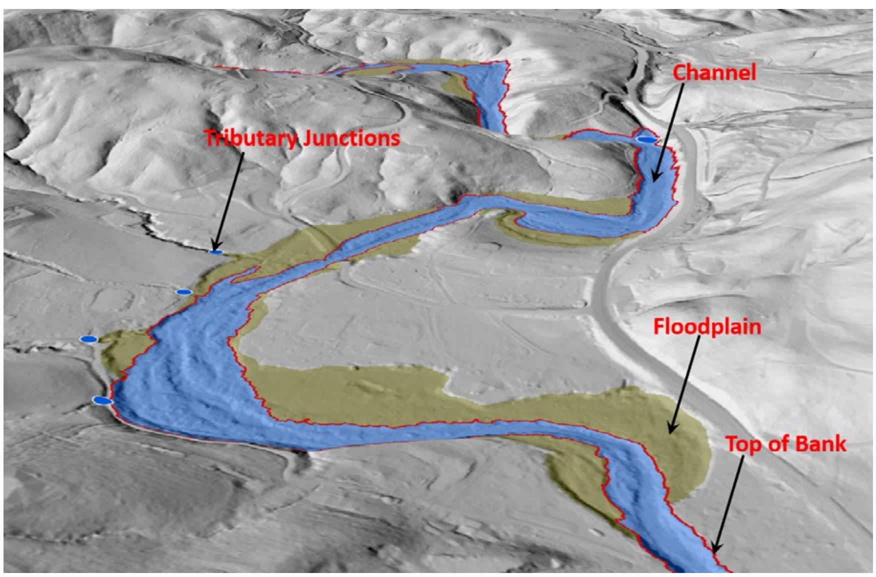
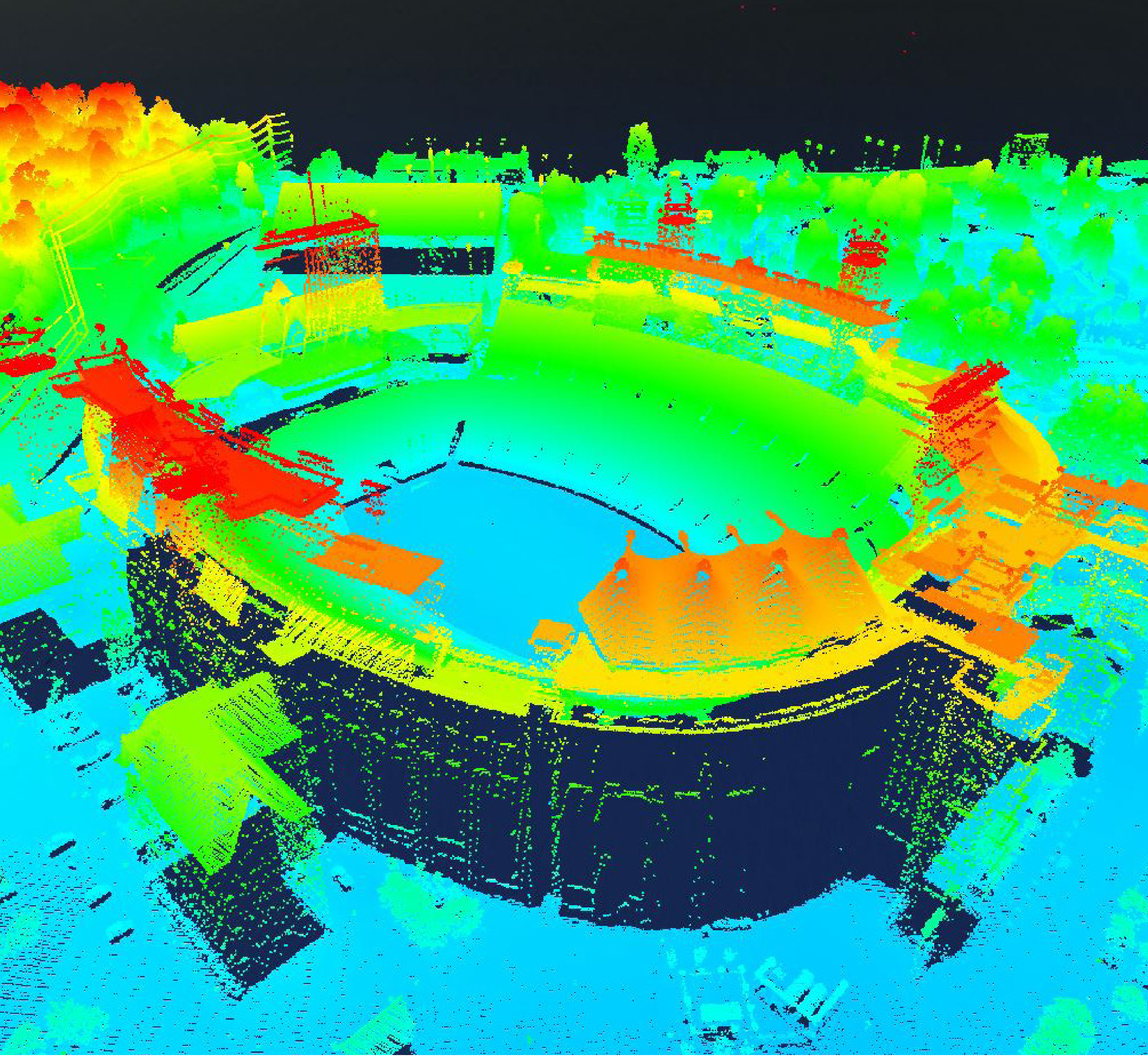


Figure 5: Functional riparian corridor map used in riparian restoration and conservation planning.
Source: Tukman Geospatial.



that contributed to the wide variety of fire behavior. The resulting analysis showed that six variables—ladder fuels[6], canopy density, vegetation type, weather/climate variables, slope, and distance from streams—were the primary drivers of post-fire woody canopy condition following the fires[7]. Incredibly, five of the six variables were created using lidar data. The identification of ladder fuels as an important predictor of wildfire impacts was a major impetus that led each of the three Bay Area programs, plus Napa County, to include maps of wildland fuels and ladder fuels in their wildfire planning and prevention projects. Sonoma, Santa Clara, and Santa Cruz are also moving forward with the development of county-wide Wildfire Risk Indices, also based heavily on lidar products (**Figure 7**).

Lidar products have also been critical in post-fire emergency response. As part of the Santa Clara and Santa Cruz program, SCMSN had QL1 lidar flown for Santa Cruz County in the early summer of 2020 by Quantum Spatial. The point cloud was delivered very shortly before a lightning storm initiated the CZU Complex fires on August 16, 2020. Tukman Geospatial was able to quickly produce a canopy height model, normalized digital surface model, hillshade, and digital terrain model from the Santa Cruz lidar data, which was immediately made available to the public on Midpeninsula Regional Open Space District (a network member) servers. Agency use of the products was widespread and the products were quickly incorporated into the work of Cal Fire and the California Department of Conservation for their CZU Watershed Emergency Response Team (WERT) evaluations of landside and debris flow risk in the burn areas[8] (**Figure 8**). As Rich Sampson, Cal Fire San Mateo and Santa Cruz Division Chief mentioned, "The lidar derived topographic layers delivered in the immediate aftermath of the CZU fire prompted the WERT team to remark that they felt as though their work had finally entered the 21st century."

Figure 6: Wine Country fires threaten agriculture and homes.
Source: Karen Gaffney.

Factors for success

While the genesis and organization of each of the three programs were different, they share common factors which have led to their success, including:

- Standardized map legends. All of the lidar data was produced to USGS 3DEP standards. The California Native Plant Society and the California Department of Fish and Wildlife developed the vegetation classification schemes, descriptions and keys for each of the programs. The fuel models follow the rules and standards established by Scott and Burgan[9] nationwide. As a result, the maps are specific enough to support on-the-ground local management decisions, but also fully synchronized to enable regionwide analysis.
- Coordinated management and technical teams. While each program is overseen by a different umbrella organization, the strategy, fundraising, day-to-day management, and technical teams have remained basically unchanged, allowing for the capture of economies of scale between programs and maintenance of standards across the region.
- Easy access to the products. All of the products are placed in the public domain via intuitive data access tools. As an example, Sonoma Ag + Open Space provides three different methods for users to access their program products. All of them are easy to use and do not require GIS expertise[10]. As a result, product use is considerable.
- Decentralized, diverse, motivated and engaged consortium members who remain committed throughout the program. Some consortium members, like USGS, have been involved in all three programs. Other members are interested in only a specific area within one of the counties. While each program has its own members and emphasis, each program's success is wholly dependent on the alliance that develops between organizations and individuals, who are focused on the common goal of providing foundational fine-scale landscape data sets to support decision-making and resource management over time. Nothing is more important to the success of a program than the commitment of its constituents.
- Finally, the inclusion of lidar data has made the program products

more detailed, precise, accurate, and robust. This has guaranteed their adoption and use. SCMSN manager Dylan Skybrook summarized, “The lidar products are going to guide land management decisions for years to come and provide foundational data upon which collaborative and long-lasting landscape-scale stewardship projects can be built.” ▪

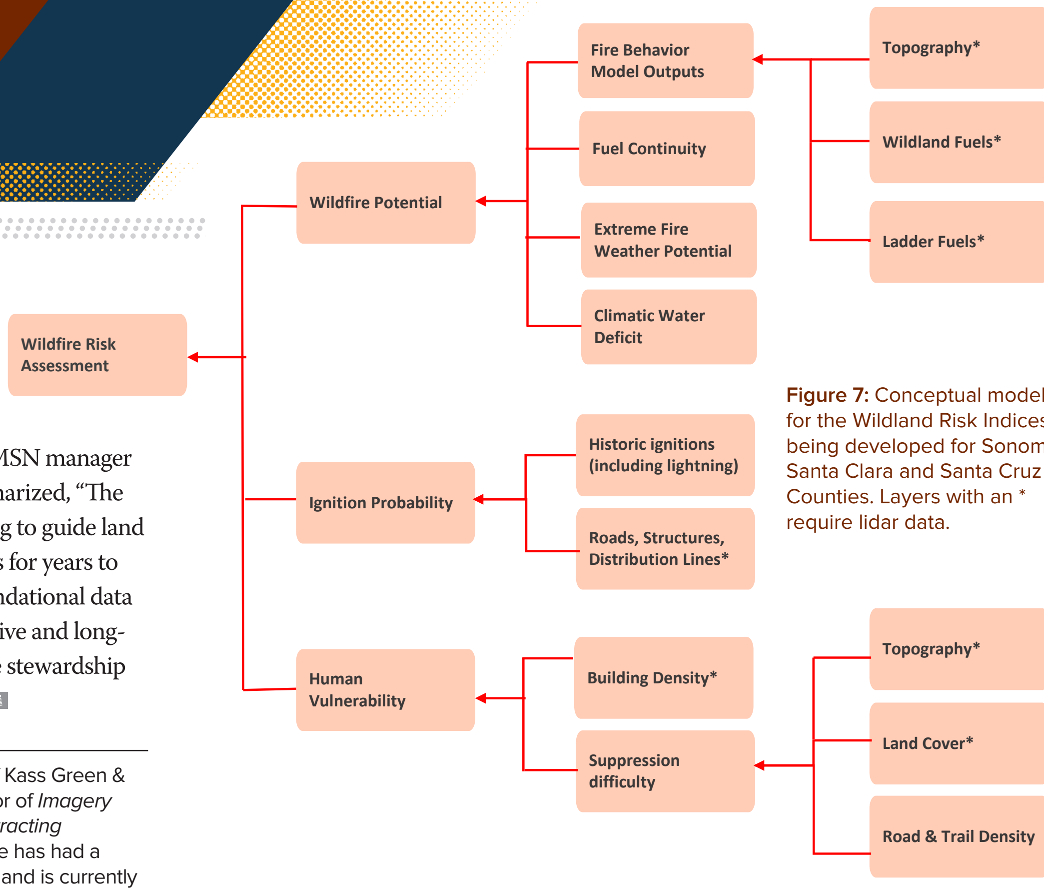


Figure 7: Conceptual model for the Wildland Risk Indices being developed for Sonoma, Santa Clara and Santa Cruz Counties. Layers with an * require lidar data.

Kass Green is the President of Kass Green & Associates, and the lead author of *Imagery and GIS: Best Practices for Extracting Information from Imagery*[11]. She has had a long career in remote sensing and is currently supporting all three of the Bay Area vegetation and landscape database programs.

1 *sonomaopenspace.org*

2 In December 2020, Quantum Spatial changed its name to NV5 Geospatial: further information about the company is available on *quantumspatial.com* and *nv5.com/services/geospatial-technology/*.

3 The One Tam partnership is a collaboration of the National Park Service, California State Parks, The Marin Municipal Water District, Marin County Parks and Golden Gate National Parks Conservancy, focused on ensuring a vibrant future for Marin County’s Mt. Tamalpais: *onetam.org*.

4 *parksconservancy.org*

5 *scmsn.net*

6 Ladder fuels are vegetation (live or dead) below the canopy of a forest that can allow a fire to leap from the ground into the forest canopy. The accumulation of ladder fuels has long been identified as a contributor to fire intensity. The Sonoma research showed lidar-derived ladder fuels were key indicators of wildfire behavior.

7 Green, K., M. Tukman, D. Loudon, A. Schichtel, K. Gaffney and M. Clark, 2020. Sonoma County Complex Fires of 2017: remote sensing data and modeling to support ecosystem and community resiliency, *California Fish and Wildlife Journal*, Fire Special Issue 2020: 14-45.

8 Watershed Emergency Response Team (WERT), 2020. *Watershed Emergency Response Team Evaluation CZU Lightning Complex*, CA-CZU-005205, October 1, 2020, 205 pp.

9 Scott, J.H. and R. E. Burgan, 2005. *Standard Fire Behavior Fuel Models: A Comprehensive Set for Use with Rothermel’s Surface Fire Spread Model*, USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-153, 72 pp.

10 *sonomavegmap.org/data-downloads*

11 Green, K., R. Congalton and M. Tukman, 2017. *Imagery and GIS: Best Practices for Extracting Information from Imagery*, Esri Press, Redlands, California, 418 pp.

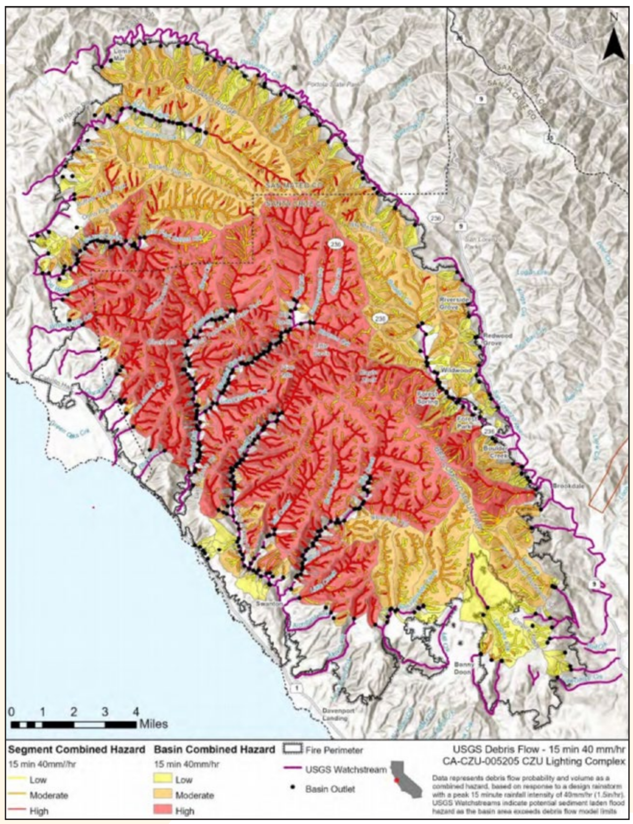
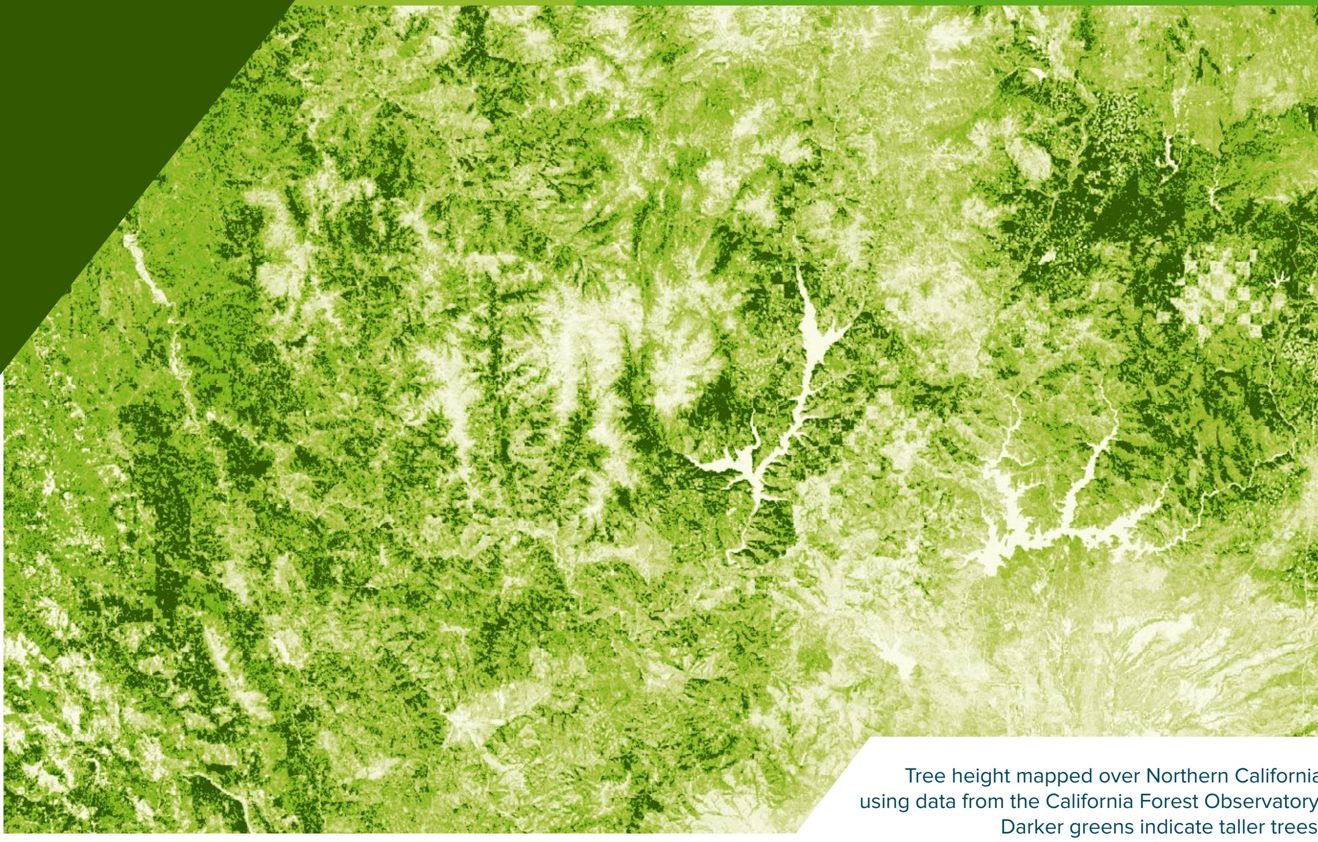


Figure 8: Watershed Emergency Response Team evaluation of CZU Lightning Complex CA-CZU-005205 October 1, 2020.



Tree height mapped over Northern California using data from the California Forest Observatory. Darker greens indicate taller trees.

New Views of California's Forests

Monitoring wildfire hazards with satellites, lidar and AI

I suspect I have a sympathetic audience in these pages when I state that lidar is a premier technology for forest mapping and vegetation management. Building on decades of research and sensor development, new methods for mapping forest carbon dynamics—from terrestrial[1], airborne[2] and spaceborne[3] instruments alike—are helping scientists and governments monitor the stocks and flows of carbon in order to plan climate change mitigation projects. In the private sector, it's also one of several technology platforms behind the precision forestry revolution[4], driving efficiency gains throughout the timber sector supply chain. And, living up to its reputation as a swiss-army-knife technology, lidar is increasingly being deployed to map the vegetation fuel loads that drive wildfire behavior.

Vegetation interacts with light in many ways—absorbing some for

1 https://besjournals.onlinelibrary.wiley.com/doi/full/10.1111/2041-210X.12301

2 https://lidarmag.com/2014/03/25/lidar-drone-system-maps-height-of-rainforest-for-the-first-time/

3 https://gedi.umd.edu/

4 https://www.mckinsey.com/industries/paper-forest-products-and-packaging/our-insights/precision-forestry-a-revolution-in-the-woods#

BY CHRISTOPHER ANDERSON

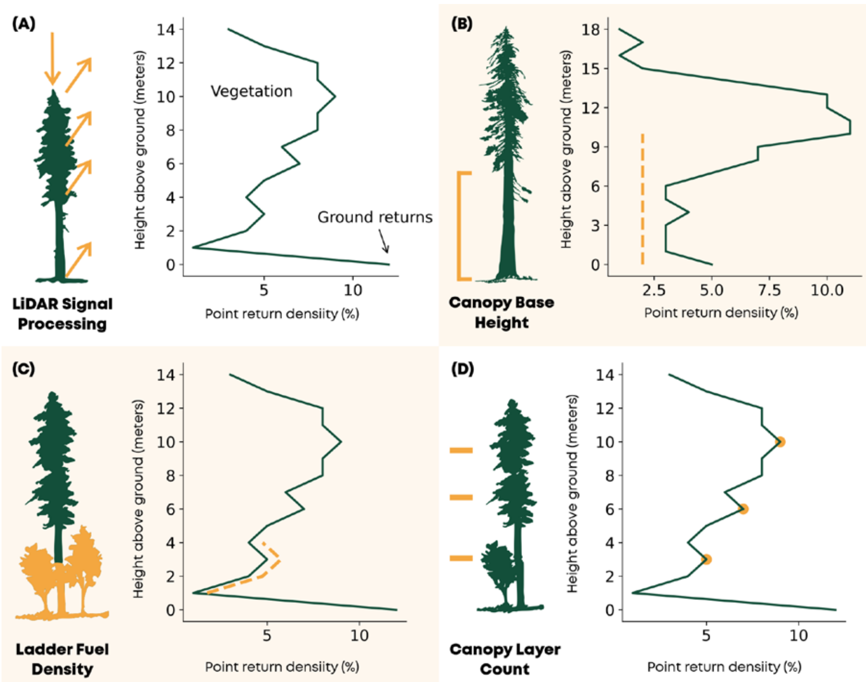


Figure 1: (A) Vegetation fuel metrics can be derived by analyzing lidar pseudo-waveforms. Some examples include (B) canopy base height, the distance between the ground and the lowest canopy layer, (C) ladder fuel density, the proportion of short vegetation fuels and (D) canopy layer count, an estimate of the number of unique vertical canopy layers.

photosynthesis, reflecting some as photoprotection, and transmitting the rest to the understory—and these interactions change across wavelengths. At the wavelength of infrared energy emitted by many lidar scanners (1064 nanometers), leaves reflect and transmit light in a nearly 50/50 split, absorbing little to no energy. This means that, from airborne platforms, lidar pulses can transmit through dense forest canopies and measure energy reflected from mid-canopy branches, understory plants and the forest floor, constructing rich, 3D measurements of canopy vertical structure. This is often done by converting discrete return data into pseudo-waveforms (**Figure 1**). Pseudo-waveforms group all the points along vertical intervals within a voxel (a 3D volumetric pixel) and normalize by the density of points to construct a dataset that approximates raw lidar waveforms.

This ability to measure sub-canopy structure patterns is important for fuel mapping. The size of a canopy can be used to estimate the volume of fuel that could be consumed in a crown fire. The spatial distribution of tall and short trees across a landscape can slow bursts of wind as gusts fan the flames. The amount of understory vegetation can predict the likelihood that a surface fire transitions into a crown fire. As the frequency and intensity of wildfires is increasing, especially in seasonally arid landscapes like California, it is becoming more and more important to develop precise and dynamic maps of fuel distributions to predict which areas are at risk and how risk changes over time. Lidar plays a central role here, but its utility is limited by two operational constraints.

Limits in space and time

The first constraint is that lidar coverage is spatially limited, either by extent or by point spacing. Terrestrial and airborne systems are deployed to map specific areas—like cities, watersheds or landscapes—but comprehensively mapping large areas like states tends to be a major

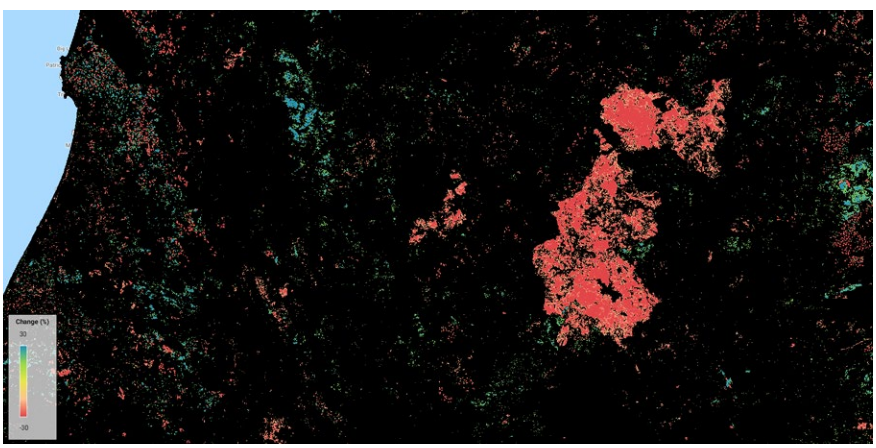


Figure 2: Canopy cover change patterns from 2016 to 2020, mapped at the scale of the individual tree. Canopy loss is mapped in warm colors, and canopy growth in cool ones. The large fire extent is from the Carr Fire of 2018.

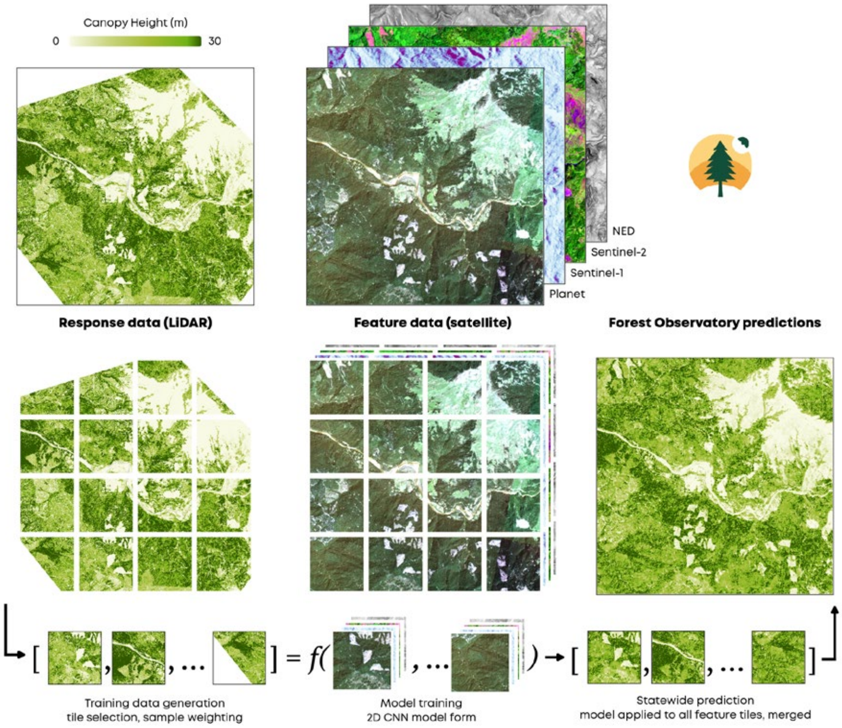


Figure 3: The Forest Observatory workflow. Airborne lidar data is processed to metrics of forest structure and fuel loads. This data is co-aligned with satellite imagery and used to train AI algorithms. The model is then applied to every feature data tile to predict fuels across the state.

logistical challenge. Spaceborne sensors on the other hand, like GEDI (the Global Ecosystem Dynamics Investigation), can provide nearly comprehensive spatial coverage, but through point sampling. GEDI's 30 m diameter large-footprint measurements have approximately 600 m of cross-track spacing, creating large data gaps between points.

It's important to comprehensively characterize the fuel patterns that drive fire behavior, because wildfires are growing in size and intensity as the climate gets warmer and drier. This means that fires often spread beyond the extents of publicly-available lidar datasets. Among the 2020 California wildfires[5], for example, were ten separate fires that grew to more than 100,000 acres each, including the million-acre August Complex fires.

The second constraint is that it's expensive to collect repeat observations to characterize change over time (**Figure 2**). As its name implies, fire season comes and goes with each year, and the areas most likely to burn change based on where the weather is driest, how much fuel has accumulated, and the amount of time that has passed since the last fire. I mention this as a reminder that wildfire is a dynamic process, and that patterns of pyrogeography are bound to change as the environment does.

The need for rapid-refresh data isn't as common in other earth sciences domains where lidar is frequently used. With the exceptions of landslides or subsidence due to groundwater depletion, most terrain models can be expected to remain fairly static. But the need is clear in the context of fuels monitoring. Ecosystems are rapidly changing in response to climatic shifts like droughts and floods, resource-extraction activities like timber harvests, land-use changes like farming and cattle grazing, ecological growth and species turnover. These effects all interact to create a patchwork mosaic of change in vegetation communities, shifting where we expect fires to occur each year.

Other satellite data sources, such as multispectral and synthetic aperture radar sensors, are not subject to these same problems. They complement lidar by providing repeat and spatially comprehensive measurements around the world. These instruments are sensitive to patterns of ecosystem structure, like tree height and forest type, and to patterns of ecosystem function, like vegetation growth rates and water use. But satellite data are subject to other pitfalls. While these instruments are sensitive to vegetation patterns, there are very few well-established methods for directly retrieving quantitative fuel estimates. There are problems with cloud cover and of measurement consistency, which can change throughout the year with sun and sensor positions and with vegetation phenology. And, critically, they don't get to claim the benefit of laser precision.

To address these problems, we at Salo Sciences built the Forest Observatory[6], a forest monitoring system that combines airborne lidar and global satellite data to map vegetation fuels continuously over large scales, starting in California. This system trains deep learning algorithms, a form of pattern recognition AI, using airborne lidar to identify fuel patterns in satellite imagery. The fuel metrics

5 https://www.fire.ca.gov/incidents/2020/

6 https://forestobservatory.com/tour

derived from airborne lidar serve as labeled "ground truth" data, and the algorithms learn to identify those patterns using the spatial and spectral features of the satellite data. It's like facial recognition for forests. Once trained, this model can be applied to new satellite imagery to map changes in fuels over time. This enables characterizing the drivers of wildfire behavior in fine detail at large scales, providing up-to-date information on fuels and hazard. The workflow is summarized in **Figure 3**.

As a conservation technology company, Salo Sciences strives to accelerate the pace and scale of investments in natural climate solutions—conserving, restoring and improving stewardship in ecosystems—by using technology to identify conservation opportunities, monitor ecosystem health and predict environmental change. Wildfire is a major source of land-based carbon emissions, especially in California, and it's an important driver of environmental change. With new and incredibly detailed data on vegetation fuels, forest structure and wildfire hazards, we see a tremendous array of opportunities to use the Forest Observatory to reduce both risk and emissions while increasing social and ecological resilience.

Starting good fires, stopping bad ones

The design and development goals for the Forest Observatory included building a system that would support efforts to start more good fires and reduce the number of bad ones. Let me clarify the distinction.

Fire is an essential ecosystem process. Heat and smoke can spur seed germination for many fire-adapted species, and fire promotes nutrient cycling at much faster rates than natural decomposition. This is especially important in Mediterranean climates where rainfall and warm temperatures—which jointly promote decomposition—occur at different times of year. Regular, low-intensity surface fires can also thin or clear understory vegetation, reducing the likelihood of initiating high-intensity crown fires. Some ecosystems have adapted to fire return intervals as short as five to ten years, meaning that fire would return to each part of the landscape at least once per decade.

Fire is also an essential cultural process. Indigenous cultures regularly use fire[7] as a means to sustain and harvest natural resources, as well as promote healthy ecosystem function. Elizabeth Azzuz, a member of the Yurok Tribe, summarized[8] that, "We rely on fire to maintain our basketry materials, medicinal plants, acorn trees and hunting grounds." By intentionally burning landscapes at the same frequency as their fire return interval, groups like the Yurok and Karuk would reduce the risk of pest and pathogen infestation to the resources they use and depend on, as well as to reduce the likelihood of high-intensity fires.

It's also an important cultural symbol for contemporary urban culture. Books like *Earthquakes Mudslides Fires & Riots*[9], a review of the history of graphic design in California, demonstrate how symbols of fire, experiences of fire and shared stories of loss all contribute to our perception of what it means to live in this state. These perceptions are then represented and codified in the unique styles of California visual designers, subtly shifting the standard color palettes of pop art towards oranges, reds and dark yellows. I suspect the images of apocalyptic orange skies from this past

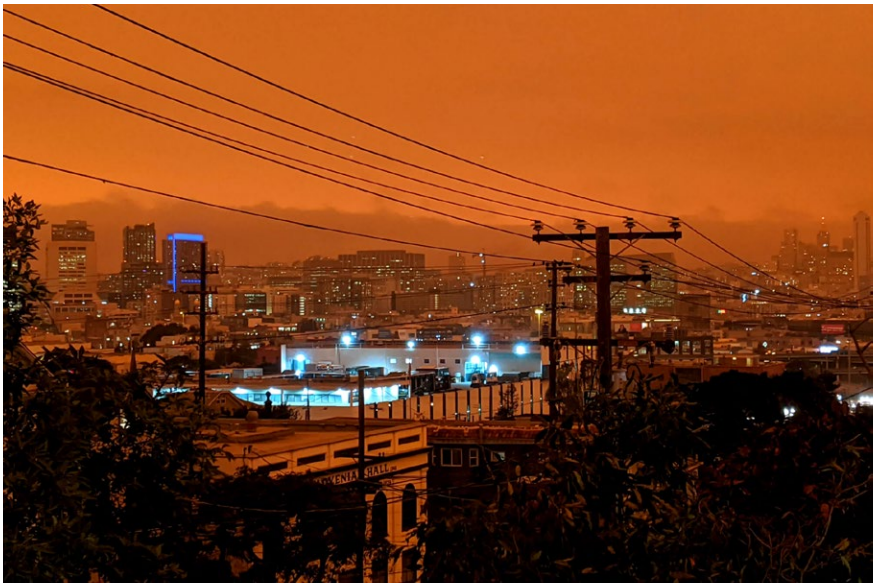


Figure 4: The sight of orange, smoke-filled skies in California from the 2020 wildfire season is something many people will never forget.

7 https://www.sciencedirect.com/science/article/pii/S0378112719306826
8 https://mronline.org/2020/10/23/indigenous-solutions-to-californias-capitalist-conflagrations/
9 https://www.artbook.com/9781938922619.html

Figure 5: A complex matrix of burned and unburned areas, leading to either regeneration or continuation, arrayed across the Los Padres National Forest.

wildfire season will further define what we expect the future of our state to look like (**Figure 4**).

Prescribed fire, as applied in forest management contexts, is one of the most effective tools for wildfire hazard reduction, and many hope it will be deployed at scale in the coming years. By intentionally starting fires during favorable weather conditions and guiding the path of a fire across the landscape, forest managers emulate natural ecosystem processes and indigenous burn practices to clear brush and reduce hazards.

The benefits of prescribed fire are analogous to the benefits of "flattening the curve" with covid-19. With covid, it's beneficial to slow the rate of transmission so that the health care system can accommodate a steady number of patients with severe symptoms and provide them with adequate care. Rapid transmission instead overloads the healthcare system so some patients aren't able to receive the care they need. This means that, even if the total number of cases were the same between slow and rapid transmission scenarios, the overall health costs would be lower with slow transmission. With fire, if you burn the same amount of area in a controlled fashion over a longer period of time, the amount of smoke produced is distributed over space and over time. Intense fires, however, overload the atmosphere's ability to diffuse harmful particles, creating disproportionately negative health consequences. Prescribed fires limit toxic smoke exposure and reduce severe respiratory illness rates compared to high intensity wildfires.

The examples above are mostly examples of "good fires" that have beneficial ecological effects (**Figure 5**). The deployment of good fire at the scale required—the state set a target of five hundred thousand acres per year in addition to US Forest Service targets—is limited in part by a lack of planning and forecasting tools. With high-resolution data on current fuel distributions, as well as current and forecasted weather trends, burn teams should be able to create more precise simulations for how a prescribed fire will burn and reduce the uncertainty that it will escape control—two key limitations. The Forest Observatory was designed to make it easier to start more good fires as a means to reduce wildfire hazards at large scales—and, as mentioned above, to reduce the number of bad fires.

Some fires, on the other hand, have strictly negative consequences with no beneficial social or environmental impact. These mostly start in populated areas, on roadsides or as a result of electrical equipment failures, which then spread through communities, disrupt lives, and damage homes and other property. One high-profile—but relatively infrequent—source of these fires includes ignitions that start from utilities infrastructure. The 2018 Camp Fire is a tragic example of such an event. Started by the failure of a Pacific Gas & Electric transmission line hook[10], the fire was carried by high winds through the city of Paradise, devastating the community and killing 85 people. Wildfires started by utilities infrastructure have earned attention and ire from regulators, courts and the public alike over the past 15 years: this can be traced back to the 2007 Malibu Canyon fire, the result of a pole failure[11] on Southern California Edison's distribution grid.

Though the examples above were driven by equipment failures during extreme weather events, the majority of such ignitions are caused by vegetation contact, according to data from the Public Utilities Commission[12]. These ignitions only occasionally result in high

10 https://www.sfchronicle.com/california-wildfires/article/Attorneys-say-this-photo-shows-the-PG-E-hook-that-14882924.php
11 https://www.latimes.com/local/la-xpm-2013-may-21-la-me-0521-malibu-fire-settlement-20130521-story.html
12 https://www.cpuc.ca.gov/fireincidentsdata/

profile fires, but you could understand why utilities now need to do everything in their power to reduce the likelihood of a failure that would lead to catastrophe. And as covered by this magazine[13], lidar has a key role to play.

Cost-effective solutions for utility-strike tree analysis

Utilities have become an important consumer of terrestrial and airborne lidar data, which provides value to multiple business verticals. These measurements provide precise information on transmission and distribution assets, including wires, towers and poles, and can also be analyzed to quantify line sag and the locations of overhanging trees. These datasets support the information needs of asset management, vegetation management and risk analytics teams alike.

As noted at the beginning of this article, terrestrial and airborne lidar can be expensive to collect over large areas. It's challenging to navigate collection platforms along the complex, irregularly shaped networks that make up distribution grids, which range from thousands to hundreds of thousands of line miles depending on the utility, leading to long lead times on data acquisition and processing. A one-time investment in data collection is sufficient for many assets, as towers, poles and wires remain stationary. But what of the patterns that change? The locations of most assets haven't changed in the past 50 years—why have their risk profiles?

Vegetation management and risk analytics teams appear to be among the most interested in mapping change over time. Vegetation encroachment continues throughout the year, shifting priorities for where to trim and remove trees each year, and analysts are eager to quantify the value of these and other risk reduction activities over time. Satellite-derived estimates of vegetation growth and encroachment can complement lidar data by mapping change over time, albeit with lower precision. As new imagery is collected and processed, satellite-based monitoring systems can provide up-to-date vegetation data, quantifying shifts in encroachment and risk over time.

PG&E has emerged as a leader in adopting new technologies in this space, developing and publishing a 1,000+ page wildfire mitigation plan[14] detailing its risk reduction activities for 2021. It uses both lidar and satellite-derived datasets to support its vegetation management plans and risk reduction efforts. These datasets, along with other environmental and asset health information, are used to predict both the probabilities and consequences of ignitions across their grid, and are a part of a broader effort to adopt a suite of next-generation technology systems. These efforts are designed to reduce systemic risks to PG&E's infrastructure and the communities it serves, limiting its liability and ensuring price stability for customers.

The mitigation plans, while ambitious now, are a direct response to prior negligence, litigation and regulation following several tragedies for which PG&E was responsible as a result of mismanagement. I won't argue that the current settlements provide sufficient restorative justice[15] to the victims of these tragedies, but I do believe that the mechanisms of accountability—the courts, regulators and the many smart and thoughtful individuals within the organization—are promoting safer, more stable, and more risk-conscious operations inside PG&E. I suspect the PG&E example will provide an opportunity for other utilities to anticipate—rather than react to—the shifting landscape of risk.

As the climate warms, as utility infrastructure ages and as vegetation fuels accumulate, I expect the demand for new technologies that identify, monitor and predict systemic risks will grow, and many of the readers of this magazine will be responsible for developing and deploying these technologies at scale. I look forward to the opportunity to work together to start more good fires, and reduce the number of bad ones.

Disclosure: *Salo Sciences is a data provider and analytics contractor to PG&E, and is named in its 2021 wildfire mitigation plan.*

Christopher Anderson is co-founder and CTO of Salo Sciences[16], a conservation technology company, and a researcher at the Center for Conservation Biology[17] at Stanford University. He recently received his PhD in biology at Stanford University. He previously worked at the Carnegie Institution for Science in the Department of Global Ecology as a part of the crew of the Carnegie Airborne Observatory, an airborne lidar and imaging spectroscopy platform. You can read more on his personal website[18].

13 https://lidarmag.com/2013/03/23/integrating-lidar-with-wildfire-risk-analysis-for-electric-utilities/

14 https://www.pge.com/pge_global/common/pdfs/safety/emergency-preparedness/natural-disaster/wildfires/wildfire-mitigation-plan/2021-Wildfire-Safety-Plan.pdf

15 https://www.forbes.com/sites/morgansimon/2020/07/27/we-treat-corporations-like-people-except-when-it-comes-to-punishment/?sh=64fdd31f2748

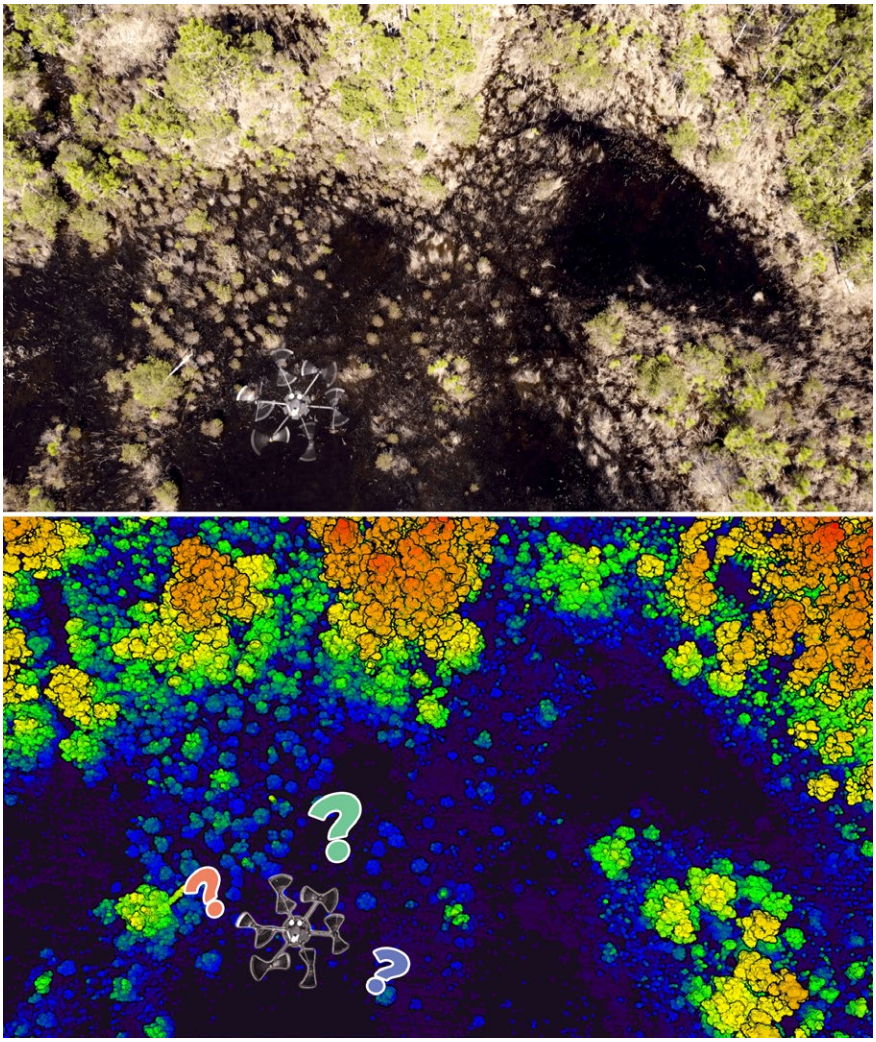
16 https://salo.ai/

17 https://ccb.stanford.edu/

18 https://cbanderson.info

A Rewarding Pyramid Scheme

Portable and accurate UAS lidar targets



The lack of primitive surfaces in natural scenes presents a challenge for adjusting and validating UAS lidar data. Researchers at the University of Florida have found a unique solution.

Researchers at the University of Florida have been working with UAS lidar for several years. This includes low-level investigation into the sensor and platform technology as well as collaborative projects with a variety of scientists and managers including those involved in wildlife biology, forestry, and ecology. We have collected point clouds in areas from dense forests to sandy beaches, almost always in some rural locale away from buildings, roads, and other convenient, regular structures that facilitate processing and validation. Early on, we ran into the problem of identifying discrete locations in these point clouds to perform adjustment, *in situ* calibration, and accuracy assessment. Like many other users, we first explored using flat targets, relying on intensity to find them in the point cloud. The inconsistency of intensity values from the systems, however, made it difficult to discriminate the targets from the background, particularly in natural scenes. We found that precisely identifying the horizontal reference point of these flat targets, usually the center, was also difficult, depending on the distribution of points that fell on it.

To address this, we developed a "geometric" UAS lidar target. The target is a

BY BEN **WILKINSON** AND H. ANDREW **LASSITER**

Figure 1: The targets deployed at various locations.

trilateral pyramid, i.e. the base is a triangle, and the intersection of the three planes that slope upwards from the base serves as the reference point, allowing for precise determination of both the horizontal and vertical components of locations within the point cloud (**Figure 1**). The base of the pyramid has sides about one meter long and the structure measures about 40 cm from base to tip. With the help of a local artist who specializes in foldable, morphing installations, the target was designed to fold flat for storage and transport. Since it is made of corrugated plastic, it is light, and about twenty can be carried by a single crew member.

Geometric targets for lidar are not a new idea. Practitioners have used spheres, cylinders, elevated reflector arrays and other designs—many can recall Dr. Toth's trampolines. Similarly, using the intersection of planes to measure 3D locations within a point cloud is also a well explored idea, exemplified by the excellent work of USGS on using these features for accuracy assessment. Here we outline our approach for automatic measurement of the pyramidal UAS lidar targets.

Methodology

The target measurement method is template-based. In other words, the planes of the target are not pre-identified or solved and intersected initially. Since the shape of the target is known, an iterative least-squares solution is used to fit a 3D template to the points in the neighborhood of the target in the point cloud. This works by minimizing the sum of the squares of the distances of candidate points to their (iteratively selected) closest facet. The major steps of the algorithm are the following:

1. Coarsely identify and isolate points on the targets

Begin with a small section of the point cloud which fully contains the target (**Figure 2**). Because the algorithm will automatically cull non-target points, one can be aggressive in choosing these candidate sections: careful snipping is unnecessary. The only requirement is that the highest point in the snip should be near the target apex.

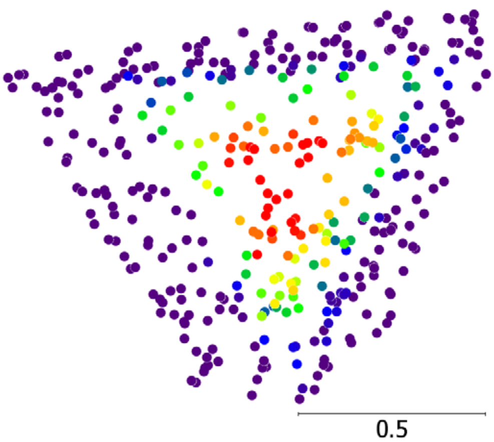
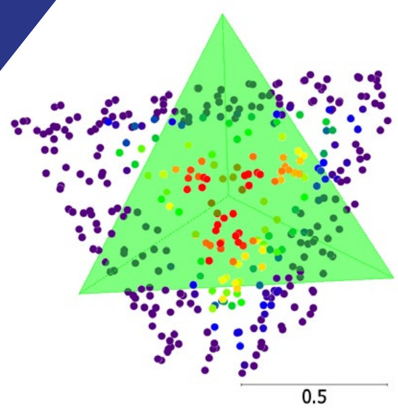


Figure 2: Coarsely identified candidate target points in the vicinity of the target. Scale bar in meters.



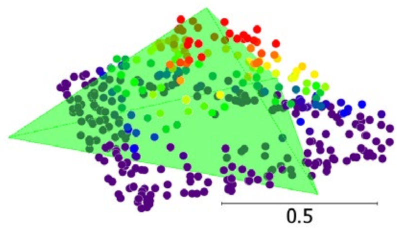


Figure 3: Top and side view of automatically initialized template/reference point location. Scale bars in meters.

2. Initialize the target reference location

The top of the pyramid template is initialized at the highest of the candidate points, the base is initialized as level, and the azimuth can be arbitrarily initialized and still lead to convergence (we always initially align one edge in the east-west direction). See **Figure 3**.

3. Iterative least-squares solution

An iterative least-squares solution is used to solve for the 3D angular orientation and position of the target template within the point cloud (**Figure 4**). Each iteration requires recalculation of point-facet associations, since the template can move quite a bit from the initial position. Rejected points are excluded from the observation equations.

4. Determine target position from least-squares solution

Recall that the reference point of the pyramid—its top—was initially set to the highest point among our candidate points from the initial snip. The least-squares solution solves for the translation of that initial point (the rotation from its initial orientation is also part of the solution). Applying that translation gives us the estimated coordinates of the reference point in the point cloud.

5. (Optional) resolve the reference point by solving for the three planes and their intersection point.

With a solution for the measured pyramid in hand, we can determine which face of the pyramid each point belongs to. As a further check on our work, we can fit a new plane to each of the three groups of points and solve for the intersection of the three planes. This solution should be close to the results of step 4, and can serve as a check on the solution.

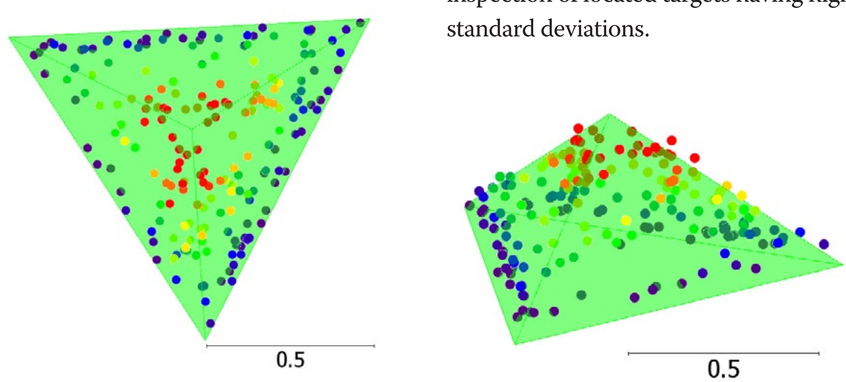


Figure 4: The solved template location. The reference point location is the peak of the pyramid. Note that non-target points have been automatically removed. Scale bars in meters.

Precision of the results

A benefit of using a least-squares approach to resolving the reference point is that the estimated uncertainty of its location can be derived. The uncertainty is closely linked with the number of points incident on the target. Experiments indicate that for typical, easily obtainable point densities >100 pts/m^2, the reference point can be found with an estimated uncertainty of $\sigma = 1$ cm for X, Y, and Z. This was corroborated with experiments where the targets were field-measured using PPK GNSS with the same base-station as that used to process the trajectory of the lidar UAS. It should be mentioned that these results are under ideal circumstances, and various mission parameters can influence the results, including flying height and scan angle, and similarly these estimated uncertainties should not be conflated with absolute accuracy of the point cloud, which is likely much poorer. Experiments have also shown that point distribution, for example only a few points falling on one of the target facets, does not substantially hinder measurement. Along the same lines, the effect of the distribution of points is reflected well in the estimated uncertainty, prompting manual inspection of located targets having high standard deviations.

Issues to be considered

Using the targets for many field collects has led to the discovery of some potential issues and development of mitigation strategies. For example, in high wind, the targets can become airborne due to their shape and light weight. Since they are made of plastic, it is easy enough to stake them to the ground, as long as care is taken not to warp any of the facets. Another potential issue is that very low-density UAS point clouds may lead to bias in the height component. This is typically not a problem, unless the target is under canopy or at the project edge. One solution is to constrain the tilt of the template in the estimation algorithm, holding it fixed as level, but this can be done only if the ground is relatively flat and level. Another major consideration is that the shape of the targets theoretically weakens resolution of the height component compared to flat targets. A solution to this when using the targets as checkpoints is placing a flat target next to the base of the pyramid, say on the west side, for height measurement or as a check on the height of the 3D pyramid target.

Use of the targets

The targets can be and have been used in accuracy assessment, calibration, adjustment, and as control points. Depending on the goals and requirements of an accuracy assessment, the targets can be surveyed using a level and total station, or by using GNSS. The 3D-printed cap for the pyramids, designed by Connor Bass, an MS student at the University of Florida's Geospatial Mapping and Applications Lab, and shown in **Figure 1**, may be used to precisely place a GNSS antenna directly over the reference point. For strip adjustment or boresight calibration, several targets may be placed in an array so that they are covered from multiple flight lines, at varied locations within swaths, and from diverse perspectives. The point clouds may then be adjusted in one of two ways based on the density of the point cloud. Since the algorithm automatically identifies points that fall on the pyramid, they may be isolated from the rest of the points in the point cloud. The adjustable parameters, e.g., the strip transformation parameters or boresight calibration parameters, may then be estimated by finding those that minimize the sum of the squares of the distances to the template facets. The template parameters may also be included in the unknown parameters using this method. In the case of sufficiently dense point coverage, another method is to separate target points into flight lines or collection units and find the adjustable parameters using optimization based on the iterative closest point algorithm.

> "The ability to locate discrete features, particularly in remote rural locations, helps to ensure accurate and reliable products."

Conclusion

The pyramid targets described here have been a successful addition to our fieldwork and processing/analysis workflow. The ability to locate discrete features, particularly in remote rural locations, helps to ensure accurate and reliable final products along with an avenue to precisely check the data. The simple design can and has been replicated by others, and the mensuration algorithm is similarly simple and includes uncertainty estimates to inform the proper use of the coordinates.

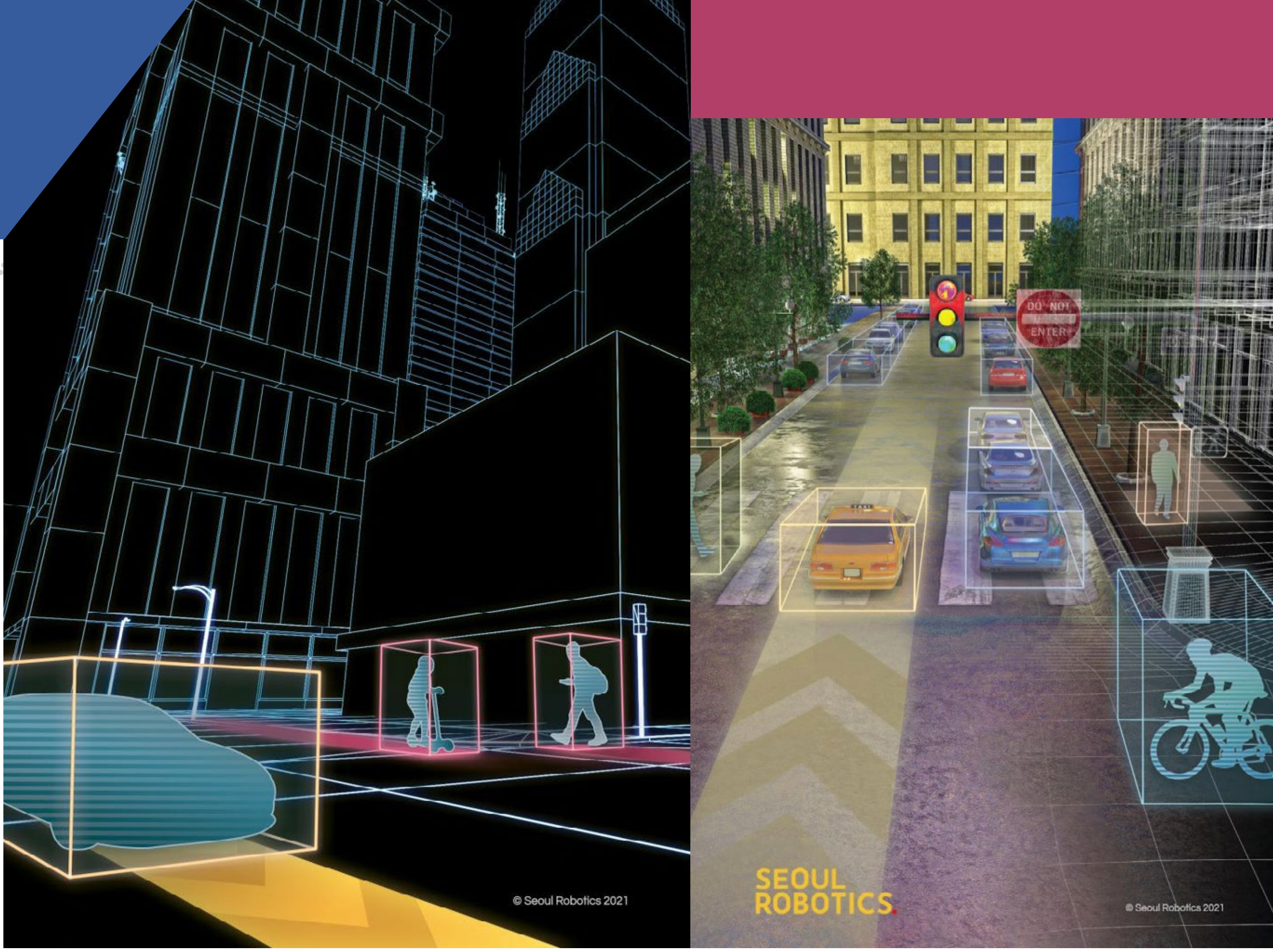
For more information on the targets, including a more detailed look into the algorithm and experiments validating the uncertainty estimates and point distribution requirements, please see the journal article below.

Reference

Wilkinson, B., H.A. Lassiter, A. Abd-Elrahman, R.R. Carthy, P. Ifju, E. Broadbent and N. Grimes, 2019. Geometric targets for UAS lidar, *Remote Sensing,* 11(24): 3019. 20 pp.

Dr. Ben Wilkinson is an Associate Professor at the University of Florida's Geomatics Program and co-director of the Geospatial Mapping and Applications Lab (GMAP). His research focuses on photogrammetry, lidar, and UAS.

Dr. H. Andrew Lassiter is a postdoctoral associate in GMAP. His most recent work includes sensor modeling for optimizing UAS lidar and photogrammetric data acquisition.



Illustrations from Seoul Robotics depicting the classification capabilities of its SENSR software.

Seoul Robotics Makes Lidar Discovery

HanBin Lee, founder and CEO of Seoul Robotics

Perception software for multiple sensors from Korean start-up

On 7 January 2021, Seoul Robotics, a Korean start-up, created a stir when it launched Discovery, a first-of-its-kind "plug and play" product in the lidar space. It consists of both hardware and software, but its heart is SENSR, Smart 3D perception Engine by Seoul Robotics, for tracking vehicles and people. We wanted to know more and put some questions to Seoul Robotics CEO, HanBin Lee (HL), who likes to style himself "Capt'n".

LM: First of all, tell us about SENSR. It's software, but what does it do? You describe it as "sensor-agnostic perception software". Do any of the lidar sensor manufacturers offer software like this for their own sensors?

BY STEWART **WALKER**

The hardware and firmware unit of the Discovery product.

HL: SENSR is really the backbone of Seoul Robotics. It is our proprietary perception software that uses machine learning to analyze and understand 3D data to support a range of functions from basic tracking and monitoring to autonomous mobility. It's incredibly accurate even while operating at a very high processing speed. The unique feature about SENSR is that it is sensor-agnostic and is compatible with more than 70 different types and models of 3D sensors. Any time a new lidar or 3D sensor is released to the market, we train the software for the new sensor. This has been a huge advantage for our partners, as they are able to select the type of sensor that best works for the application they need.

For many years, perception software for lidar sensors was being made in-house at self-driving car companies. It is a massive undertaking to develop and many people outside the AV industry just didn't have the resources to dedicate to building their own software. What we're trying to do at Seoul Robotics is bring lidar technology to the masses and show the world how versatile the technology can really be.

LM: We'll come back to SENSR soon, but next please tell us about Seoul Robotics. What is the company's history; how big is it; how is it funded; does it have offices in addition to the Seoul headquarters; what other products does it offer?

HL: My co-founders and I met online while taking a course on machine learning from Udacity. We were running a company remotely even before it was the norm! We actually didn't all meet in person until a year after we founded Seoul Robotics.

Each of us has a background in 3D data processing and we were interested in learning more about developing AI and machine learning systems. In 2017 we teamed up for a competition held by Udacity to develop a software system for self-driving cars. At the time, many people were using other sensor modalities—camera, radar and lidar—but we challenged ourselves to see what we could do if we relied on data only from lidar sensors. We ended up coming in 10^{th} place out of more than 2000 teams, which really validated the application of applying machine learning to lidar for mobility.

This type of AI-integrated lidar software was really available only for the self-driving market, but as the price of lidar sensors has continued to drop over the last several years, we saw an opportunity to bring this technology to additional markets. Seoul Robotics has become a bridge between lidar manufacturers and companies and organizations that can benefit from having more insight from 3D data.

It's been a busy few years! In 2019, we raised $5M, and we've been quietly expanding operations and partnerships around the globe. Our team of 30 is growing, and we've got offices in Seoul, Silicon Valley, Munich, and Detroit. Currently, we are funded by global financial institutions in South Korea, Hong Kong, and Australia.

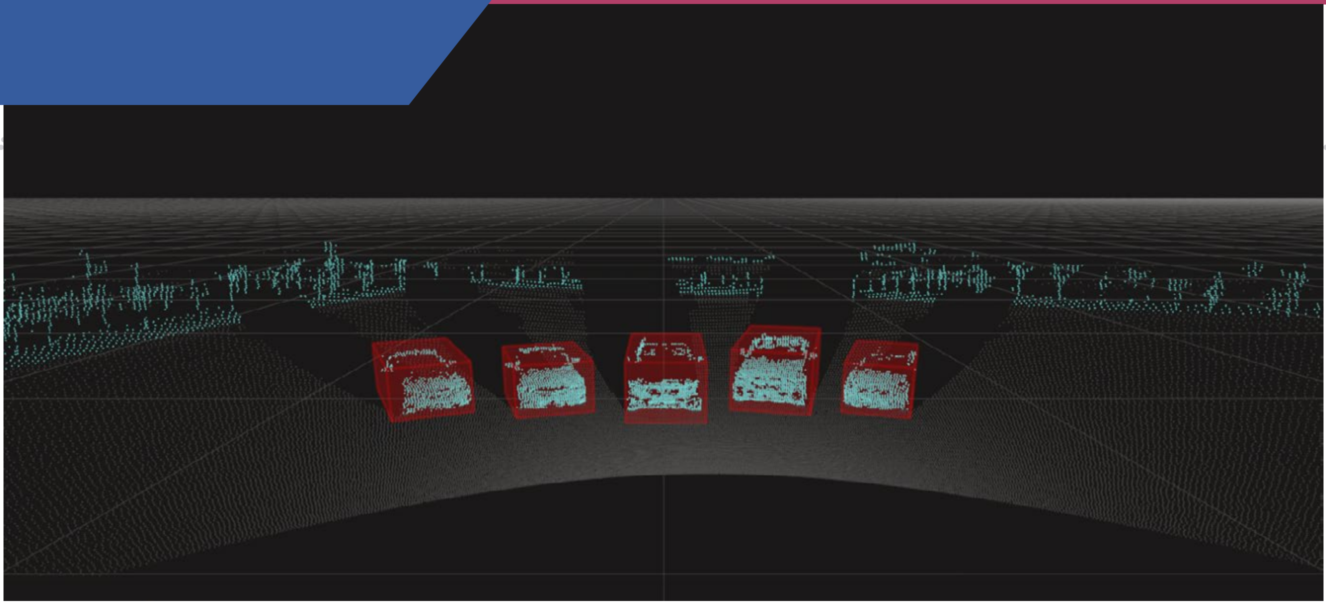
In addition to SENSR, we recently launched Discovery, which is an all-in-one sensor and software system—the first-of-its-kind lidar processing unit (LPU). Our goal with Discovery is to simplify the lidar experience and lower the barrier to entry for companies looking to implement 3D data insights into their systems and processes. It used to take up to two years if you wanted to deploy a lidar-powered application for a specific need. We know this from experience! Now, with Discovery, we can reduce this to just a few minutes. Discovery is truly "plug and play" and quickly turns any lidar sensor into an IoT device. We send everything you need—software and hardware—to quickly set-up and begin benefitting from lidar-based solutions[1].

LM: What about yourself? Tell us a little bit about yourself and the path you followed in order to take the helm at Seoul Robotics.

HL: I went to Penn State[2], where I was briefly exposed to CFD (computational fluid dynamics), which is essentially

1 Both SENSR and Discovery are described in detail on the firm's website, www.seoulrobotics.org, but the operation of the products is easier to understand through its YouTube channel, https://www.youtube.com/channel/UCcfXs-yXfkN3VfhAwUTooFg.

2 Pennsylvania State University, www.psu.edu.



Vehicles tracked by SENSR, showing the underlying point clouds.

simulating moving 3D point clouds in Linux. After college, I served in the Korean military for two years as a tank engineer, where I was briefly exposed to lidar. When I left the military, I got really into studying machine learning and AI and began taking online classes with Udacity. It was really exciting to be a part of the online community. Many people would keep sharing their breakthroughs and students were able to confirm the latest code right at home.

It wasn't until Udacity put together a self-driving competition, which allowed me to meld 3D point clouds and machine learning—that I really figured out that we had something special. This combination of technologies just made sense to me. In 2017, the camera software company Mobileye was sold for $15B USD[3]. When I looked at the lidar space, I realized there was no Mobileye of lidar. So I thought to myself, someone needs to make software for all of these lidar sensors because lidar is like a camera. It is just a raw imaging sensor, but it is only as good as its software. I knew that 3D computer vision—processing 3D point clouds with machine learning—was the future and would be a must-have ingredient for anything related to autonomous systems. We founded Seoul Robotics and here we are today!

LM: Could you please describe Seoul Robotics's current customer base?

HL: Our current customer base is extremely varied, which is exactly what we had hoped when we started the company! We're working with companies across multiple industries as well as with lidar manufacturers on deployments. In the retail space, we've currently got contracts with one of the largest retailers in Korea, as well as a partnership with Mercedes-Benz to provide information on the customer journey within its showrooms. We're also partnering with multiple Departments of Transportation on smart city applications—our latest just went live in Chattanooga, Tennessee—and we are a part of the Qualcomm Smart Campus. Mobility customers will also be an important part of our business. We're currently working with BMW to automate logistics as well as with the team at the University of Michigan's Mcity on smart city and autonomous mobility applications.

LM: Your background and that of Seoul Robotics are heavily slanted to autonomous vehicles, but lidar is used in multiple ways. What non-automotive markets are exciting for you? Are you actually involved in robotics?

HL: We do get asked the robotics question a lot! The answer broadly is, yes. At the end of the day, 3D computer vision is the main component of any mobility system. We're helping robots and machines of all kinds understand and perceive their world. That said, the non-automotive markets are just as exciting for us. Lidar has long been talked about as an AV technology, but the core components of mapping and tracking can be used for so much more. It's been incredibly exciting to be able to drive the expansion of the technology into new markets.

One of the most interesting use cases for us has been within the retail industry. Lidar has the ability to help stores understand how long customers are queuing, the time it takes for a customer to check out, where customers are spending their time and how they move about the store. Stores haven't been able to track these types of insights until now.

3 By Intel: see https://lidarmag.com/wp-content/uploads/PDF/LIDARMagazine_Walker-Intel_Vol10No4.pdf.

LM: The sensor-agnostic feature of SENSR is critical and your website has photos of many of the lidar sensors with which you interface—Hesai, Intel, Ouster, Velodyne Lidar etc. Our readers, of course, are familiar with many of these sensors. Are you continuing to add more sensor suppliers to your list of partners? And please let me ask you a slightly different question. Do you, or do you plan to, interface with the lidar sensors on the iPad Pro and iPhone 12 Pro?
HL: Absolutely. We are continually looking to work with new sensor manufacturers and help bring their sensors to new markets. As I mentioned, anytime a sensor is released, we will train our software to be compatible with the new sensor.

Right now, the lidar on the iPad Pro and iPhone 12 has limited computing resources and you can't really build new algorithms on top of it at this point. However, it is something we are keeping an eye on and could potentially look into in the future.

LM: Do you foresee Seoul Robotics participating in any way in the airborne survey world, i.e. the processing of lidar data captured from the air for the purpose of generating geographic information, or is this too much of a niche market?
HL: We've actually had several conversations with mapping and survey companies around the world looking to automate the processing of geographic information. I'm very interested in this space and there are a few startups that we're keeping an eye on. This is a very natural industry for Seoul Robotics. Stay tuned!

LM: You have built relationships with several significant high-tech companies—BMW, EmboTech, Mercedes-Benz and Qualcomm. Could you please expand on these relationships? Are there any other important partners that you want to talk about?
HL: While we can't dive into the specifics of these partnerships, I'm happy to provide an overview of where we are today.

Seoul Robotics headquarters team in high spirits. They can also be seen on the company's website, holding some of the lidar sensors that the company's products support.

Last December, Seoul Robotics was selected as a Tier 1 software provider for BMW Group. Together with Swiss directional software start-up EmboTech, we're working to develop a SaaS fleet automation platform that will be used for automated functions for various internal logistics and assembly processes at BMW's HQ in Munich. This is a fast-moving project and we hope to have more to share here later this year!

Mercedes-Benz is actually a retail partnership. We've worked with them to install our Discovery product in their retail showrooms to better understand which vehicles are attracting the most attention from customers. We discovered that nearly 60% of customers spend their time looking at the trunks of vehicles and that it is important to provide more access to all sides of the vehicle on display.

Qualcomm is building a Smart Campus and has selected Seoul Robotics as the software provider for its smart city accelerator program. We feel strongly that smart cities are going to start seeing the benefits of lidar and 3D data and wanting to implement this technology soon. Cities want to provide safer spaces for pedestrians and drivers and lidar makes that possible. This program will be the blueprint for cities around the world.

We also just announced a partnership with Mando, the global auto parts manufacturer to car makers like Hyundai and Kia Motors. Mando will combine SENSR with its smart sensors, and together we're working to develop all-in-one, hardware-software solutions for mobility applications spanning autonomous vehicles, smart cities, smart factories, and unmanned robots.

This year will be very important for our business and we have so many exciting things in our product and partner pipeline. We can't share these just yet, but be on the lookout! The best place to check-in for company updates is on LinkedIn[4].

> "I truly feel that the future of mobility is going to rely on 3D sensors. I trust in 3D sensors, and right now, lidar is the best one there is."

LM: One of your partners is the University of Michigan. This is interesting, because we had an article in the magazine about an Ann Arbor firm called May Mobility that uses multiple sensors, including lidar, in autonomous vehicles, which are operational in Detroit[5]. Can you say more about your links to the University, please?

HL: One of our offices is located in Detroit. This is the center of so much innovation in the mobility space and it made sense to have a presence here. For many years now, we've worked with the University of Michigan and its Mcity program on a variety of mobility and smart city applications. Each year, we also run an internship program with the University and Mcity and work with students to build new algorithms for our software and continue to expand its applications.

LM: How are you approaching getting Discovery into the market? Do you have, or plan to have, a distributor network? What sort of pricing model do you use?

HL: We have an incredible team of veterans within the lidar space, whom we will formally announce later this year. Their expertise and relationships have been invaluable to the company as we have grown and deployed our product over the last few years. In addition to this expertise, we also work with distributors around the world and currently have partners in APAC, EMEA, and North America.

LM: I've learned from your website that you drive a Tesla but, unlike Mr. Musk, you trust lidar. Would you like to say more?

HL: I drive a Tesla daily. It's really a fantastic car, but I have gotten a few scratches while using autopilot. Given that I do drive in a very densely populated area of Seoul, the limitation is quite severe.

I truly feel that the future of mobility is going to rely on 3D sensors. Cameras and 2D systems just do not provide the insight that is needed for safe autonomy at scale. Our hope is that anywhere a camera or 2D system has previously been in place, it will eventually be replaced by 3D sensors.

Even Tesla is trying to jump from 2D systems to 3D sensors—they want to jump straight into 4D imaging radar, which really is another 3D sensor. There will be no way to get around processing 3D data, and Seoul Robotics is here when people recognize this and need help. In a sense, I trust in 3D sensors, and right now, lidar is currently the best one there is.

Lastly, I know Mr. Musk publicly denied the use of lidar, but I think he does understand its importance. Why else would he use it on a recent SpaceX launch! Recently in a talk on the new audio chat app, Clubhouse, he specifically mentioned that he did build lidar for SpaceX. According to him, if he didn't trust the technology he wouldn't have done so. So while we might not see it on Teslas, it's encouraging to hear this from someone so highly regarded in the mobility space.

LM: HanBin, thank you for taking time to answer our many questions. We look forward to learning more about Seoul Robotics' successes in the future as SENSR and Discovery diffuse into the market-place and the range of applications grows.

4 https://www.linkedin.com/company/seoul-robotics/

5 https://lidarmag.com/2018/09/24/autonomous-vehicles-operational-thanks-to-lidar/

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

Hurricanes Wreak Change on Puerto Rico's Coasts

Shoreline mapping with time-series topobathymetric lidar

This is a follow-up to an earlier article by the same authors: Karlin, A., R. Miller and A. Nayegandhi, Measuring Maria's havoc: evaluating hurricane damage with multi-temporal lidar, *LIDAR Magazine*, 3(5): 26-33, October/November 2020.

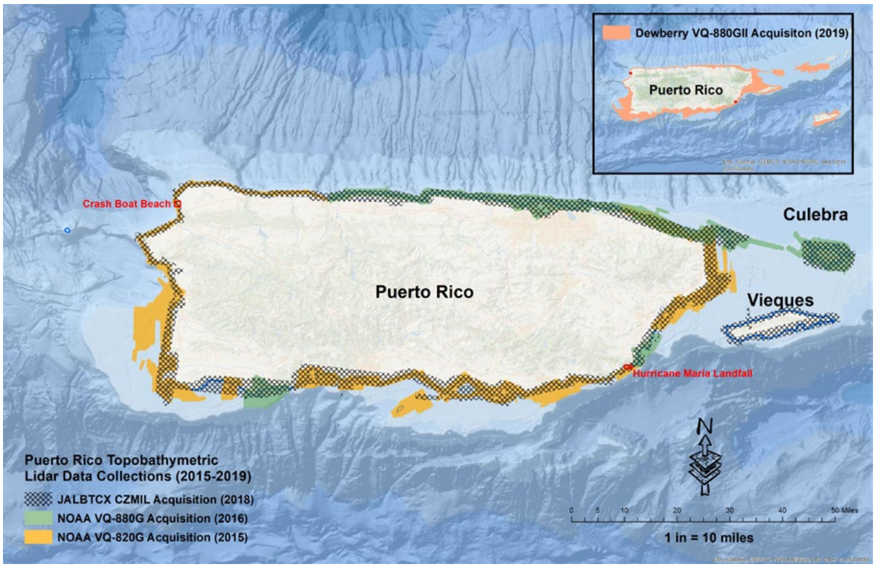


Figure 1: Topobathymetric lidar acquisitions between 2015 and 2019. The NOAA 2019 topobathymetric survey is shown on the inset map; the USGS 2019 topographic survey is not shown.

One of the classic questions posed to geography students is, "How long is the coastline?" The answer, of course, is that it depends—on the measurement techniques, the scale of reporting, the timeframe of the question (because coastlines are dynamic and always changing), and several other factors. The importance of the coastline for defense and commerce, however, was recognized in 1807 by President Thomas Jefferson, when he signed "An Act to provide for surveying the coasts of the United States", which created the US Coastal Survey Office, one of the oldest scientific agencies in the United States. Through the decades after Jefferson, the US Coastal Survey Office's name changed several times, until 1970, when it became part of the National Oceanic and Atmospheric Administration (NOAA).

After 1897, as new territories were added, commerce increased and, with the discovery of gold in California and Alaska, the importance of the coastal mapping effort grew. Each coastal chart would be built from two types of surveys: a nautical (or hydrographic) survey, which mapped offshore hazards and the depths of coastal waters; and a topographic survey, which mapped the land, including the shoreline, natural and cultural features, and elevations above the sea.

Just as the name of the US Coastal Survey Office has changed since 1807, so have the techniques for mapping the coastline. The early surveys, like the survey of New York harbor, were conducted with conventional lead soundings, levels and transits. Cameras deployed from dirigibles at the turn of the 20th century gave way to fixed-wing aerial photogrammetric surveys and, most recently, lidar technologies for both topographic and bathymetric survey.

In the early 2010s, with commercially available topobathymetric sensors, i.e.

BY AL **KARLIN**, RAYMOND **MILLER** AND AMAR **NAYEGANDHI**

"green lasers", operating at 532 nm, capable of measuring range distances both on land and through moderate depths of water, hydrographic and topographic surveys could be accomplished simultaneously to facilitate the process of shoreline mapping. The surveys that previously took months to produce can now be conducted in hours or a few days. This increase in mapping efficiency permits revisits over coastal areas following storm events to assess coastal changes in the shoreline. As a result of a combination of planned and unforeseen natural events between 2015 and 2020, the shoreline of Puerto Rico was surveyed three times using topobathymetric lidar sensors.

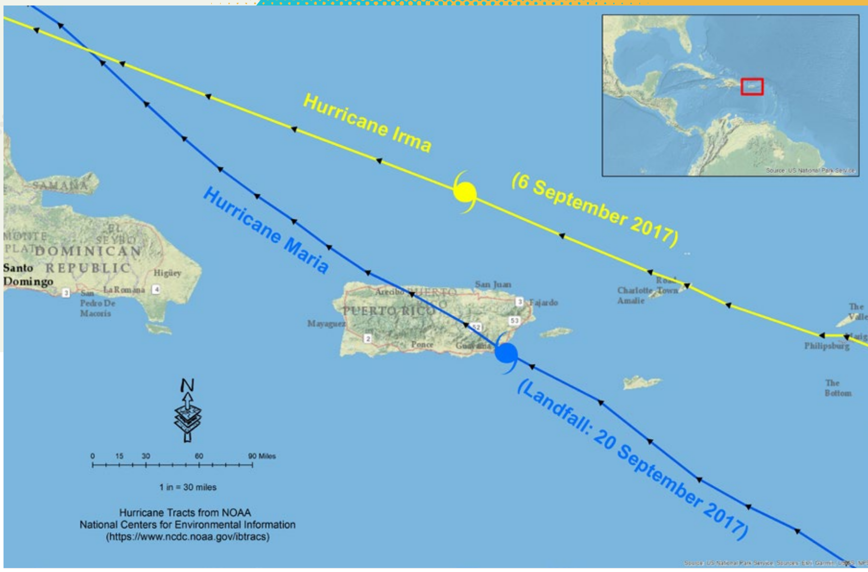


Figure 2: Paths of Hurricane Irma (6 September 2017) and Hurricane Maria (20 September 2017).

Topobathymetric lidar shoreline surveys in Puerto Rico

2014-2015: NOAA (the first survey)

In mid-2016, Dewberry received a Task Order through the NOAA Coastal Mapping Program to assist with processing Riegl VQ-820-G topobathymetric lidar data collected by NOAA between November 2014 and May 2015. This project included approximately 310 square miles (800 miles of coast) of the island of Puerto Rico including the island of Culebra (**Figure 1**; data available on NOAA DigitalCoast[1]). The data was intended for high-resolution shoreline mapping at scales from 1:5000 to 1:20,000 for both the mean high water (MHW) level and the mean lower low water (MLLW) level to 2000 feet inland. Later in 2016, NOAA revisited selected

1 https://coast.noaa.gov/dataviewer/#/

	VQ-820-G (2016)	CZMIL (2018)	VQ-880-G II (2019)
Acquisition dates	October 2014 – May 2015 and January – February 2016	July 2018	January – June 2019
Nominal point density (bathymetric)	≥ 0.5 ppsm	≥ 0.5 ppsm	≥ 0.5 ppsm
Nominal point density (topographic)	≥ 3 ppsm	See notes	≥ 2 ppsm
Vertical accuracy (bathymetric)	See notes	See notes	23.6 cm (95% confidence)
Horizontal accuracy (bathymetric)	See notes	See notes	See notes
Vertical accuracy (topographic)	19.6 cm (95% confidence; see notes	19.6 cm (95% confidence)	NVA: 16.8 cm (95% confidence) VVA: 25.1 cm (95th percentile)
Horizontal accuracy (topographic)	1 m (95% confidence)	1 m (95% confidence)	69.6 cm (95% confidence)

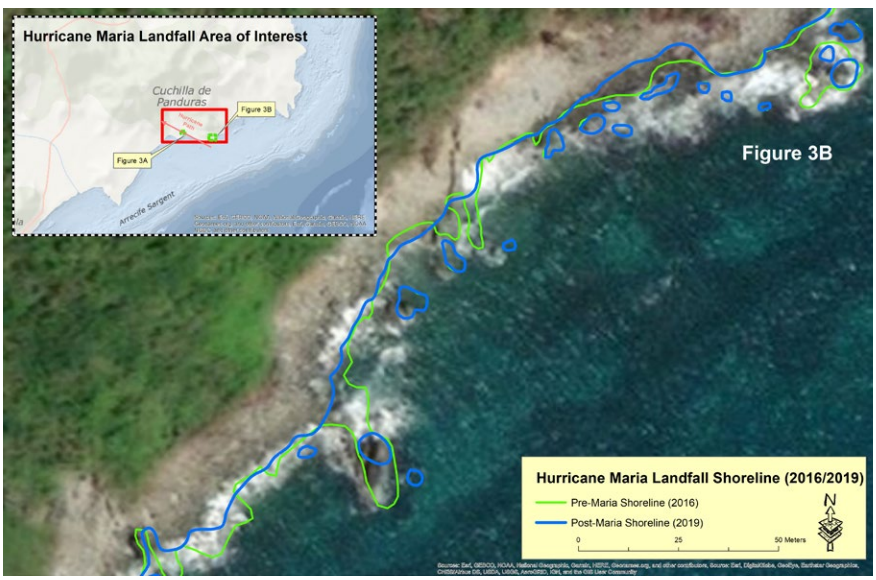
VQ-820-G:
- Vertical accuracy (bathymetric): better than ± 15 cm @ 1 σ
- Horizontal accuracy (bathymetric): not reported
- Horizontal accuracy (topographic) based on 8 check points.

CZMIL: recorded as "compiled for" accuracies dependent on water depth (d):
- Vertical accuracy (shallow channel) = $\sqrt{[(0.20)^2 + 0.0075d^2]}$ m
- Vertical accuracy (deep channel) = $\sqrt{[(0.30)^2 + 0.013d^2)]}$ m
- Horizontal accuracy = 3.5 + 0.05d m
- Nominal point density (topographic): topographic points not classified

VQ-880-G II
- Horizontal accuracy (bathymetric): inferred as inherited from lidar source

Table 1: Topobathymetric lidar acquisition parameters.

Figure 3: Changes in shoreline geometry in Puerto Rico near the landfall of Hurricane Maria (2016 – 2019). **Figure 3A** shows a section of shoreline where shoreline accretion occurred; **Figure 3B** shows a section where shoreline loss occurred.



areas along the coast of Puerto Rico and surveyed using a newer Riegl VQ-880-G topobathymetric lidar sensor.

2018 JALBTCX (the second survey)

Following the 2017 hurricane season, when Hurricane Irma drifted past the northern coast of Puerto Rico (6 September 2017) and then, two weeks later, on 20 September 2017, Hurricane Maria made landfall as a Category 5 storm (**Figure 2**), the coastline was resurveyed. The Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX) acquired topobathymetric lidar using the Coastal Zone Mapping and Imaging Lidar (CZMIL) sensor along the coast, shown as the hatched area in **Figure 1**, immediately following the storms in the early summer of 2018.

2019 NOAA/USGS/Dewberry (the third survey)

In mid-2018, USGS and NOAA tasked Dewberry to resurvey the entire island (both topography and bathymetry) and to remap the coastline following the hurricane events. Poor weather conditions in late 2018 resulted in low visibility through the water column and delayed data collection. Dewberry completed this acquisition with a new Riegl VG-880-G II sensor in June 2019.

Thus, there were three topobathymetric lidar surveys—a NOAA survey (2015/16), a JALBTCX survey (2018) and a NOAA/USGS/Dewberry survey (2019)—of the coastline of Puerto Rico within a four-year timespan; including pre- and post-Maria surveys. **Table 1** and accompanying notes detail the specifications of the three surveys. Although there were temporal and sensor differences for the three surveys, the general specifications, in terms of topographic and bathymetric point density, and horizontal and vertical accuracy, were very comparable to each other.

Hurricane Maria moved across the island on a northwestern trajectory for 30 hours, battering the island with rain and winds, until it exited the island to the west of Arecibo. We will focus attention on two locations: a 2.1 km^2 area near Yabucoa Municipality, located on the southeastern side of the island close to where Maria made landfall; and a recreational area, Crash Boat Beach, on the northwest side of the island, in a vicinity affected by both Hurricane Irma and Hurricane Maria.

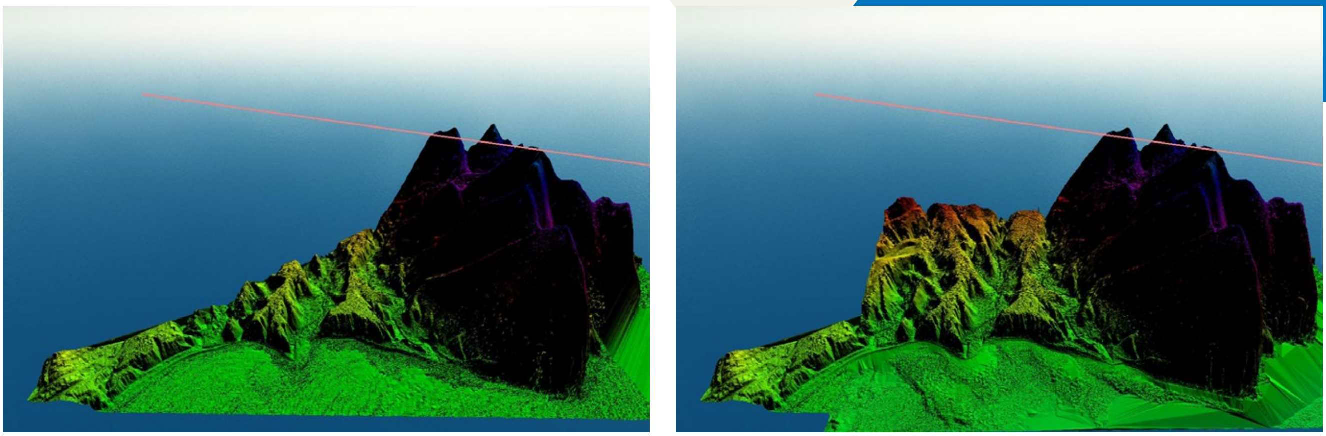


Figure 4: Topobathymetric lidar bare-earth digital elevation models of an area of the coastline of Puerto Rico near landfall of Hurricane Maria. **Figure 4A** shows Riegl VQ-820-G (2015) lidar data pre-Maria. **Figure 4B** shows CZMIL (2018) lidar data post-Maria. The pink line indicates the northwestern direction of Hurricane Maria as it passed through the alcove.

Landfall near Yabucoa municipality

On 20 September 2017, Hurricane Maria made landfall in a sparsely populated area along the southeastern portion of the island near Emajagua (**Figure 2**) at 1015 UTC as a high-end Category 4 hurricane with winds of 155 mph. The southern portion of the island was hardest hit by the hurricane with hundreds of homes in the towns of Yauco, Guanica and Guayanilla collapsing.

Table 2 shows a detailed summary of the changes to the shoreline within the 2.1 km^2 area near Yabucoa. While the total length of the continuous coastline increased by only approximately 202 m, the sinuosity coefficient, as measured within this area of interest, increased by 7%. These increases indicate that the hurricane not only changed the length of the shoreline, but also affected its shape. The most obvious shoreline features, the isolated sand bars, increased by nearly 25% in number, but decreased in average area and perimeter. Although the net shoreline change was an increase following the hurricane, the actual shoreline movement was very local. These changes are illustrated in **Figure 3**.

Figure 3A shows a site within the 2.1 km^2 landfall area of interest, where Hurricane Maria resulted in approximately a 3 m deposition of material to the shoreline. In this alcove area, the hurricane pushed sands and sediments toward the shoreline at a uniform rate. In **Figure 3B**, which shows an area approximately 1 km further eastward along the coast, in a less protected location, and hence further from the hurricane landfall, there are many areas where Hurricane Maria moved sediments away from the shoreline. It is also seen in **Figure 3B** that many isolated sand bars

	Shoreline with isolated sand bars length (m)	Shoreline-only length (m)	Shoreline Sinuosity*	Number of isolated sand bars	Isolated sand bar area (km^2)	Isolated sand bar perimeter (m)
Pre-Maria	3471	2994	1.43	31	551 (mean = 17.7**)	447 (mean = 15.4**)
Post-Maria	3765	3196	1.53	39	622 (mean = 15.9**)	569 (mean = 14.6**)
Post-Maria change	+8.5%	+6.7%	+7%	+25% (+8 sand bars)	-11% average area	-6% average perimeter

Table 2: Summary metrics of mean high water (MHW) net shoreline change pre- and post- Maria.

* Straightline distance = 2085.2 m
** Means are shown for comparative purposes. The isolated sand bar areas and perimeters were not normally distributed.

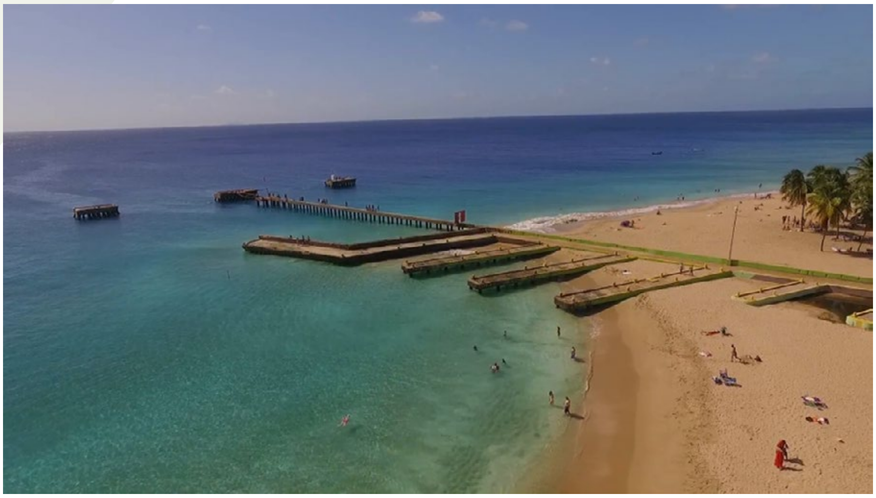


Figure 5: Oblique pictures of Crash Boat Beach prior to Hurricane Maria (**Figure 5**A), and shortly after the hurricane (**Figure 5**B).

(small polygonal areas) have been formed as a result of the hurricane scouring the sands and sediments. Although these shoreline changes, which are the focus of the NOAA Coastal Mapping projects, are noteworthy, the nearshore topobathymetric lidar illustrates more dramatic effects of the hurricane.

Figure 4 presents the topobathymetric lidar in the small cove (**Figure 3A**) before (**Figure 4A**; Riegl VQ-820-G) and after (**Figure 4B**; CZMIL) Hurricane Maria made landfall. Note that the 2019 Riegl VQ-880-G II data was collected closer to the shoreline for mapping and did not extend into the ocean. The seaward area in the pre-Maria lidar (**Figure 4A**) is shelf-like in appearance. The sands and other sediments are evenly distributed in the foreground. This is in sharp contrast to the rough appearance of the foreground area in **Figure 4B**. Hurricane Maria pushed the sands and sediments landward, resulting in mounding and uneven distribution.

Exit near Boat Crash Beach (northwestern side of Puerto Rico)

After nearly 30 hours of battering Puerto Rico with heavy rains, over 500 mm in most spots, and winds of 145 mph or more, Hurricane Maria exited Puerto Rico on 21 September 2017 as a Category 3 hurricane. The meteorological values are estimates, because the monitoring stations on Puerto Rico were incapacitated owing to damage from Hurricane Irma, two weeks prior to Hurricane Maria.

Crash Boat Beach (**Figure 5**), on the northwestern side of the island, is a resort area used by both locals and tourists. It is the most popular beach in the region. The main attractions are water sports favored by the crystal clear, turquoise waters, including diving, snorkeling, swimming and surfing. Hurricane Maria exited Puerto Rico in this vicinity as a Category 3+ storm. On the exit path of the hurricane, we observed severe beach erosion as the storm carried sands and sediments seaward. The degree of beach erosion is evident in the before (**Figure 5A**) and after (**Figure 5B**) images. Comparing these images clearly illustrates that boat docks partially buried in the sands pre-Maria were exposed in the ocean (**Figure 5B**) post-Maria.

The severe beach erosion is also apparent in viewing profiles of the NOAA 2016 (before) and JALBTCX 2018 (after) topobathymetric data (**Figure 6**). As the JALBTCX 2018 topobathymetric lidar was captured prior to the NOAA/USGS/Dewberry 2019 lidar, and the two surveys are indistinguishable from each other, **Figure 6** uses the former as the post-Maria surface and shows a comparison between the NOAA (2016, in green) and JALBTCX (2018, in yellow) profiles. The arrows

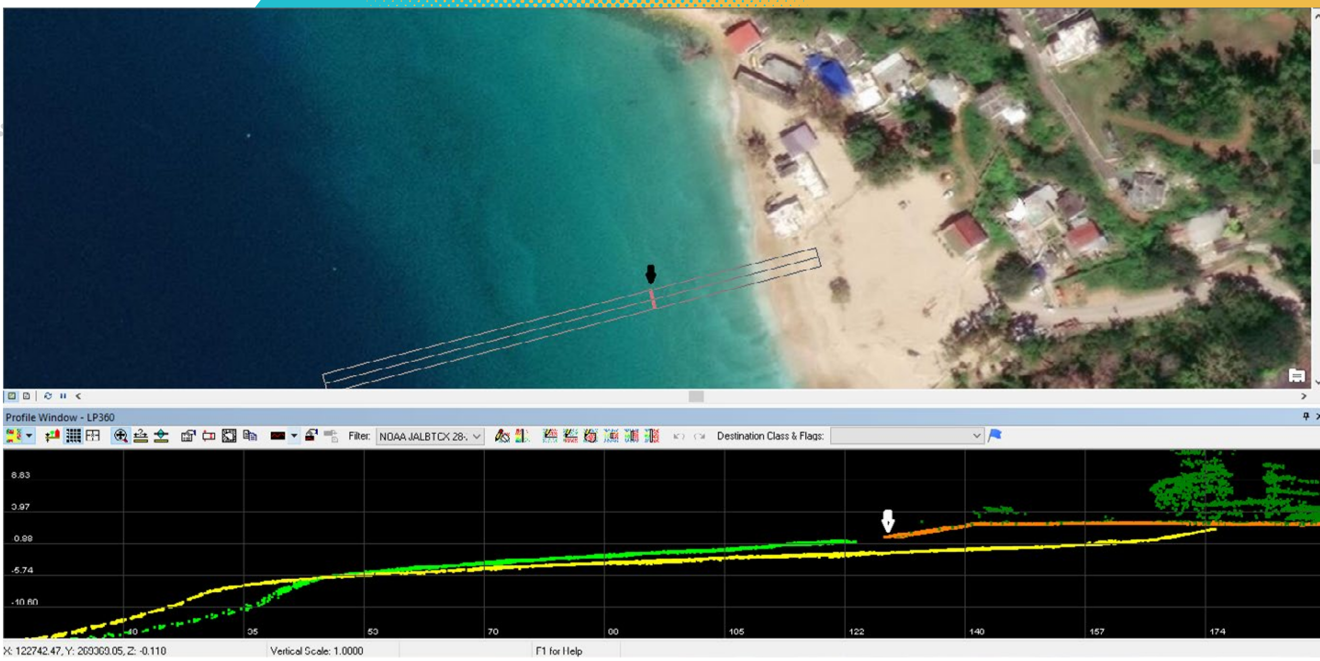


Figure 6 Profile view showing beach erosion along Crash Boat Beach. Bright-green points are from the NOAA 2016 lidar survey; yellow points are from the JALBTCX 2018 lidar survey. The arrows indicate the same locations on the imagery and profiles.

in **Figure 6** point to the coincident locations on the 2019 aerial image and the lidar profile. Clearly, the beach that was at the arrow location in the 2016 data has receded, and the extent can be measured in the topobathymetric lidar. Similarly, the materials were carried seaward and resulted in deposition on the western (left) side of the profile.

Lessons learned

As a result of a combination of circumstances—the NOAA Shoreline Mapping Program and an unusually severe hurricane season in 2017—three topobathymetric lidar surveys were conducted along the coast of Puerto Rico between 2015 and 2019. This lidar time series illustrates:

1. The dynamic nature of shorelines requires repeated surveys, particularly in areas where natural forces may produce extreme effects.
2. Topobathymetric lidar is invaluable for measuring beach recession and accretion as illustrated in these repeat surveys. Topobathymetric lidar technology works very well in the tropical waters on the Caribbean.
3. It is important to have "before and after" surveys. Baseline surveys at repeated intervals should be conducted, therefore, so that the changes can be captured when a natural disaster occurs.

Acknowledgements

We thank the United States Geological Survey, National Oceanic and Atmospheric Administration, Joint Airborne Bathymetric Lidar Technical Center of Expertise, Commonwealth of Puerto Rico, and the National Park Service, which funded these projects. We also thank Tim Saultz and Gail Dunn of USGS, Mike Aslaksen of NOAA National Geodetic Survey, and Jennifer Wozencraft and Chris Macon of JALBTCX for their coordination efforts and overall support.

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Raymond Miller, Jr., CP, CMS, GISP is a project manager in Dewberry's Tampa, Florida, office. He has extensive experience in GIS, remote sensing, and relational database management. He has developed geospatial solutions for water resources, floodplain mapping, and hazard mitigation projects for clients that include the SWFWMD, NOAA and the Florida Division of Emergency Management. His experience includes lidar data production and analysis, digital terrain modeling, watershed evaluation and management planning, floodplain mapping, and geodatabase management. He is a Certified HAZUS Professional, ASPRS Certified Mapping Scientist – Remote Sensing, and a GIS Certification Institute Professional.

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

EVON SILVIA

LAS Working Group Releases First Public Registry

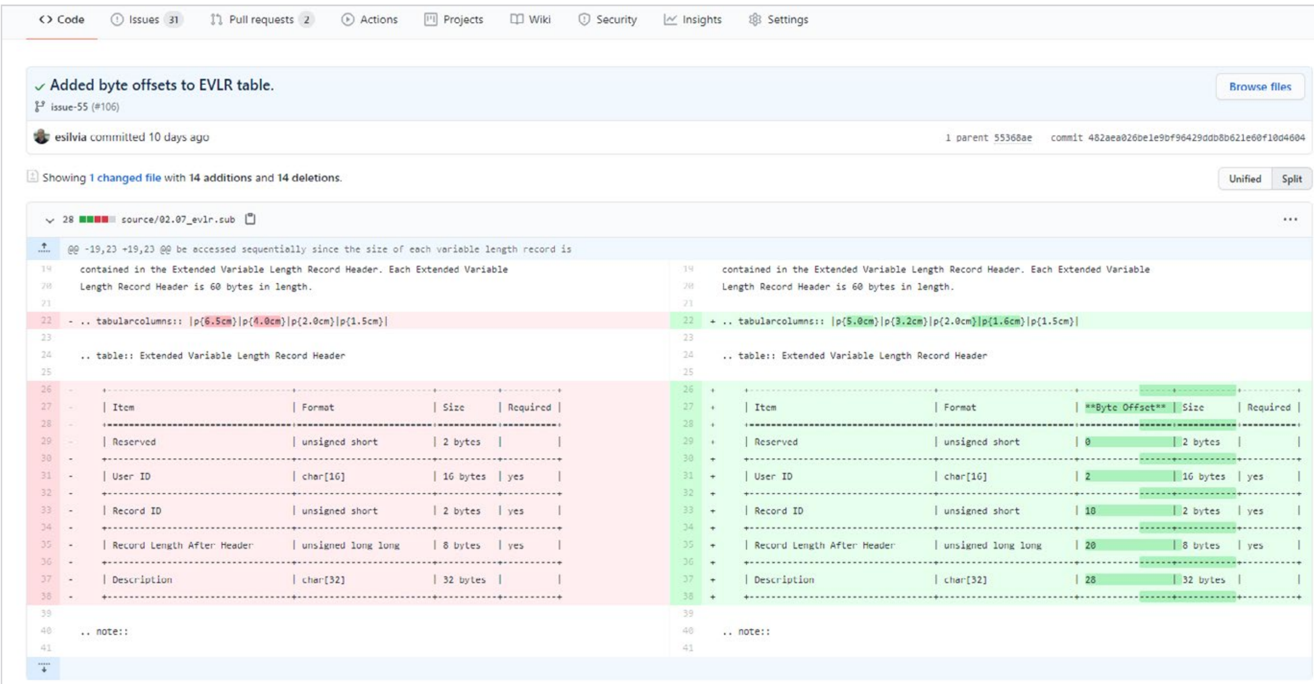

Figure 1: This example Commit shows the incremental changes in the plain text files of the specification itself. In this case, a "Byte Offset" column was inserted into the EVLR header table.

The meeting of the LAS Working Group (LWG) on 18 January 2021 meeting began with a review of updates to its wiki pages[1]. With a new sidebar, we've made navigation within the wiki significantly easier. We also added a new page with wiki editing tips to facilitate community edits to the wiki.

Most importantly, the Standard System Identifiers[2] page was officially released as the first published public registry now being maintained on the LWG GitHub page. In the works for a couple of years, this registry provides a concise methodology for encoding multiple sensors and/or platforms into the System Identifier field of the LAS header. This is a necessity for properly representing the source system for tiled LAS datasets that contain data from multiple sources. Examples and lookup tables are also provided to simplify integration into existing software.

1 https://github.com/ASPRSorg/LAS/wiki
2 https://github.com/ASPRSorg/LAS/wiki/Standard-System-Identifiers

PDF build procedure

Over the holidays, the LWG also made a significant behind-the-scenes change in how the specification is maintained. Let's begin with a little background.

The LAS specification's raw format is a set of text files encoded with mostly Markdown formatting and a sprinkling of LaTeX. By storing the raw format as text instead of binary (such as the Microsoft Word *.docx format) we can leverage the power of Git and GitHub to show line-by-line differences and merge multiple versions together with minimal

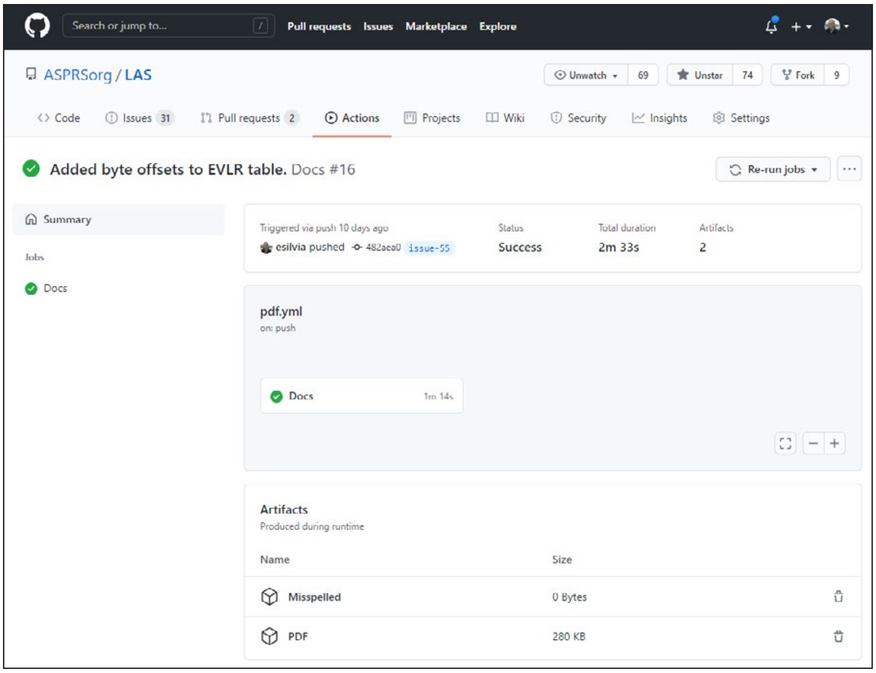

Figure 2: Every change to the specification automatically results in a new draft PDF that incorporates those changes in a human-readable PDF. These PDF "artifacts" persist for 60 days before being automatically deleted to prevent circulation of unwanted drafts.

effort. This approach has an added advantage: most software developers are familiar with GitHub.

Despite the convenience of maintaining plain text files, however, a static and versioned PDF is far easier to read, reference and cite when one is using the specification for development, contracting and standards. Therefore, we needed some sort of automated system for conveniently converting the plain text files into PDFs, preferably with zero manual effort and minimal maintenance.

When we made the transition to GitHub, LWG elected to use Sphinx[3], an open-source documentation generator that can convert raw text files into a human-readable and attractively formatted PDF, for this purpose. Every time a new commit was made to the GitHub repository, an elaborate series of scripts would create a virtual machine using third-party software, run Sphinx, and post the PDF to an Amazon Web Services (AWS) S3 bucket, which was generously paid for by an LWG member. This system was extremely complex, hard to maintain, and relied on the member to continue his munificence.

The new system still relies on Sphinx, but instead leverages GitHub Actions[4] to create the virtual machine and run Sphinx within GitHub itself. The build system no longer relies on third-party software or AWS, making it much easier to maintain. Now, a draft PDF is available directly on GitHub every time someone makes a change. These PDFs are temporary objects that stay available for 60 days, after which they disappear. They can be recreated on-demand by rerunning the GitHub Action.

For example, in this Commit[5] (**Figure 1**), I inserted the byte offset column (see below) into the Extended Variable Length Record header table. When I finished my edits, I saved the Commit, and GitHub automatically began running this action[6] (**Figure 2**). Two and a half minutes later, the plain text files were transformed into a PDF incorporating the changes from that commit (**Figure 3**).

Byte offset columns

The remainder of the LWG call reviewed upcoming changes in the LAS 1.4 Revision 16. Most notably, the point data record format tables will have byte offset columns added (Issue-55[7]) to improve readability and usability of the specification for programmers.

Byte offset columns were added also to the VLR, EVLR and LAS header tables. This set of changes is nearly finished and currently under review by LWG.

LWG moderation notes

All public forums are vulnerable to off-topic posts and potential hijacking, and the LWG GitHub page is no different. Maintaining a helpful, positive and collaborative environment without stringent barriers on public access requires everyone's cooperation. All posts on a topic must be directly relevant to the original post. If a topic strays from its original purpose or is

3 https://www.sphinx-doc.org/en/master/

4 https://github.com/ASPRSorg/LAS/actions

5 https://github.com/ASPRSorg/LAS/commit/482aea026be1e9bf96429ddb8b621e60f10d4604

6 https://github.com/ASPRSorg/LAS/actions/runs/494835288

7 https://github.com/ASPRSorg/LAS/issues/55

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2.7 Extended Variable Length Records (EVLRs)

The Point Record Data can be followed by any number of EVLRs.

The EVLR is, in spirit, identical to a VLR but can carry a larger payload as the "Record Length After Header" field is 8 bytes instead of 2 bytes. The number of EVLRs is specified in the "Number of Extended Variable Length Records" field in the *Public Header Block*. The start of the first EVLR is at the file offset indicated by the "Start of First Extended Variable Length Record" in the *Public Header Block*. The Extended Variable Length Records must be accessed sequentially since the size of each variable length record is contained in the Extended Variable Length Record Header. Each Extended Variable Length Record Header is 60 bytes in length.

Table 22: Extended Variable Length Record Header

Item	Format	Byte Offset	Size	Required
Reserved	unsigned short	0	2 bytes	
User ID	char[16]	2	16 bytes	yes
Record ID	unsigned short	18	2 bytes	yes
Record Length After Header	unsigned long long	20	8 bytes	yes
Description	char[32]	28	32 bytes	

Note: As with the VLR, the Reserved field must be set to zero.

Figure 3: The draft PDF was automatically generated and provides an opportunity to review the incremental change enacted by the commit—in this case, the insertion of the Byte Offset column into the EVLR header table.

hijacked by personal interests, LWG members and the Chair are empowered to remove off-topic posts at will. If the post is helpful, but simply a different topic, we will likely seed a new Issue with that post so that both conversations may continue unabated.

If the errant posts are not relevant to LWG at all or obviously motivated by personal interests, the user will receive a public warning or ban for repeated or egregious offenses. In the spirit of collaboration and community, I'd prefer to keep this to a minimum. The formula seems to have worked so far. Let's keep it that way.

Welcome new members and closing remarks

In January, LWG welcomed new member Carol Lockhart (Woolpert), an expert in the topobathymetric domain. To join LWG, you must be a paid member of ASPRS, so that the organization can continue its leadership position in the remote sensing community.

Keep an eye on the ASPRS newsletter and LAS homepage[8] for the final review of LAS 1.4 Revision 16, which is expected to go up for publication in the first quarter of 2021.

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

8 https://github.com/ASPRSorg/LAS

Graham, *continued from page 48*

away. Even though it might have been the drone itself that caused all the grief, the entire premise of surveying by UAS is sometimes dismissed. I find this to be especially true amongst those who used web portals to process data. For some of the cloud solution providers, spatial reference systems and network accuracy checks seemed a foreign concept. There was an assumption (always a bad idea, of course) on the part of the customers submitting data that the cloud software was smart, imbued with lots of newfangled AI. As it turns out, often it wasn't and a lot of bad data was delivered by some embarrassed service providers.

Now we have scaled back our expectations and realized that surveying with a drone is just a small-scale version of the lidar and photogrammetry surveying from manned aircraft that we have been (very successfully) accomplishing for years. This scaling applies not only to project size, where it now makes sense to use airborne resources on 20-acre projects, but also to the cost to play. We have users of our 3D Imaging Sensors who are claiming recovery of total system cost in four months or less. That's an ROI worth writing home about!

If you are one of the unfortunate ones who was burned by missteps in Generations 1 and 2, you should come back for an updated look. The technology does work and it works very well. The missing ingredient, I think, was the expertise needed by the folks who deploy this technology. In the hands of someone who has been competently performing topographic surveys using ground-based gear, UAS-deployed sensors are a (positive) game changer. Go forth and fly!

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


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RTK Dual Antenna
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RANDOM POINTS

LEWIS GRAHAM

If at First You Don't Succeed...

It's 2021 and we are many years into the evolution of using drones with high accuracy sensors for surveying and mapping applications. In fact, I think I would say we are at Generation 3 (at least), where the line-up is:

- Generation 1 – everyone is focused on the drone and not so much the sensor
- Generation 2 – it will all be done via web portals, requiring no skill on the part of the practitioner
- Generation 3 – oh, it is actually just another survey tool!

Figure 1: Leica Aibotix X6.

> "In the hands of someone who has been competently performing topographic surveys using ground-based gear, UAS-deployed sensors are a (positive) game changer."

Generation 1 saw a total focus on the drone and very little on the sensor itself. We saw both Trimble and Hexagon acquire companies which were making drones but not sensors. This seemed odd to me at the time. It would be comparable to a purveyor of mobile laser scanning systems ignoring the scanner and acquiring a truck company! Thus we saw exotic drone designs (consider the Leica Aibotix of **Figure 1**) with no focus (pun intended) on the sensor - it was usually just a prosumer camera. I cannot help but wonder how different our drone mapping world would be today if Leica Geosystems had chosen to work on the sensor side of this emerging market.

Both acquirers soon realized the error of their ways and divested or emasculated their drone companies. But they did not move into their core competence of sensors, choosing instead to move to the sidelines, occasionally selling someone else's kit.

Generation 2 included the rise of companies which were very focused on "scaling" the operation of drone-collected data. These schemes usually involved the end user flying the sensor, uploading data to the "cloud" service and receiving pristine results. The first of these offerings were "mechanical Turks", where, behind the cloud curtain, were humans processing the data. This scaling was not all that attractive to the VCs funding these activities, however, so the follow-on schemes tried to fully automate the process or trained the end user to employ web-deployed tools in a self-service scheme. Fully automated failed too often to be useful (automatically detecting stockpiles in a crowded mine site is not as easy as initially thought). This led to a surge in "do it yourself" data processing, similar to taking all your ingredients to a communal kitchen except you did not get to have conversations with the other chefs! Serious surveyors who were out on this bleeding edge soon realized that what these models were really providing was monthly access to their wallets!

Thus we are entering Generation 3. We now realize that it is all about the sensor and that a professional needs to be intimately involved in both the data collection and data processing loops. In hindsight we could have easily skipped the previous generations - it's not as if surveying is a new thing!

Unfortunately, some of those burned by dabbling in Generation 1 and Generation 2 seem to have a bad taste in their mouths they just cannot wash

continued on page 46