TECHNOLOGY CHANGES DURING MY 60-YEAR MAPPING CAREER

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I am retiring at the end of 2022, after two wonderful 30-year careers in the mapping sciences – 30 years as a topographic engineer officer in the U.S. Army Corps of Engineers (USACE) (Figure 1) and 30 years as a geospatial senior project manager with Dewberry (Figure 2). Both careers included photogrammetric and topographic mapping and production of Digital Elevation Models (DEMs) – my specialty, for which I served as editor/co-author of three editions of the DEM Users Manual (Figure 3).

Figure 1. Colonel in the U.S. Army Corps of Engineers, 1961-1991. Source: Personal image.

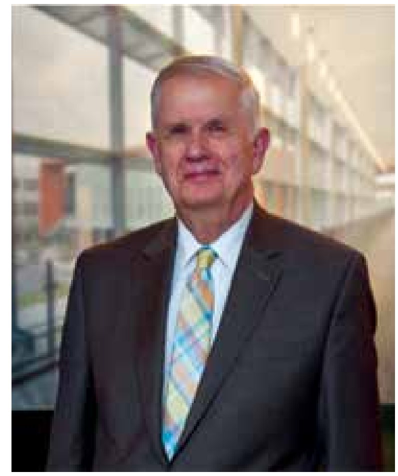

Figure 2. Senior Project Manager at Dewberry, 1992-2022. Source: Personal image.

In addition to Army schools, assignments to topographic engineering battalions in Germany and Hawaii, the Army sent me to The Ohio State University (OSU) to get M.Sc. and PhD degrees in geodetic science and photogrammetry. Prior to the advent of GPS, we were taught how to use T-3 theodolites, star catalogs and precise celestial navigation techniques to determine latitude and longitude; it took me weeks to complete all calculations and adjustments for a single position; I knew there had to be a better way. Similarly, I studied analog and analytical photogrammetry, again knowing there had to be a better way. My PhD dissertation on photogrammetric self-calibration won ASPRS' Talbert Abrams Grand Award in 1976 for what was then considered to be pioneering research in digital photogrammetry. Self-calibration has evolved into today's Structure from Motion (SfM) photogrammetry.

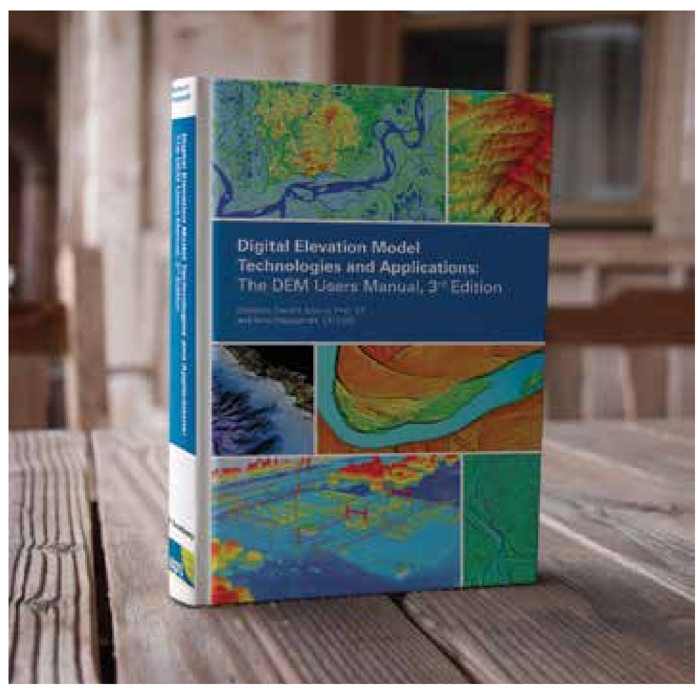

Figure 3. Editor of three editions of the *DEM Users Manual*, 2001, 2007, 2018. Source, Dewberry.

As an Army topographic engineer, we helped to map allied countries that asked for America's help in mapping for nation building, and we mapped and performed terrain analyses of countries where we might potentially go to war. I retired from the Army in 1991 as the Commander and Director, U.S. Army Topographic Engineering Center (TEC) – now the U.S. Army Geospatial Center (AGC) – where we developed many mapping technologies in common use today.

While at Dewberry from 1992 to the present, I'm best known as Project Manager for our major geospatial contracts with the U.S. Geological Survey (USGS) and the National Oceanic and Atmospheric Administration (NOAA) Office for Coastal Management (OCM) and National Geodetic Survey (NGS). I also supported the Federal Emergency Management Agency (FEMA) for the National Flood Insurance Program (NFIP) and emergency response contracts. All these contracts gave me experience with lidar and other elevation technologies and applications which led me to serve as editor and principal author of three editions of *Digital Elevation Model*

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Technologies and Applications: The DEM Users Manual (Figure 3), published by ASPRS.

I have been intrigued by the changes in surveying and mapping technologies during my 60-year career, summarized in the ten technology sections below. I do not look back to the "good old days" but cherish the progress made during my 60 years as a mapper.

CHANGES IN CARTOGRAPHY

In his testimony to Congress on December 5, 1884, John Wesley Powell, 2nd Director of the USGS, stated: "A Government cannot do any scientific work of more value to the people at large than by causing the construction of proper topographic maps of the country." Until the 21st century, USGS' 7.5-minute topographic quad maps (Figure 4) were America's standard mapping product. U.S. military organizations produced similar topographic maps of foreign countries at different scales. Cartographic features are either mapped as points, lines, or polygons. "Feature separates" are merged into "color separates" for each color used on the printed map, normally black, red, blue, green, and brown, and sometimes magenta to show map updates.

For vector "feature separates", scribing was used to produce lines for cartographic map compilations before the use of computer-based geographic information systems (GIS). Lines produced by manual scribing are sharp, clear and even. Using large walk-in cameras (Figure 5), pencil manuscripts were photographed onto scribe sheet material. Using a light table (Figure 6), lines on the scribe sheet were traced with a metal scribe tool to remove thin lines of translucent coating to produce a negative image (compared with drafting that produces a positive image). Scribing produced a result superior to drafting, but it is more time-consuming. A separate stylus was required for each thickness of line required, and some were used for parallel double-line road casings. Scribing was so time-consuming that a cartographer could spend a year or more scribing linear features for a single map sheet.

Text was set by using a Leroy lettering set, a popular mechanical lettering template used by cartographers and draftsmen; laminated plastic templates had characters engraved on the front, in different sizes, with the lines serving as guide grooves for the cartographer or draftsman to ink letters, numbers, and characters consistently.

Using "peel coats" to open windows for polygons, area features were screened with patterns to depict swamps, forests, lakes, built-up areas, etc., or to lighten colors by dotted screens with differing amounts of white between the colored dots. For example, a river centerline might be printed with dark blue

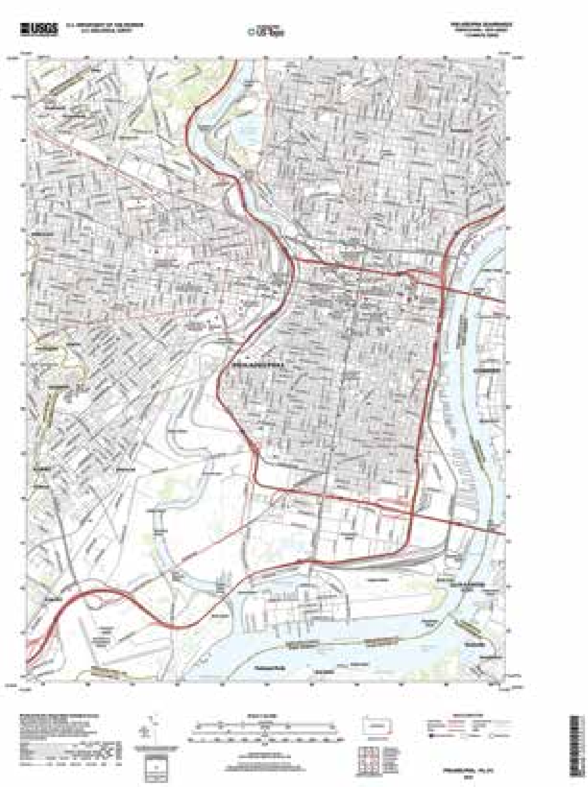

Figure 4. Topographic quadrangle maps produced by USGS until about 2002. Source: USGS.

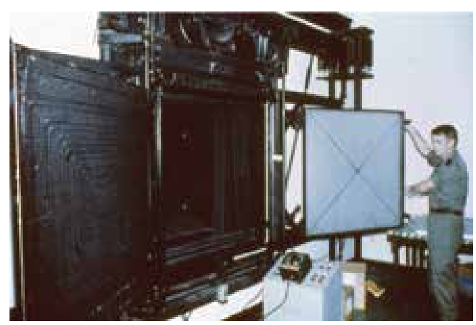

Figure 5. Walk-in mapping camera used by my topographic engineer battalion in Hawaii to produce the L653 series of topographic maps for U.S. Forces, Korea. Personal image.

Figure 6. Although these scribed lines are thick for visualization purposes, most scribed lines are a small fraction of a mm thick and require a steady hand scribing beneath a microscope. Personal image.

ink, but a lake or double-line stream would be screened so that the same dark blue ink appears to be light blue on the map.

Army topographic engineer units did much more than produce topographic maps. My topographic engineer battalion in Germany had three terrain intelligence detachments whose mission was to perform terrain analyses of countries where NATO units may go to war. Soldiers would need to determine the bridge-bearing capacity of bridges in potential enemy territory, the soil-bearing capacity for armored units travelling off-road, and obstacles in moving through cities, towns, and villages. Soldiers would need to know potential parachute landing zones, landing beaches, obstacles to cross-country movement, areas for cover and concealment, etc. My battalion produced such map-based terrain analysis studies of eastern European countries, and most of those studies were either Confidential or Secret. Thus, security of printed terrain analysis studies in our map warehouses was always a challenge.

GIS is like cartography but with key differences. Both include base maps to which additional data are added, but a GIS has no limit on the amount of supporting data that can be added, including massive geodatabases for example, and a GIS can automate analyses of connectivity, adjacency, and/or proximity. National mapping agencies, including the Defense Mapping Agency (DMA) and USGS, started adopting GIS technology and best practices in the 1980s, but they also continued using traditional cartography until the turn of this century.

Soldiers now use computers in the field with GIS software for visualizing the terrain and performing geospatial intelligence tasks in combat brigades and divisions. Most data come from the National Geospatial-Intelligence Agency (NGA), but Army geospatial intelligence analysts perform on-demand terrain analysis tasks in combat zones, tailored to satisfy tactical requirements.

For the National Map (TNM) in the U.S., US Topo is USGS' current topographic map series, modeled on the legacy 7.5-minute topographic quad maps but mass-produced quickly from GIS databases and published as digital documents. US Topo has various digital layers that overlay and can be turned on and off, including elevation, imagery, hydrography, transportation, structures, land cover, boundaries, and geographic names.

The *PE&RS GIS Tips and Tricks* column by Dewberry Senior GIS Professional Al Karlin routinely stimulates thinking on the evolving use of GIS technology.

CHANGES IN MAP PRODUCTION AND DISTRIBUTION

Five-color topographic maps were prepared from feature separates, then merged into five color separates. For example, the black color separate might consist of (1) road vectors scribed with single or double-lines for different types of roads, (2) scribed buildings to be mapped in black, (3) black text throughout the map containing street names, highway numbers, city/town names, etc. (4) open-window "peelcoats" for screening with dots to create different shades of gray on the map; (5) map graticule, and (6) map marginalia including scale bar; north arrow/magnetic declination diagram; legend explaining the various colors and symbols used, accuracy information, and information about the map that today is called metadata. All six of these black feature separates would be photo-copied onto a black color separate, a film negative, that would subsequently be burned onto a press plate for that color. Similar color separates would be prepared for all features to be mapped with red, blue, green, or brown ink. Color proofs would then be made for quality control to see if any color incorrectly overlays another color. When the color-proofing process indicated everything was within specifications, only then could the press plates be sent for printing on single- or multi-color presses. With single-color presses, the entire system would be inked separately for the five different press plates – the paper running through the press five different times with different colors.

Map paper cutting and trimming was also a science. Blank paper map sheets need to be trimmed prior to printing to ensure that edges are perfectly square and straight, to avoid press jams and other mechanical press problems. In binding and finishing operations, cutting and trimming are performed to reduce large-size press sheets to the desired trim size and to remove extraneous edges containing registration marks. Most cutting and trimming are performed on a powerful guillotine cutter, a large device consisting of a flat bed on which the paper is stacked, and a wide, sharp steel or steel-carbide knife, which is lowered through the paper mechanically. Side and back gauges on the cutter bed also helped position the paper accurately and squarely, allowing for the ability to trim to a very accurate size. A cutter clamp holds the paper securely beneath the knife and expels air from the stack of sheets, eliminating distortion of sheets which can result in improper cutting. Cutting and trimming were also performed using cropmarks, lines in the trim area of the sheets which indicate the proper size of the finished stock. When stacks of maps are properly trimmed, automated counting machines could be used for accurate inventory audits.

These printing and finishing processes continued, worldwide, until the early 2000s when maps became digital.

During most of my 30-year Army career, topographic engineer battalions had Areas of Responsibility for which they maintained map reproducibles for all maps of countries for which they might need to provide maps to combat units; and they also maintained map warehouses for storing and shipping maps to users. Some maps were prepositioned in caves or bunkers in potential combat zones. The Army Map Service (AMS), and subsequently the Defense Mapping Agency (DMA), provided these services worldwide; and USGS did so nationwide with their topographic quadrangles. These larger agencies all maintained their libraries of map reproducibles and map warehouses. To the best of my knowledge, such brick and mortar facilities are no longer needed with the advent of digital mapping products.

Figures 7 and 8 show the map reproducible library and one of our printing presses in my topographic engineer battalion in Hawaii. Figure 9 shows a row of map warehouses in my topographic engineer battalion in Germany where trucks were coming and going daily, moving freshly printed maps in from the printing presses and moving new maps out to the combat units throughout Germany. Of course, as truckloads of new maps were delivered, truckloads of old maps were continuously being returned and normally destroyed. In later years, we reused old map stock by printing lines on the reverse side so recycled maps could be guillotined into 8.5”x11” writing pads.

Today, the Army no longer has topographic engineer battalions supporting Army potential theaters of operation; instead, many forms of imagery and digital data are analyzed by geospatial-intelligence specialists at Army division and brigade level, using computers with specialized GIS software and various forms of digital datasets to perform terrain analyses in support of the Army doctrine known as Intelligence Preparation of the Battlefield (IPB).

Figure 7. Map feature separates and color separates maintained by my topographic engineer battalion in Hawaii. Personal image.

Figure 8. Printing press at the base plant operated by my topographic engineer battalion in Hawaii. Personal image.

Figure 9. Map production & warehouse buildings (four large buildings in the rear) in my topographic engineer battalion in Germany. Personal image.

CHANGES IN MAP ACCURACY STANDARDS

The N*ational Map Accuracy Standards* (NMAS) of 1947 pertained to graphic contour maps with a published scale and contour interval, defining horizontal and vertical accuracy as follows:

- Circular Map Accuracy Standard (CMAS): “For maps on publication scales larger than 1:20,000, not more than 10 percent of the points tested shall be in error by more than 1/30 inch, measured on the publication scale; for maps on publication scales of 1:20,000 or smaller, 1/50 inch. These limits of accuracy shall apply in all cases to positions of well-defined points only.”
- Vertical Map Accuracy Standard (VMAS): “Vertical accuracy, as applied to contour maps on all publication scales, shall be such that not more than 10 percent of the elevations tested shall be in error more than one-half the contour interval. In checking elevations taken from the map, the apparent vertical error may be decreased by assuming a horizontal displacement within the permissible horizontal error for a map of that scale.”

The NMAS had no limits on the magnitude of errors for the 10 percent outliers.

In 1990, ASPRS published its Accuracy Standards for Large-Scale Maps, again focused on printed maps:

- “Horizontal map accuracy is defined as the root-mean-square (rms) error in terms of the project’s planimetric survey coordinates (X, Y) for checked points as determined at full (ground) scale of the map. The rms error is the cumulative result of all errors including those introduced by the processes of ground control surveys, map compilation and final extraction of ground dimensions from the map. The limiting rms errors are the maximum permissible rms errors established by this standard.” The limiting rms errors for Class 1 maps were tabulated in tables, along with typical map scales associated with the limiting errors.
- “Vertical map accuracy is defined as the rms error in elevation in terms of the project’s elevation datum for well-defined points only. For Class 1 maps the limiting rms error in elevation is set by the standard at one-third the indicated contour interval for well-defined points only. Spot heights shall be shown on the map within a limiting rms error of one-sixth of the contour interval.”
- Class 2 and Class 3 maps could have errors 2 or 3 times larger, respectively, than Class 1 maps.

In 1998, the Federal Geographic Data Committee (FGDC), assuming all mapping errors follow a normal error distribution, published the National Standard for Spatial Data Accuracy (NSSDA), specifying that horizontal and vertical errors should be reported at the 95% confidence level, based on RMSEx and RMSEy, translated into radial RMSEr for horizontal accuracy, and RMSEz for vertical accuracy.

- Horizonal accuracy at the 95% confidence level (ACCURACYr) = 1.7308 × RMSEr
- Vertical accuracy at the 95% confidence level (ACCURACYz) = 1.9600 × RMSEz

I subsequently performed extensive research into lidar errors and determined that: (1) lidar bare-earth DTM errors in vegetated terrain do not follow a normal error distribution; (2) the use of RMSEz in vegetated terrain significantly overstates the vertical errors; and (c) vertical errors in vegetated terrain should be defined in terms of the 95th percentile, rather than RMSEz. This resulted in publication of the National Digital Elevation Program (NDEP) *Guidelines for Digital Elevation Data*, Version 1.0, as well as the *ASPRS Guidelines, Vertical Accuracy Reporting for Lidar Data*, Version 1.0, both published in 2004.

In 2014, the *ASPRS Positional Accuracy Standards for Digital Elevation Data* were published. I chaired the committee that also included Dr. Qassim Abdullah, Karl Heidemann, and Doug Smith. These new standards replaced the existing *ASPRS Accuracy Standards for Large-Scale Maps* (1990) and the *ASPRS Guidelines, Vertical Accuracy Reporting for Lidar Data* (2004) to better address current digital mapping technologies. Map accuracy classes 1, 2, and 3 no longer exist.

- Recognizing that many applications of horizontal accuracy cannot be tied directly to compilation scale, resolution of digital source imagery, or final pixel resolution, and that geospatial data does not suddenly get more accurate just because an analyst on a computer can display digital data at higher resolution, horizontal accuracy is defined in terms of horizontal accuracy classes based on RMSEx and RMSEy, from which RMSEr and horizontal accuracy at the 95% confidence level can be computed. Tables included horizontal accuracy classes between 0.63 cm and 10 meters. The new standard also specifies the allowable size of orthoimagery mosaic seamline mismatches, in terms of horizontal accuracy classes for RMSEx and RMSEy.
- Vertical accuracy is computed using RMSEz statistics in non-vegetated terrain and 95th percentile statistics in vegetated terrain. Tables included vertical accuracy classes between 1 cm and 3.33 meters and included standards for Non-Vegetated Vertical Accuracy (NVA) at the 95% confidence level and Vegetated Vertical Accuracy (VVA) at the 95th percentile.

The 2014 standards provided additional guidance on checkpoint density and distribution, accuracy reporting, designation of low confidence areas, and other factors.

CHANGES IN SURVEYING AND GEODESY

At Ethiopia's request, my topographic engineer battalion in Germany was tasked to establish geodetic control monuments in Ethiopia in the 1960s as the foundation for topographic mapping. Like national mapping agencies worldwide, Army surveyors used T-3 theodolites to measure vertical and horizontal angles for triangulation from Bilby towers, also used by the U.S. Coast and Geodetic Survey (USC&GS) through the 1980s (Figures 10 and 11). We used surveyor tapes to measure distances prior to the introduction of electronic distance measuring equipment (EDME). We used Bilby towers to see above obstacles and establish line-of-sight to survey targets at long distances; on a clear day, T-3 theodolites could accurately measure horizontal and vertical angles to survey targets over 50 miles away.

Bilby towers had two unconnected parts – an internal tower for mounting surveying instruments and an external tower for surveyors. This separation allowed for isolating the instruments from vibrations caused by people, increasing the precision of measurements. These survey techniques formed the backbone of America's spatial reference framework. Military and civilian surveyors also use(d) differential leveling (Figure 12) to measure vertical offsets between two points to transfer an elevation from a benchmark (BM, with known elevation) to another point (unknown elevation) by a series of

Figure 10. Bilby tower with internal tower (for instrument) isolated from external tower (for surveyor). NOAA Photo Library.

Figure 11. T-3 triangulation measurement from a USC&GS Bilby tower. NOAA Photo Library.

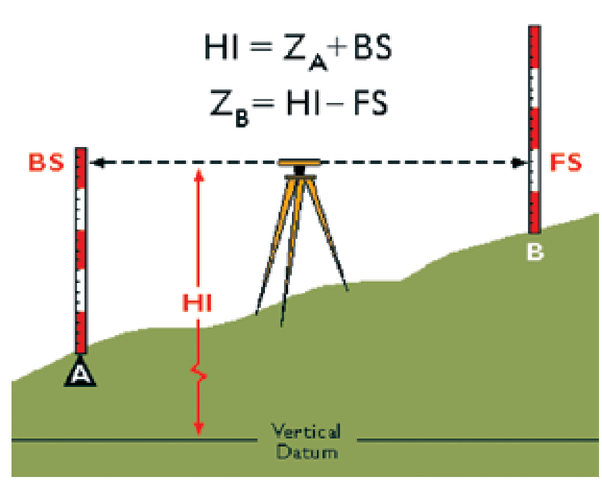

Figure 12. Differential leveling used levels that took foresight (FS) and backsight (BS) elevation differences measured on marked survey leveling rods. NOAA Photo Library.

foresights (FS) and backsights (BS). It took considerable time and expense to establish horizontal monuments and vertical benchmarks nationwide using such techniques.

The Department of Defense's NAVSTAR, now the Global Positioning System (GPS), became fully operational in 1995, though originally intended for military purposes. In 1998, under contract with NGS, I authored the *National Height Modernization Study: Report to Congress* and documented the costs and benefits of modernizing the national height system in the U.S. based on differential GPS measurements relative to Continuously Operating Reference Stations (CORS). Initially seen as a quick way to determine horizontal positions accurately, NGS proved that accurate elevations could also be obtained from high quality GPS receivers and rigorous procedures. Today, following procedures in NOAA Technical Manual NOS NGS-58, *Guidelines for Establishing GPS-Derived Ellipsoid Heights (Standards: 2cm and 5cm)*, GPS is routinely used to transfer elevations from the nearest CORS to local survey points to 2 or 5 cm at the 95% confidence level, negating the need for benchmarks which are subject to subsidence and may otherwise be unstable. GPS revolutionized the surveying and geodesy professions. Airborne GPS is also vital for all types of aerial surveys.

Readers are invited to read "The Evolution of GPS" by Adam Goetsch, at https://illumin.usc.edu/the-evolution-of-gps/

CHANGES IN AERIAL AND SATELLITE IMAGERY

Figure 13. Ted Abrams founded Abrams Aerial Surveys and designed his plane so photos would not be fogged by engine smoke. Source: The Abrams Foundation.

Figure 14. In 1977, Dr. Abrams presented me the Talbert Abrams Grand Award for my research in photogrammetric self-calibration. Source: Personal image.

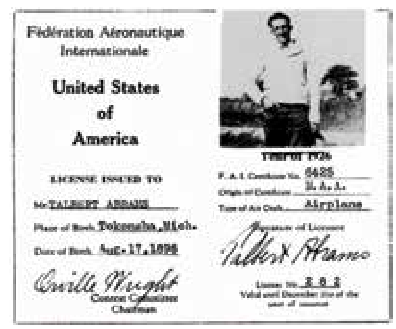

Figure 15. Dr. Abrams bought me a beer and showed me his pilot's license signed by Orville Wright. Source: The Abrams Foundation.

Dr. Talbert "Ted" Abrams was named the *Father of Aerial Photography* for his innovations in aerial photography. As a Marine Corps aerial photographer in Germany during WWI, he took pictures over the side of an open airplane and knew there had to be a better way. He founded Abrams Aerial Surveys and designed an airplane (Figure 13) so that the engine smoke did not obscure aerial images taken with a mounted camera. Film cameras, normally with 6" focal length, acquired 9" × 9" aerial film negatives for decades until large format metric digital cameras were introduced in the early 2000s. He also founded ASPRS' Talbert Abrams Award. When I won his top award in 1977 for my research in photogrammetric self-calibration (Figure 14), he showed me his pilot's license signed by Orville Wright (Figure 15).

Figure 16. Now on display at the National Museum of the United States Air Force near Dayton, OH, the KH-9 Hexagon reconnaissance satellite was declassified on 9/17/2011. At 60-foot length and weighing 15 tons at launch, 19 KH-9 satellites were launched between 1971 and 1986. Panoramic images were film, not digital. Personal image.

I was introduced to satellite imagery in the early 1970s when the US military used Hexagon KH-9 reconnaissance satellites (Figure 16) to map countries with or without their knowledge or consent. I was the Officer-in-Charge of Production for a NATO unit responsible for mapping the Soviet Union, and I was the "sanitation board" authority for determining the security classification of NATO products produced from Top Secret imagery. The KH-9 used film, not digital imagery. Operators ejected the undeveloped film towards earth in reentry vehicles deployed by parachutes. When the object entered the upper atmosphere, the parachute would open and was then "snatched" mid-air by an airplane, with a hooking apparatus beneath the plane, sent to the parachute's expected point of entry. This seemingly difficult feat was remarkably successful, with only one reentry vehicle lost in 15 years of operation. For photogrammetric compilation, the KH-9 panoramic images required rectification to remove distortions caused by tilt. During the Cold War, 19 Hexagon missions imaged 877 million square miles of the earth's surface between 1971 and 1986.

NASA's Earth Resources Technology Satellite (ERTS) was launched July 23, 1972, collecting digital multispectral imagery. Later renamed, Landsat 1 became the first earth-observing satellite explicitly designed to study planet earth. In 1993, the U.S. Department of Commerce granted DigitalGlobe the first license for private enterprise to build and operate a satellite system to gather high-resolution digital imagery of earth for commercial sale. Today, there are dozens of options for collecting aerial or satellite panchromatic, natural-color, multispectral, hyperspectral, or radar digital imagery optimized for a large variety of user applications.

In 2001, Leica introduced the first large format, calibrated digital mapping camera with its ADS40 pushbroom camera; Dewberry was the first to produce digital orthophotos for USGS using a digital mapping camera. Other calibrated metric digital mapping cameras soon followed. All digital mapping cameras have continued to improve to this day, widely used for federal, state, and local mapping projects. With the recent popularity of Structure from Motion (SfM) photogrammetry, small-format consumer-grade non-calibrated cameras are now used for image acquisition for small mapping projects where redundant observations by multiple look angles allow for camera self-calibration.

The *PE&RS Mapping Matters* monthly column by Dr. Qassim Abdullah, has chronicled the recent advances in aerial imaging and photogrammetry.

CHANGES IN PHOTOGRAMMETRY

The May 2021 issue of *PE&RS* included my Tips & Tricks article on aerial triangulation over the years with what I call four generations of photogrammetry: analog, analytical, digital, and SfM. I first learned to be a photogrammetrist using first-generation analog stereo plotters, which attempted to physically replicate the geometry that existed when aerial film photos were taken. Stereoplotters used glass stereo diapositives to compile topographic maps.

The Army trained me to use the Multiplex (Figure 17), which had a series of projectors with reduced-scale 2" × 2" diapositives in individual projectors for each photo in a flight line. The long projector bar could be lengthened with more projectors added for longer flight lines. Based primarily on optics, Multiplexes were still used by the U.S. Army in the 1960s, unchanged from what was used during WW II. Subsequently, Kelsh Plotters were widely used with full-size 9"x9" diapositives. When I went to OSU, I learned analog photogrammetry on the Wild A-7 (Figure 18), an optical-mechanical stereo plotter with hand cranks to move in x and y directions and a foot petal to change elevations for contouring; by keeping a "floating dot" on the ground for a set elevation, the photogrammetrist would trace a contour line of equal elevation. We also learned 2nd-generation analytical photogrammetry which mathematically replicated the physical geometry when stereo hardcopy photos were taken by metric film cameras. My PhD dissertation was on photogrammetric self-calibration, which became relevant with the latest 4th-generation SfM photogrammetry that does not require calibrated metric cameras. Dewberry has used SfM on several Alaska airfield mapping projects.

As fate would have it, I became heavily involved with the development of third-generation digital photogrammetry. As Commander and Director of the U.S. Army Engineer Topographic Laboratories (ETL) and Topographic Engineering Center (TEC) between 1988 and 1991, my organization developed the first Digital Stereo Photogrammetric Workstation (DSPW), now marketed as SocetSet, as well as the first high-resolution scanner to convert film images into

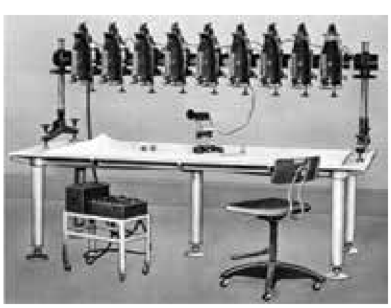

Figure 17. Multiplex projectors where I first learned to perform stereo photogrammetric map compilation in the Army. This was the easiest to visualize how aerial geometry was replicated at reduced scale to perform relative and absolute orientation. Source: US Army.

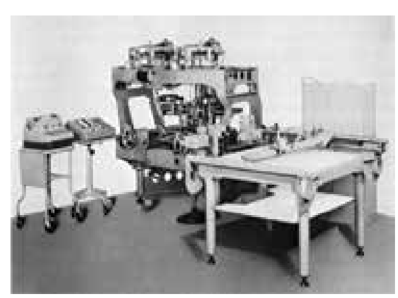

Figure 18. Wild A-7 stereo plotter with drafting table that I used to study photogrammetry at OSU. Here, only one stereo pair at a time underwent relative orientation. Although this had advantages, absolute orientation was harder to perform after bridging between multiple stereo pairs, one at a time. Source: Personal image.

digital images, subsequently marketed as PhotoScan-1. These two systems were part of the Army's Terrain Information Extraction System (TIES) introduced in 1991. Dewberry now uses SocetSet as our prime digital photogrammetric software. Thus, in one way or another, I have worked with all four generations of photogrammetry during my 60-year career.

Founded in 1934 as the American Society of Photogrammetry (ASP), and renamed the American Society for Photogrammetry and Remote Sensing (ASPRS) in 1985, the society has now published six editions of the *Manual of Photogrammetry* as well as many other publications dealing with various forms of remote sensing, imaging, and geospatial information, as well as the *ASPRS Positional Accuracy Standards for Digital Geospatial Data*.

CHANGES IN RADAR

During my Army career, we used many forms of aerial and satellite radar systems for mapping and intelligence purposes. Several Synthetic Aperture Radar (SAR) exploitation systems were developed by ETL/TEC. During the first Gulf War in 1991, General Normal Schwarzkopf named several of our Army SAR systems as being instrumental in his ability to see the total battlefield in Iraq better than Saddam Hussein could see in his own back yard, or words to that effect. Of course, the main advantage of radar is that it enabled allied forces to perform our mapping and surveillance operations in all weather conditions, as radar maps through clouds, fog, and haze.

During my Dewberry career, one of my major achievements was in mapping all of Alaska with aerial Interferometric Synthetic Aperture Radar (IfSAR). I chose this technology because it mapped through clouds, a persistent problem in Alaska that, until 2008, had prevented Alaska from being mapped to established mapping standards at any scale. Figure 19 shows the advantage of aerial IfSAR in Alaska that also had the advantage of showing hydrographic features loud and clear. These IfSAR datasets are now used by Dewberry and others for Elevation Derived Hydrography (EDH) of Alaska.

Today, SAR satellites are extremely common for continental-scale mapping and change detection, and Differential Interferometric Synthetic Aperture Radar (DInSAR) is ideal for mapping the annual rates of land subsidence that compounds the effects of sea level rise worldwide.

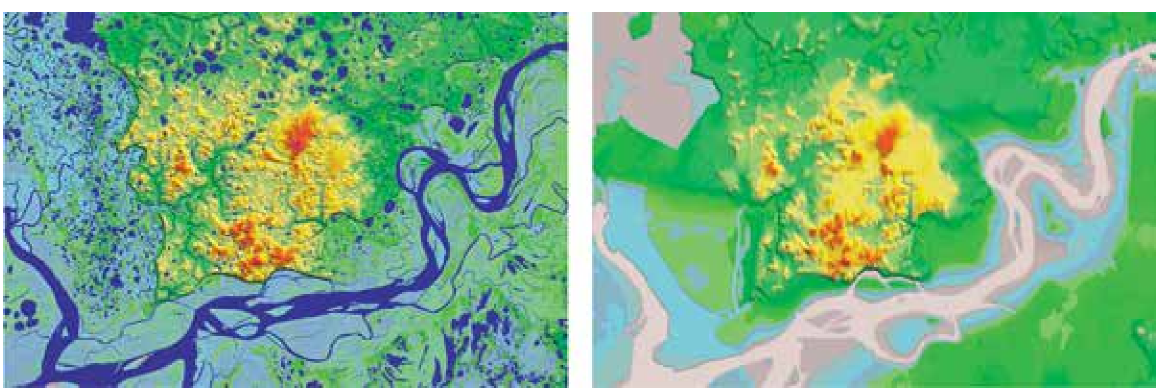

Figure 19. The aerial IfSAR Digital Terrain Model (DTM)(left) was vastly superior to the prior photogrammetric DTM (right) produced from satellite imagery for the National Elevation Dataset (NED). Source: Intermap

CHANGES IN LIDAR

In 1997, for the Federal Emergency Management Agency (FEMA), I evaluated the use of lidar and IfSAR for floodplain mapping and modeling for the National Flood Insurance Program (NFIP), and I wrote all of FEMA's lidar guidelines and specifications between 1997 and 2010 when USGS published its first Lidar Base Specifications. In 1998, for the National Geodetic Survey (NGS), I authored the *National Height Modernization Study: Report to Congress* on how to modernize the National Height System in the U.S. based on GPS surveys relative to CORS (in lieu of differential leveling), and nationwide elevation mapping with lidar and IfSAR (in lieu of photogrammetric mapping of DEMs).

In 2000, ASPRS asked me to write a book on lidar and IfSAR, and I agreed to edit and co-author the first edition of *Digital Elevation Model Technologies and Applications: the DEM Users Manual* (published in 2001) with chapters on photogrammetry, IfSAR, topographic lidar, bathymetric lidar, and sonar, as I've always visualized a worldwide DEM from the tops of the mountains to the depths of the seas, including inland bathymetry.

Whenever I autograph a copy of the DEM Users Manual, I write "May all your DEMs come true!" When the second edition was published in 2007, I had three basic dreams: (1) Development of high-accuracy, affordable elevation technologies for betterment of society; (2) Development of DEM technology standards, guidelines and specifications, and (3) Implementation of a nationwide program to produce and maintain standardized high-quality DEMs used by all. These three dreams have largely been realized and documented in the third edition published in 2018. My lidar dreams for the future are documented in the third edition.

Although I had almost nothing to do with the development of lidar or IfSAR (my dream #1), I was the major champion of lidar for 20 years and ended up being named the Father of Lidar by the International Lidar Mapping Forum (ILMF) and *LiDAR Magazine* in 2018 for my roles in dreams #2 and #3, having authored the major lidar standards, guidelines and specifications, as well as the National Enhanced Elevation Assessment (NEEA) that led directly to today's 3D Elevation Program (3DEP).

The 3DEP is widely heralded as a major success, having acquired Quality Level 2 (QL2) or better topographic lidar for most of the country, and QL5 IfSAR of Alaska. The map at Figure 20 shows the geographic extent of completion of the first-ever national baseline of consistent high-resolution elevation data – both bare earth and lidar point clouds – as of 2022.

Recognizing the importance of dual-frequency (red/green) topographic-bathymetric (topobathy) lidar, my boss, Amar Nayegandhi, has been an industry leader and authored the topographic lidar and bathymetric lidar chapters in the third edition of the *DEM Users Manual*, as well as in USACE EM 1110-1-1000, *Photogrammetric and Lidar Mapping*, for the U.S. Army Corps of Engineers. Dewberry now owns and operates two state-of-the-art topobathy lidar sensors, as well as a topographic lidar sensor.

When water clarity allows, topobathy lidar does an outstanding job of mapping both the topographic and bathymetric surfaces, as shown in Figure 21 which revealed the previously unknown bathymetric surface beneath waters in the Potomac River. When water clarity is poor, because of water turbidity and/or presence of significant aquatic vegetation, as shown in Figure 22, topobathy lidar data voids will occur that require sonar to fill in the gaps.

In September of 2022, the 3D Nation Elevation Requirements and Benefits Study (Figure 23) was completed by Dewberry for NOAA/NGS and USGS, primarily authored by Sue Hoegberg of Dewberry. I was pleased to see that the "3D Nation" vision included inland topography and inland bathymetry (for USGS), and nearshore and offshore bathymetry (for NOAA) – each with their own technologies and user applications. The USGS link to the study is at https://

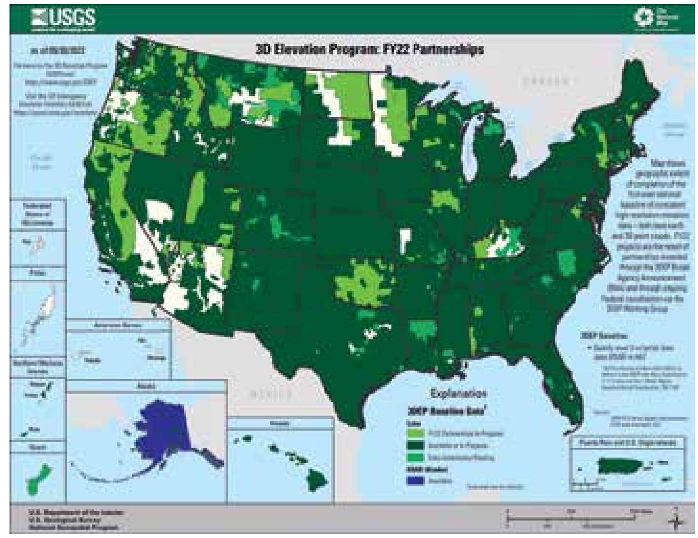

Figure 20. Geographic extents of QL2 or better lidar for 49 states and US territories and QL5 IfSAR of Alaska. Source: USGS.

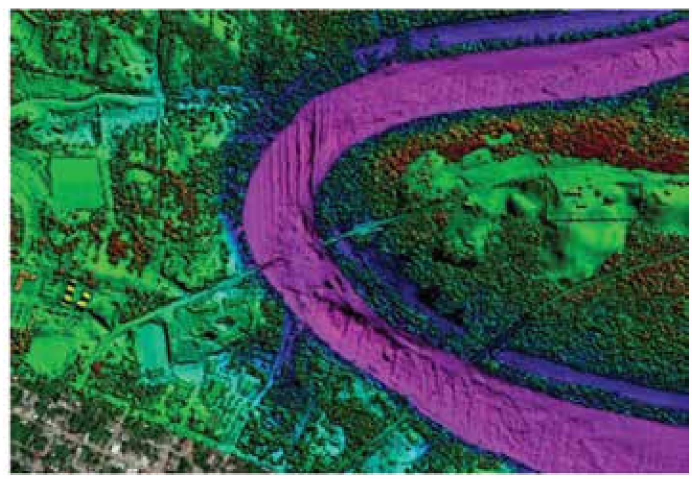

Figure 21. Topobathy lidar produced by Dewberry for USGS, showing the topo-bathy surface along the Potomac River near Shepherdstown, WV. Source: Dewberry.

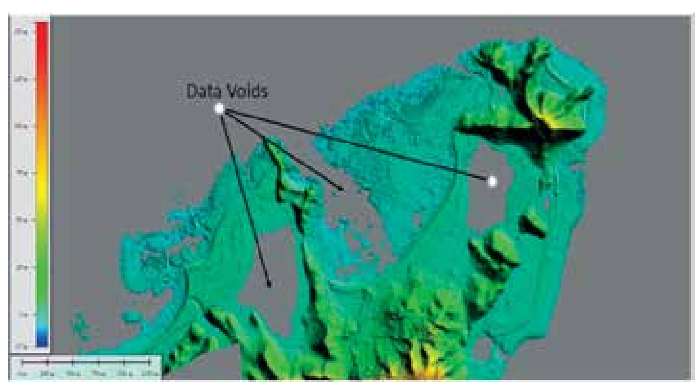

Figure 22. Example of a seamless topobathy lidar data surface in Puerto Rico, including data voids where aquatic vegetation, bioluminescence or sediments in the water prevented penetration by the green laser. The data voids in outer areas occurred where the laser extinction depth was exceeded. Source: Dewberry

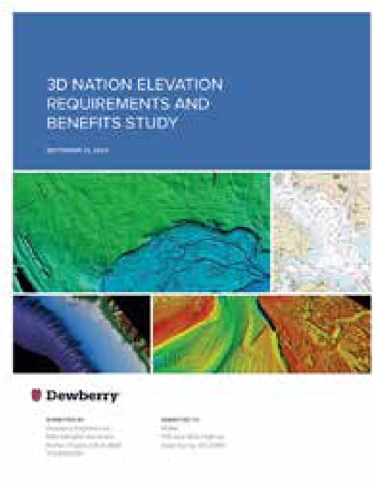

Figure 23. Front cover of the 3D Nation Elevation Requirements and Benefits Study. Source: Dewberry

www.usgs.gov/3d-elevation-program/3d-nation-elevation-requirements-and-benefits-study, which points to https://www.dewberry.com/services/geospatial-mapping-and-survey/3d-nation-elevation-requirements-and-benefits-study.

In October 2022, USGS posted a technical announcement for the 3D Nation Study, which can be found here: https://www.usgs.gov/news/technical-announcement/results-are-3d-nation-study-report-now-available.

Kevin Gallagher, USGS Associate Director for Core Science Systems said: "This study is foundational to our future direction of the 3D National Topography Model that integrates elevation and hydrography in 3D. The 3D National Topography Model will provide the terrestrial component of the 3D Nation vision we share with NOAA to build a continuous elevation and hydrography surface from the peaks of our mountains to the depths of our waters." Similarly, NOAA developed a blog post about the study.

For inland bathymetry, Figure 24 shows where topographic lidar was merged with topobathy lidar of the Lower Withlacoochee River (Florida) for a 22.5 mi^2 area. The CZMIL topobathy lidar coverage area was 12.5 mi^2. Topobathy lidar was unable to get bottom returns in the deeper parts of the river channel due to multiple bathymetric factors: depth, tannic water, and mucky bottom substrate. The areas outside the channel were shallow enough to overcome the bottom and water turbidity issues. Figure 25 shows where Multibeam Echo Sounder (MBES) sonar was collected for the deeper parts of the channel (0.3 mi^2 or 14 linear river miles); and Single Beam Echo Sounder (SBES) sonar with a HyDrone in the two dam spillway areas that were too shallow for MBES and too turbid for lidar. Figure 26 shows the successful merger of the topographic lidar, topobathy lidar, and sonar data to map the entire topographic-bathymetric surface. This is representative of what needs to be done for rivers and lakes nationwide in order to fully satisfy objectives of the 3D Nation initiative.

Figure 24. Topobathy lidar mapped portions of the river, but not the deeper tannic waters with mucky bottom. Image source: Dewberry.

Figure 25. Multibeam sonar mapped the deeper parts of the river not mapped with topobathy lidar. Image source: Dewberry.

Figure 26. By merging the two datasets, the entire topographic and bathymetric surface was mapped seamlessly. Image source: Dewberry.

CHANGES IN SONAR

During my first 30-year career, in the U.S. Army Corps of Engineers, I never managed hydrographic surveys. However, between 1988 and 1991, while serving as Commander and Director, U.S. Army Engineer Topographic Laboratories (ETL) and Topographic Engineering Center (TEC), my organization authored what was then the latest version of USACE Engineering Manual EM 1110-2-1003, *Hydrographic Surveying*, which explained technologies and best practices for SBES and MBES surveys.

During my second 30-year career with Dewberry, I specialized in DEMs from all technologies, and all three editions of my *DEM Users Manual* included chapters on photogrammetry, IfSAR, topographic and bathymetric lidar, and sonar. The sonar chapters were all authored by Captain Guy Noll (NOAA Corps, retired) and different co-authors he selected. I always considered the underwater bathymetric surface to be a continuation of the above-water topographic surface.

Between 2015 and 2022, I served as a member of NOAA's Hydrographic Services Review Panel (HSRP), which authored numerous issue papers relevant to sonar and hydrographic surveys. In 2019, the Presidential Memorandum on *Ocean Mapping of the United States Exclusive Economic Zone (EEZ)* and *Shoreline and Nearshore of Alaska* was issued. Section 2 called for a National Ocean Mapping, Exploration, and Characterization (NOMEC) strategy. Section 3 of that memorandum directed the NOAA Administrator, in coordination with the state of Alaska and the Alaska Mapping Executive Committee (AMEC) – co-chaired by NOAA and the USGS - to develop a proposed strategy to map the shoreline and nearshore of Alaska and inform actions of the Ocean Policy Committee and relevant agencies. NOAA subsequently developed two strategies – one for the NOMEC and another for the ACMS. I was the primary author of the HSRP whitepaper with HSRP recommendations to NOAA on the implementation plan for the ACMS, including the use of Uncrewed Surface Vessels (USVs) and Autonomous Surface Vessels (ASVs).

By then, the 3D Nation Elevation Requirements and Benefits Study had already been in progress for several years, documenting how nearshore bathymetry had not been collected for most of coastal Alaska, and offshore bathymetry had not been collected for major portions of the U.S. Exclusive Economic Zone (EEZ). As stated above, the final 3D Nation Study report was released in September of 2022, including evaluations of relevant technologies that could most cost-effectively address the major unmet needs for MBES surveys. See: https://www.dewberry.com/services/geospatial-mapping-and-survey/3d-nation-elevation-requirements-and-benefits-study, which includes an analysis of technology trends and risk considerations.

Whereas there are many excellent commercial multibeam sensors available, it is the platforms for those sensors that will have the greatest impact on future benefits vs. costs. For years, crewed systems for MBES have been the norm; but uncrewed systems are now making inroads as force-multipliers, either with a crewed mothership (Figures 27 and 28) or as stand-alone collection platforms. But crewed motherships are very expensive to operate, e.g., $40,000 or more per day for the mothership shown in Figure 27.

To reduce costs dramatically for MBES surveys of large areas, several new ASV platforms have emerged that do not require crewed motherships. They are generally powered by wind-energy, solar-energy, batteries and/or micro diesel engines. They operate 24/7, often monitored and controlled from mission control thousands of miles away. They often have complex situational awareness sensors and communications for data transfer and to enable remote operators to monitor progress and take corrective actions if needed. Depending on the platform used, they can autonomously collect MBES data for hours, days, weeks, and months between services.

I see these ASVs as the future for ocean mapping, and I believe they will revolutionize the way that multibeam sonar is collected, cost-effectively, for the world's large unmapped oceans and coastlines.

Figure 27. Larger vessel (mothership) used for traditional MBES surveys in deeper water and CW5 USV (yellow) used for shallow-water surveys. Source: TerraSond.

Figure 28. With the mothership in the background, such USVs are ideal for shallow-water surveys using a variety of SBES or MBES sensors. Source: TerraSond.

CHANGES IN GEOPHYSICAL MAPPING

Geophysical mapping involves the non-invasive investigation of subsurface conditions in the earth through measuring, analyzing, and interpreting physical properties at or close to the surface.

When geodesists like myself study geophysics, it normally boils down to measurements of gravity, needed to develop or improve geoid models to convert ellipsoid heights (from GPS observations) into orthometric heights (elevations). For years, Dewberry has been collecting airborne gravity data for NGS' Gravity for the Redefinition of the American Vertical Datum (GRAV-D). Dewberry has also used Ground Penetrating Radar (GPR) to detect underground utilities; and in 2016, we sponsored a GPR survey to measure the depth of the ice and snow on the peak of Denali, America's tallest mountain; we had previously determined the elevation at the top of the ice and snow using redundant GPS/GNSS receivers. When I started mapping, I barely understood magnetic declinations and the earth's changing magnetic field.

In 2019, USGS announced the Earth Mapping Resources Initiative (Earth MRI), apparently choosing this acronym for its similarity to a human MRI which maps inside the human brain. The Earth MRI is a geophysics initiative to map geologic features beneath the surface of the earth.

USGS' Earth MRI home page (https://www.usgs.gov/special-topics/earth-mri) states that the goal of Earth MRI is to improve our knowledge of the geologic framework in the U.S.

and to identify areas that may have the potential to contain undiscovered critical mineral resources. Enhancement of our domestic mineral supply will decrease the Nation's reliance on foreign sources of minerals that are fundamental to our security and economy. The home page provides greater details on why Earth MRI is needed; how the Earth MRI is being implemented; and Earth MRI acquisitions completed or planned.

As part of our Geospatial Products and Services Contracts (GPSC3 and GPSC4) with USGS, the Dewberry team has been awarded Earth MRI task orders for over a million line-kilometers of magnetic and radiometric (MAG-RAD) data acquired at low-altitude, typically 80 to 100 meters above the terrain, where safety is a major factor. Data are acquired at higher altitudes over cities and other sensitive locations. Two dimensional drape surfaces are established to provide vertical guidance over the terrain to an aircraft flying narrowly spaced traverse lines normally flown perpendicular to the dominant local geological trend, spaced a few hundred meters apart, and widely spaced tie or control lines flown perpendicular to the traverse lines, spaced from 5 to 10 times greater than the traverse line spacing. At the crossing points between traverse lines and tie-lines, flying heights must agree within small tolerances, requiring special aircraft guidance systems and expert pilots. When the terrain is relatively flat, specially equipped fixed wing aircraft are used, as shown at Figure 29, with the magnetic sensor housed in a "stinger" at the rear. In rugged terrain, specially equipped helicopters are required, shown equipped with a stinger in Figure 30, or alternatively with a "bird" towed beneath the helicopter as shown in Figure 31.

The airborne equipment includes cesium vapor magnetometers (used to acquire aeromagnetic data), gamma-ray spectrometers, downward facing and upward facing NaI crystals (used to acquire gamma-ray data), navigation and data acquisition systems, GNSS receivers, digital radar altimeters, laser altimeters, digital barometric altimeters, and outside air temperature sensors. Base station equipment includes cesium vapor magnetometers, GNSS receivers, and data acquisition computers.

Wikipedia explains why aeromagnetic surveys are acquired using aircraft with magnetometers housed in "stingers" or towed birds in order to separate the metallic aircraft and its magnetically noisy engine and electronics from the sensitive magnetic sensors. As the aircraft flies, the magnetometer measures and records the total intensity of the magnetic field at the sensor, which is a combination of the desired magnetic field generated in the earth as well as variations mostly due to the temporal effects of the constantly varying solar wind and the magnetic field of the survey aircraft. By subtracting the solar, regional, and aircraft effects, the resulting aeromagnetic map reflects the spatial distribution and relative abundance of magnetic minerals (most commonly the iron oxide mineral magnetite) in the upper levels of the earth's crust. Because different rock types differ in their content of magnetic minerals, the magnetic map allows a visualization of the geological structure in the subsurface, particularly the spatial geometry of bodies of rock, intrusions of volcanic material, and the presence of faults and folds. This is particularly useful where bedrock is obscured by surface sand, soil or water. Aeromagnetic data was once presented as contour plots, but now is more commonly expressed as thematic (colored) and shaded computer generated pseudo-topography images. The apparent hills, ridges, and valleys are referred to as aeromagnetic anomalies. A geophysicist can use mathematical modeling to infer the shape, depth, and properties of the rock bodies responsible for the anomalies.

In "Mineral Exploration: Principles and Applications," the author, Swapan Haldar, explains that radiometric surveys detect and map natural radioactive emanations (γ ray) from rocks and soils. The gamma radiation occurs principally from the natural decay of isotopes of the elements U, Th, and K.

The radiometric method is capable of detecting these elements at altitudes up to 300m above the surface, or greater depending on the strength of the radiation. Some common radioactive minerals that can be detected are uraninite (^{238}U), monazite, thorianite (^{232}Th), feldspar (^{40}K), muscovite, and sylvite in acid igneous rocks. Exploration for these minerals by radiometric survey became important because of the demand for nuclear fuels and also for detection of associated nonradioactive deposits such as titanium and zircon. Isotopes are elements whose atomic nuclei contain the same number of protons but different number of neutrons. Certain isotopes are unstable. They disintegrate spontaneously to generate other elements. Radioactivity means disintegration of atomic nuclei by emission of energy and particles of mass. The by-products of radioactive disintegrations are in various

Figure 29. Fixed-wing geophysics aircraft with stinger in the rear. Image source: Sander Geophysics Ltd.

Figure 30. Rotary-wing geophysics aircraft with stinger in the front. Image source: Sander Geophysics Ltd.

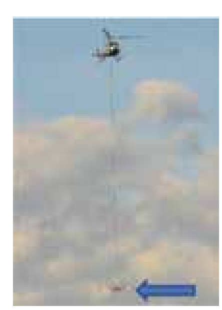

Figure 31. Helicopter with towed "bird" with MAG RAD sensors. Source: Sander Geophysics Ltd.

combinations of alpha (α) particles of helium nuclei, beta particles (β) of electrons emitted by splitting of neutrons and gamma (γ) ray of pure EM radiation. Only the gamma (γ) ray radiation is detectable at any appreciable distance above the ground and emanates from only the top 10cm or less of the earth's surface. Even so, maps of gamma-ray radiation and their relative abundance often reflect underlying geological formations and alteration of lithology, while keeping in mind that in areas of significant overburden the character of the surface gamma-ray may reflect transported material.

When asked how USGS uses this MAG-RAD data for the Earth MRI, Anjana Shah, a Geophysics Chief Scientist at USGS, pointed me to a recently-published article on one of the first Earth MRI projects: https://www.geosociety.org/GSA/Publications/GSA_Today/GSA/GSAToday/science/G512A/article.aspx. She also pointed to upcoming articles in *Economic Geology* explaining how these MAG RAD surveys have identified previously unknown mineral deposits.

SUMMARY – THE BIG PICTURE

I am amazed with the vast improvements in mapping technologies over my 60-year career.

Cartography: In my Army topographic engineer battalion in Germany in the 1960s, we had dozens of the finest German civilian cartographers and dozens of U.S. Army cartographers who spent two years compiling maps and preparing text, scribecoats, and peelcoats for the mapping of one city—Munich, Germany. Those maps were never completed while I was there. After two years, we were told by headquarters, US Army Europe, that new aerial photography was being flown, and we would need to update many of the features we had compiled the past two years.

Recently at Dewberry, we had a FEMA emergency response contract where we proved that, for cities or disaster areas up to 100 square miles, aerial imagery could be acquired, and high-resolution natural color digital orthophotos could be produced and delivered to FEMA within 48 hours of notice to proceed. These 1-meter orthophotos were overlaid with street and administrative boundary vectors, with names for streets and communities. Furthermore, the orthophotos were linked to a database that included location of critical infrastructure, individual building footprints, street addresses, assessed value, names of owners for potential insurance claims, and other geospatial information.

With today's GIS software, cartographic features are accompanied by geodatabases with vast amounts of supporting information. Specialized maps are produced in hours that previously would have taken years to produce.

Map Production and Distribution: With paper maps, large brick and mortar facilities were required for map production, storage, and distribution. Large quantities of new paper maps were produced daily that would replace large quantities of old paper maps that would need to be disposed of daily. Special facilities were required for paper maps and terrain analysis studies that were secret or confidential, with guards and security procedures to prevent such maps from getting into the wrong hands.

Today, with few exceptions, brick and mortar printing plants and map warehouses are obsolete. Maps and terrain analyses are prepared by geospatial specialists working at their desks with GIS or photogrammetric workstations. Digital data are stored in large databases and often served to the public via the cloud. Administrative procedures are in place to protect classified geospatial information.

Map Accuracy Standards: The National Map Accuracy Standards of 1947 defined horizontal and vertical map accuracy standards in terms of the map scale and contour interval of printed topographic maps, assuming all errors had a normal error distribution. However, with digital imagery and lidar, map scales and contour interval could be changed at the push of a button, but the data does not suddenly become more accurate just because it can be displayed at a larger scale or higher resolution on our computers. Furthermore, my personal research demonstrated that elevation errors in lidar bare-earth DEMs in vegetated terrain do not follow a normal error distribution and the 95th percentile should be used in lieu of RMSEz to define the vertical accuracy of lidar bare-earth DTMs in vegetated terrain. I was proud to be a co-author of the ASPRS Positional Accuracy Standards for Digital Geospatial Data, 2014, that established positional accuracy standards for digital orthoimagery, digital planimetric data, and digital elevation data from lidar, and other elevation technologies.

Surveying and Geodesy: The 1st edition of the *DEM Users Manual* has figures that show the large number of miles of First Order differential leveling used for the NGVD 1929 vertical adjustment, as well as the much larger vertical control network required in the NAVD 1988 adjustment. These differential leveling survey lines were extremely expensive and time-consuming. Surveyors needing to establish local vertical control would first need to identify the best and closest benchmarks in the National Spatial Reference System (NSRS); and it could then take days or weeks of differential leveling to determine an acceptable elevation for a single local benchmark or FEMA Elevation Certificate.

Today, in one hour, a surveyor equipped with a geodetic grade GPS receiver can establish local vertical control accurate to 2-cm or 5-cm at the 95% confidence level, relative to Continuously Operating Reference Stations (CORS) located nationwide. Thankfully, Bilby towers are long gone.

Aerial and Satellite Imaging: For my first decade in the mapping profession, film imagery was the only option.

Navigating largely by visual means, looking out the airplane windows and through view-finders, pilots and aerial photographers had to be extremely skilled to acquire aerial photos of the desired area with the correct position for photo centers, forward overlap, sidelap, and exposure controls; and experienced photolab personnel developed the film to produce acceptable film negatives and diapositives. Then think of the complexity in retrieving satellite film imagery from space, having to return miles of film from space to the earth for developing as we did with the KH-9 Hexagon satellites.

Today, with modern digital mapping cameras, automated exposure controls, inertial measurement units, airborne GPS, and modern flight management systems, personnel can be quickly trained to acquire digital imagery with the correct photo centers, forward overlap and sidelap, and optimal exposure controls. Of course, satellite images are now all digital and are easily transmitted back to earth for mapping and analyses.

Photogrammetry: When I first learned photogrammetry on the Multiplex, it would take up to eight hours to bring a single stereo pair of images into relative orientation. Then additional images would be added, one at a time, to bring subsequent stereo pairs into relative orientation. Then at the end of a flight line, absolute orientation would need to be performed on the entire strip in order to correctly scale the model and fit ground control on both ends of the strip. We didn't have a good way to perform block triangulation with dozens or hundreds of overlapping flight lines.

Today, with automated image correlation as well as position and orientation recorded for each image, Dewberry reviewed a large block triangulation with over 20,000 digital images acquired by 11 different cameras for a 4,000+ mi^2 area, and the software told us there was a problem with only one of those images. A review identified that the wrong calibration parameters had been entered for that one problem image; after correction, the block triangulation was successfully completed, in a few hours, for those 20,000+ images that each formed stereo pairs with about eight surrounding and overlapping images.

Radar: In the past, I primarily looked to radar as a low-resolution reconnaissance tool, mostly valuable to the military for broad area surveillance.

Today, I know that aerial IfSAR was the perfect tool for mapping through clouds in Alaska or anywhere worldwide where clouds are an issue. I've also learned the value of using DInSAR, with current and archived satellite SAR images, to map annual rates of subsidence at the cm- or even mm-level per year.

Lidar: For the first half of my 60-year career, neither photogrammetry nor radar could accurately map the elevations of bare earth terrain in forested areas. With aerial imagery, the ground beneath the trees could not be mapped in stereo because there were trees in the way; and radar generally mapped the top reflective surface, i.e., treetops.

Topographic lidar, with red lasers, came along in the 1990s, and we suddenly had the tool that map makers have needed for centuries to map the bare earth terrain everywhere; the 3DEP has been a huge success because of advances in topographic lidar. Bathymetric lidar, with green lasers, and topobathy lidar with both red and green lasers, came along to map subsurface bathymetry when waters are reasonably clear. The 3D Nation initiative will depend on topobathy lidar for mapping the Nation's inland and nearshore bathymetry. I will closely monitor its progress after I retire.

Sonar: The world has long needed multibeam sonar to map the bottoms of rivers and oceans; but crewed vessels with multibeam sonar are very expensive to operate, leaving vast areas of our rivers, coastlines and oceans unmapped because of affordability issues.

I see USVs and ASVs as the solution to this dilemma, and I will also closely monitor the utilization of USVs and ASVs after I am retired.

Geophysics: My prior knowledge of geophysics was minimal. My only college course in geophysics concentrated on gravity. I learned that geodesists could use satellites to gather data on gravitational changes as they pass over points on the earth's surface; on land, gravimeters measure the earth's gravitational pull on a suspended mass. Dewberry has been flying gravimeters for years for NGS' GRAV-D program needed to update our official vertical datum from NAVD88 to the upcoming North American-Pacific Geopotential Datum of 2022 (NAPGD2022); then we can more-accurately convert ellipsoid heights (from GPS or airborne GPS measurements) into orthometric heights, commonly known as elevations. I studied very little about the earth's magnetic field and knew just enough to be dangerous. I knew that the earth's magnetic field was continuously changing, and NOAA had a calculator for computing magnetic declinations shown on maps and charts. But when my boss, Sid Dewberry, asked me what Dewberry should do about the earth's changing magnetic field, I could not think of an answer.

Today, I am amazed to experience the use of magnetic and radiometric surveys for the earth MRI initiative. Being able to map the probable location of underground critical minerals and rare earth elements "blows me away." In retirement, I also plan to follow the progress of this exciting initiative so vital for our future economy and security.

During my 60-year career, we've come a long way with all these technologies. I am proud to have been actively involved in the development and/or maturation of many of these technologies, and I am so grateful to see the major improvements in our profession.