Appendix L – Technology Trends and Risk Considerations

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Introduction to Accuracy Classes, Quality Levels and Accuracy Orders

The questionnaire for the 3D Nation Elevation Requirements and Benefits Study was largely based on obtaining user requirements for topographic and bathymetric data point density and accuracy.

This section explains the American Society for Photogrammetry and Remote Sensing (ASPRS) Positional Accuracy Standards for Digital Geospatial Data which provides vertical Accuracy Classes for topographic data; topographic data Quality Levels (QLs) used by the U.S. Geological Survey (USGS) for the 3D Elevation Program (3DEP); bathymetric data Quality Levels (QLBs) used for inland bathymetry and nearshore bathymetry by USGS, the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Army Corps of Engineers (USACE); and Accuracy Orders used by NOAA and the International Hydrographic Organization (IHO) for offshore bathymetry. Subsequent sections will address technologies for satisfying those user requirements.

The most common vertical accuracy classes for Digital Elevation Models (DEMs) relevant to topographic and topobathymetric (topobathy) lidar, photogrammetry, or Interferometric Synthetic Aperture Radar (IfSAR or InSAR) are in Table L.1. For Absolute Accuracy, this table establishes Vertical Accuracy Classes based on vertical root mean square error ($RMSE_z$) in non-vegetated terrain; translates $RMSE_z$ into Non-vegetated Vertical Accuracy (NVA) at the 95% confidence level; and provides Vegetated Vertical Accuracy (VVA) thresholds at the 95th Percentile, used in lieu of $RMSE_z$ because vertical errors in vegetated terrain do not follow a normal distribution. It also provides Relative Accuracy thresholds largely designed for overlapping lidar swaths, including maximum difference and vertical root mean square deviation ($RMSD_z$).

Table L.1. ASPRS vertical accuracy classes for topographic data

Vertical Accuracy Class (cm)	Absolute Accuracy			Relative Accuracy (where applicable)		
	$RMSE_z$ Non-Vegetated (cm)	NVA at 95% Confidence Level (cm)	VVA at 95th Percentile (cm)	Within-Swath Hard Surface Repeatability (Max Diff) (cm)	Swath-to-Swath Non-Veg Terrain ($RMSD_z$) (cm)	Swath-to-Swath Non-Veg Terrain (Max Diff) (cm)
5	5	9.8	15	3	4	8
10	10	19.6	30	6	8	16
20	20	39.2	60	12	16	32
30	30	58.8	90	18	24	48
40	40	78.4	120	24	32	64
50	50	98.0	150	30	40	80
100	100	196.0	300	60	80	160

Vertical Accuracy Class (cm)	Absolute Accuracy			Relative Accuracy (where applicable)		
	RMSE$_z$ Non-Vegetated (cm)	NVA at 95% Confidence Level (cm)	VVA at 95th Percentile (cm)	Within-Swath Hard Surface Repeatability (Max Diff) (cm)	Swath-to-Swath Non-Veg Terrain (RMSD$_z$) (cm)	Swath-to-Swath Non-Veg Terrain (Max Diff) (cm)
200	200	392.0	600	120	160	320

Inland Topography Quality Levels

As used by the USGS for the 3DEP, Table L.2 shows the data density and accuracy, by topographic Quality Levels, for inland topography.

Table L.2. Quality Levels for topographic data density and absolute vertical accuracy

Quality Level (QL)	Aggregate Nominal Pulse Spacing	Aggregate Nominal Pulse Density	RMSEz (non-vegetated)	NVA at 95% confidence level	VVA at 95th percentile
QL0 HD	≤0.22 m	≥20 ppsm	≤5 cm	≤9.8 cm	≤15.0 cm
QL0	≤0.35 m	≥8 ppsm	≤5 cm	≤9.8 cm	≤15.0 cm
QL1 HD	≤0.22 m	≥20 ppsm	≤10 cm	≤19.6 cm	≤30.0 cm
QL1	≤0.35 m	≥8 ppsm	≤10 cm	≤19.6 cm	≤30.0 cm
QL2	≤0.71 m	≥2 ppsm	≤10 cm	≤19.6 cm	≤30.0 cm
QL5*	≤5 m	≥0.04 ppsm	≤100 cm	≤196 cm	≤300 cm

*Only applicable for IfSAR in Alaska

Inland and Nearshore Bathymetry Quality Levels

Table L.3 shows the data density and accuracy, by QLBs, for inland and nearshore bathymetry. These QLBs are also tied to IHO Accuracy Orders used with sonar.

Table L.3. Quality Levels for inland and nearshore bathymetric data density and absolute vertical accuracy

	QL0B	QL1B	QL2B	QL3B	QL4B
	IHO Special Order				IHO Order 1
Aggregate Nominal Pulse Spacing	≤0.7 m	≤2.0 m	≤0.7 m	≤2.0 m	≤5.0 m
Aggregate Nominal Pulse Density	≥2.0 ppsm	≥0.25 ppsm	≥2.0 ppsm	≥0.25 ppsm	≥0.04 ppsm
Depth Examples (m)	**Vertical Accuracy of submerged elevations at 95% Confidence Level (cm)**				
0	25.0	25.0	30.0	30.0	50.0
10	26.1	26.1	32.7	32.7	51.7
20	29.2	29.2	39.7	39.7	56.4
Applications	Detailed site surveys requiring the highest accuracy and highest resolution seafloor definition; dredging and inshore engineering surveys; high-resolution surveys of ports and harbors		Charting surveys; regional sediment management; general bathymetric mapping; coastal science and management applications; change analysis; deep water surveys; environmental analyses		Recon/planning; all general applications not requiring higher resolution and accuracy

Offshore Bathymetry Accuracy Orders

Table L.4 shows the data density and accuracy, by IHO Accuracy Order, for offshore bathymetry acquired by acoustic surveys (sonar) where accuracy is depth dependent.

Table L.4. IHO Minimum standards for hydrographic surveys

Order	Special	1a	1b	2
Description of areas	Areas where under-keel clearance is critical.	Areas shallower than 100 m where under-keel clearance is less critical but *features* of concern to surface shipping may exist.	Areas shallower than 100 m where under-keel clearance is not considered to be an issue for the type of surface shipping expected to transit the area.	Areas generally deeper than 100 m where a general description of the sea floor is considered adequate.
Maximum allowable Total Horizontal Uncertainty 95% *Confidence level*	2 m	5 m + 5% of depth	5 m + 5% of depth	20 m + 10% of depth
Maximum allowable Total Vertical uncertainty 95% *Confidence level**	a = 0.25 m b = 0.0075	a = 0.5 m b = 0.013	a = 0.5 m b = 0.013	a = 1.0 m b = 0.023
Full Sea floor Search	Required	Required	Not required	Not required
Feature Detection	Cubic *features* > 1 meter	Cubic *features* > 2 meters, in depths up to 40 meters; 10% of depth beyond 40 meters	Not Applicable	Not Applicable
Recommended maximum Line Spacing	Not defined as *full sea floor search* is required	Not defined as *full sea floor search* is required	3 x average depth or 25 m, whichever is greater. For bathymetric lidar a spot spacing of 5 x 5 m	4 x average depth
Positioning of fixed aids to navigation and topography significant to navigation (95% *Confidence level*)	2 m	2 m	2 m	5 m
Positioning of the Coastline and topography less significant to navigation (95% *Confidence level*)	10 m	20 m	20 m	20 m
Mean position of floating aids to navigation (95% *Confidence level*)	10 m	10 m	10 m	20 m

* TVUmax (d) $\pm\sqrt{[a^2+(b*d)^2]}$ where "a" represents that portion of the uncertainty that does not vary with the depth, "b" is a coefficient which represents that portion of the uncertainty that varies with the depth, and "d" is the depth (m).

Inland Topography Technologies and Risks

Inland topographic data are produced to Quality Levels specified in Table L.2. This section addresses topographic lidar, stereo photogrammetry, Structure from Motion (SfM) photogrammetry, and IfSAR from aircraft and satellites. Although topographic lidar and SfM photogrammetry can be acquired from Uncrewed Aerial Vehicles (UAVs) also known as drones, UAV mapping projects primarily pertain to small areas or linear features (e.g., power lines or pipelines) where pilots on the ground can maintain line-of-site view and control of the UAV. Uncrewed aerial vehicle technology only makes sense to fill small gaps -- not feasible for a nationwide program.

Topographic Data Vertical Accuracy Classes

For USGS's 3DEP, QL2 topographic lidar is the national standard for the lower 49 states and U.S. territories; QL2 lidar is required to be tested for a vertical accuracy class of 10 centimeters or better with 2 points per square meter (ppsm) point density. Some communities choose to upgrade to QL1 topographic lidar to meet the 10 centimeters accuracy class with 8 ppsm, and others upgrade to QL0 to meet the 5 centimeters vertical accuracy class with 8 ppsm. Figure L.1 shows the status of the 3DEP as of 9/30/2021.

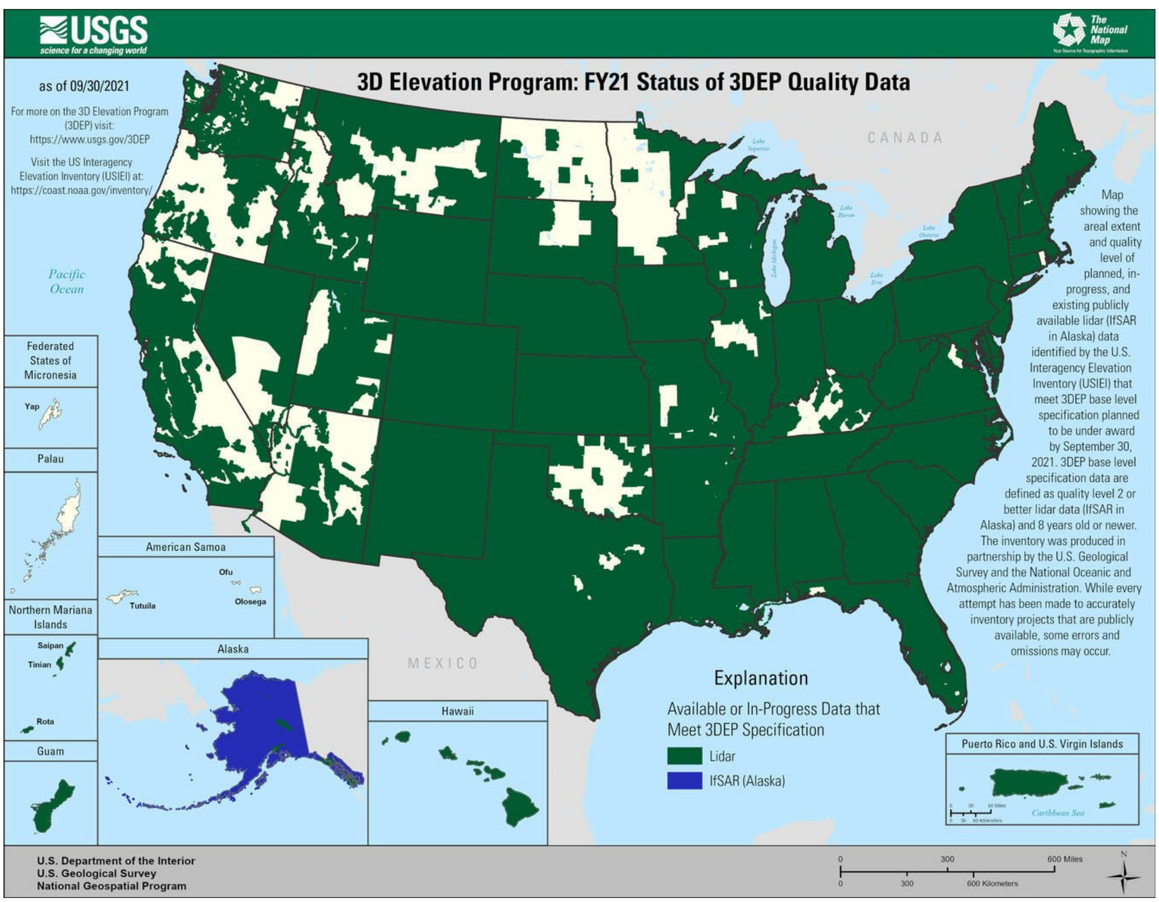

Figure L.1. This graphic shows the status of USGS's 3DEP at the end of 2021.

QL5 IfSAR data are the statewide standard for Alaska, required to be tested for an accuracy class of 185 centimeters or better. Mapping the steepest and most heavily forested areas comprising 23% of Alaska, Fugro's IfSAR data tested with a combined $RMSE_z$ of 166 centimeters. Mapping the less difficult terrain comprising 77% of Alaska, Intermap's Type-II IfSAR data tested with a combined $RMSE_z$ of 72 centimeters (compared with its specification of 1 meter or better); Intermap now offers Type-I IfSAR with $RMSE_z$ specification of 50 centimeters.

Topographic Lidar Technologies

Topographic lidar technologies are in three major categories: (a) single-photon lidar (SPL), Geiger-mode lidar (GML), and the most common linear-mode lidar (LML).

Single Photon Lidar

The Leica SPL100 (Figure L.2) is a single photon airborne lidar sensor that emits a green wavelength laser at 532 nanometers -- the same wavelength as the topobathy lidar sensors. However, its power is very low and penetrates less water than traditional topobathy lidar sensors; the SPL100 is not marketed as a bathymetric system. It has a pulse repetition frequency (PRF) of 60 kilohertz (kHz) and can penetrate semi-porous obscurations, such as vegetation, ground fog, and thin clouds.

Figure L.2. Leica SPL100. Image source: Leica

An RCD30 camera is included in the system configuration, allowing RGB (red/green/blue) or color infrared (CIR) encoding of the developed point clouds. The operating altitude is 2,000 – 4,500 meters above ground level (AGL) (6,560 to 15,000 feet AGL), resulting in typically 20 ppsm at 4,000 meters AGL and 200 knots speed over ground. Yet, because it acquires the data from significantly higher altitudes, it is ideal for large area projects or wide swaths along coastlines.

Leica has a fleet of SPL100 instruments that it uses for Hexagon projects, and it leases the system to customers. Leica considers 30,000 sq. km (~11,600 sq. mi.) as their break-even point for SPL versus LML applications; however, there are very limited use cases of this sensor on large projects.

Geiger-Mode Lidar

The term Geiger-mode comes from the use of the Geiger-mode Avalanche Photodiode (APD) detector for laser ranging applications. Technical details are explained in the 3rd edition of the DEM Users Manual. A Geiger-mode detector can detect range using very few photons. This allows ranging to be done using a low-power pulse with short pulse-width from very high altitudes by using an array of Geiger-mode APDs.

VeriDaaS's GML sensor is the first commercial airborne lidar system that takes advantage of the single photon capabilities of the Geiger-mode APD. VeriDaaS's system (Figure L.3) uses an array of 32 × 128 detectors with an instantaneous field of view of 35 µrads. A Class IV neodymium-doped yttrium aluminum garnet diode pumped solid state laser of wavelength 1,064 nanometer is used at a PRF of 50 kHz to produce approximately 205 million elevation measurements per second, yielding ultra-high point density on the ground. Altitudes of up to 11,000 meters (36,000 feet) AGL are possible, although typical flights are conducted at 4,000 – 5,000 meters AGL (13,000 to 16,000 feet.).

Figure L.3. VeriDaaS GML sensor. Image source: VeriDaaS

With a scan half angle of 15°, data acquired from 15,000 feet, for example, would enable a single swath that is over 8,000 feet. wide. Geiger-mode lidar's main advantage is that it could accurately map the elevations of very large areas from high altitudes, mapping wide swaths; but GML typically needs considerable overlap to make the probability of detection strong enough to separate out signal from noise. GML collects topographic data only and does not map bathymetric surfaces. Depending on the accuracy requirement, GML requires extensive ground control targets (both on the ground as well as above-ground) for data calibration.

Linear-Mode Lidar

At the writing of this report (2022), there are three main commercial suppliers of Airborne Lidar Systems – (a) Teledyne Optech International, headquartered in Toronto, Canada with offices in New York and Mississippi; (b) Leica Geosystems, a Hexagon Company, headquartered in Switzerland with more than 20 offices in the U.S. and worldwide; and (c) RIEGL Gmbh headquartered in Austria with offices in Florida and worldwide.

In this section, we provide an overview of current sensor technology offered by the system manufacturers with a focus on the newer sensors developed by each manufacturer. Airborne lidar technology is evolving rapidly with new sensors entering the market on a yearly basis, so this list may become obsolete quickly. Our goal is to provide the reader with information on current available technology for a variety of applications, while keeping an eye on next generation technology. All information provided in this section is based on published literature or information available on websites from the manufacturer. The author has made a significant attempt to remove any marketing campaigns that suggest a particular sensor is "better" than another sensor. Instead, some of the highlights of the sensors are presented, with distinctions on the sensor technology based on its operations and system characteristics. The "extraction" software that converts the raw data acquired from the aircraft to a point cloud is also discussed.

Each sensor comes with software to enable airborne survey planning, airborne navigation and control, real-time three-dimensional (3D) visualization, calibration, data processing, and quality control for complete workflow from planning to data delivery for lidar data and imagery from cameras.

Teledyne Optech

Established in 1974 under the name Optech, Teledyne Optech has been designing, developing, and manufacturing advanced lidar instruments for 40 years. Teledyne Optech works closely with commercial, government, military, and space-based organizations to meet their specialized application requirements. They offer standalone and fully integrated lidar and camera solutions in airborne mapping, airborne bathymetry, mobile mapping, terrestrial laser scanning, mine cavity monitoring, and industrial process control, as well as space-proven sensors. The Optech systems come with software that can be used for survey planning, operation and post-processing, allowing clients to collect, manage and deliver survey data to their customers.

Galaxy

The Galaxy (Figure L.4) is the latest of Teledyne Optech's airborne solutions for topographic lidar. It is designed for a wide range of applications including wide-area mapping and corridor surveys. Optech introduced PulseTRAK™ and SwathTRAK™ technologies (patents pending) with the Galaxy. PulseTRAK technology replaces the conventional multi-pulse technologies for high PRFs at high altitude. SwathTRAK™ maintains a fixed-width data swath in complex terrain by varying the scan field of view (FOV) dynamically in-flight. The advantage of a dynamic FOV is that a fixed-width swath over the ground is maintained, thereby maintaining more consistent point density and XY point distribution across the entire dataset. The Galaxy has a 1 megahertz (MHz) effective PRF using a single laser. The operational envelope is 150 – 4,700 meters AGL using a 1064-nanometers Class IV laser. The scan angle FOV can vary between 10^{o} – 60^{o}. The sensor and power distribution unit weigh 33.5 kg, making it suitable for installing on small airborne platforms.

Figure L.4. Optech Galaxy. Image source: Optech

Leica Geosystems

Leica Geosystems is part of Hexagon, a global provider of information technology solutions across geospatial and industrial landscapes. Leica develops geospatial solutions for a diverse mix of industries, such as surveying and engineering, building and heavy construction, safety and security. Leica products and solutions include Electronic Distance Measurement, Global Positioning System (GPS)/Global Navigation Satellite System (GNSS) technology, 3D laser scanning, tilt and angle measurement, and point cloud generation and analysis tools.

TerrainMapper-2

Figure L.5. Leica TerrainMapper-2. Image source: Leica

The TerrainMapper-2 (Figure L.5) is Leica's latest LML airborne sensor providing the highest performance for regional mapping projects. Thanks to gateless multiple points in the air, the sensor system delivers outstanding accuracy. The system is designed to offer the maximum flexibility for all applications from narrow-swath corridors to high altitude applications over complex and changing environments for the delivery of highest fidelity data.

The TerrainMapper-2 includes a 2 MHz lidar sensor combined with two nadir 150-megapixel cameras in RGB and Near Infrared (NIR). With the integration of the most innovative optical system on the market, this new lidar sensor delivers high quality images with every flight. Even during long collection days and low sun angles, the integrated camera will keep up with the lidar. The sensor can easily be upgraded with four additional oblique cameras turning the system into a 3D city mapping machine. This configuration is known as the Leica CityMapper-2.

RIEGL

RIEGL offers a wide range of airborne laser scanners and laser scan systems. All RIEGL systems digitize the echo signal online during data acquisition. The Laser Measurement Systems series of laser scanners require subsequent waveform analyses. The VQ line of laser scanners offers multiple target capability by online waveform analysis based on echo digitization. No digital data recorder and off-line waveform processing is necessary.

RIEGL provides proprietary companion software for RIEGL laser scanners. Separate programs designed for the different applications of terrestrial and airborne/mobile laser scanning enable the use of the scanners' capabilities, from optimizing the acquisition workflow in the field via providing tools for data control and data processing. RiAcquire is the system integration and data acquisition software; RiAnalyze performs full waveform analysis; RiWorld offers coordinate system transformations; RiProcess is the primary software that is used for data management, processing, and visualization; RiHydro is the processing software for hydrographic and bathymetric surveying; RiMTA Airborne Laser Scanning is the software for automated resolution of range ambiguities; and RiVLIB is the offline/online library for V-line scanners.

RIEGL currently offers the following airborne lidar scanners and systems: VQ780 II-S, VQ 1560II-S and the VQ-1560i-DW sensor.

VQ-780 II-S

The RIEGL VQ-780 II-S (Figure L.6) is a high performance, rugged, lightweight, and compact airborne mapping sensor. This system is designed for highly efficient data acquisition at low, mid, and high altitudes, covering a variety of different airborne laser scanning applications from high density to wide area mapping.

Figure L.6. RIEGL VQ-780 II-S. Image source: RIEGL

The high-speed rotating mirror design ensures a wide field of view at all flight altitudes. Based on RIEGL's waveform-lidar technology, the system provides point clouds with high accuracy, excellent vertical target resolution, calibrated reflectance readings, and pulse shape deviation for information content on each single measurement. Atmospheric clutter suppression yields clean point clouds with minimum efforts in filtering isolated noise points. The system is complemented with RIEGL's advanced acquisition and data processing software suite that utilizes parallel computing for fast data processing. The RIEGL VQ-780 II-S is designed to work with the latest inertial navigation systems, flight management systems, and camera options.

RIEGL VQ 1560 II-S

The new VQ-1560 II-S (Figure L.7) follows the successful concept of RIEGL's proven dual channel laser scanner series. With increased laser power the operational altitudes are extended up to 1,600 meters AGL at a pulse repetition rate of 4 MHz, or up to 4,000 meters AGL at a pulse repetition rate of 540 kHz (all values given for 20% target reflectance). These improved maximum ranges allow an increase of the system's productivity by about 25% for a very attractive point density range. Laser pulse repetition rates can be fine-tuned in 12 kHz steps, enabling subtle optimization of acquisition parameters in order to meet specific project requirements.


Figure L.7. RIEGL VQ 1560 II-S. Image source: RIEGL

Its unique "cross-fire" scan pattern and its wide operational range make the instrument the highly versatile. It is perfectly suited for any kind of application – from ultra-dense corridor mapping from low altitudes, over high-resolution city mapping with minimum shadowing effects in narrow street canyons, to large-scale wide area mapping up to 1,130 sq. km per hour at a density of 4 ppsm.

The system is equipped with a seamlessly integrated high-performance Inertial Measurement Unit (IMU)/GNSS unit and an optional 150-megapixel RGB camera integrated in the primary camera bay. Optionally, a second camera, such as a thermal camera or a 150 megapixels NIR camera, can be integrated on request. The design of the compact housing features a mounting flange for interfacing with typical hatches or gyro-stabilized leveling mounts.

RIEGL VQ 1560i-DW

The RIEGL VQ-1560i-DW (Figure L.8) is an airborne lidar scanning system offering two lidar channels of different wavelengths, green and IR. These wavelengths allow the acquisition of scan data of complementary information content, thus delivering two independent reflectance distribution maps, one per laser wavelength.

Figure L.8. RIEGL VQ 1560i-DW. Image source: RIEGL

Scan data acquired with the RIEGL VQ-1560i-DW are the input for well-established scan data processing methods but also for the development of highly sophisticated data processing and evaluation algorithms for new areas of application like vegetation mapping in agriculture and forestry. The VQ-1560i-DW provides a laser pulse repetition rate of up to 1 MHz per LiDAR channel, resulting in a total of more than 1.3 million measurements per second on the ground.

The VQ-1560i-DW is most productive when both lidar channels are combined, typically at altitudes up to 8,300 feet. However, each channel can also operate independently. The system also has a high performance IMU/GNSS unit and up to two optional cameras. A 150-megapixel RBG camera is intended to be used as the primary camera, and a thermal or a NIR camera can be built in as the secondary camera. The mounting flange is optimized to interface with typical aircraft hatches and stabilized mounts by means of a specific adapter ring.

Enabling Technologies for Lidar Direct Georeferencing

GNSS-aided Inertial Navigation Systems are required for Direct Georeferencing (DG) of lidar systems, aerial cameras, and aerial IfSAR. In airborne lidar installations, a DG system is used to measure the position of the laser reference point and the orientation of the laser range at the exact time of measurement. In a scanning lidar system, the laser reference point is either the scan mirror or the detection element. For flash lidar, the reference point would typically be a location at the center of the array, from which the relative location of every other detection element in the array is known. The orientation is given in Euler angles with respect to the north, east, and down directions. The IMU is mounted to the lidar housing so that it is perfectly rigid with respect to the laser reference point and remains so over temperature changes and when exposed to shock and vibration. During a mission, the DG system records the IMU and GNSS data and the time of each laser scan, all in a common time base such as GPS time. The DG post-processing software computes the time tagged position and orientation of the laser reference point at a high data rate, typically at 200 hertz. The lidar post-processing software then interpolates the DG position and orientation data to the exact time of scan. With these data and the range measured by the laser, it computes the 3D ground spot coordinates of each laser range. Typically, the software first computes the Earth-Centered-Earth-Fixed coordinates of each point and then converts these to the desired mapping frame. The resulting georeferenced point cloud is then ready for processing into data products such as Digital Surface Models (DSMs).

When a calibrated frame camera is also attached to the lidar, the DG system can be used to measure the position and orientation of each image at the exact time of exposure. This allows the imagery to be directly projected onto the point cloud from the lidar, enabling it to be colorized to produce photo-realistic 3D products. A DEM can also be extracted from the lidar and used to directly orthorectify each image, all without the need of running Aerial Triangulation (AT).

The angular accuracy requirements for a DG system for use with lidar is typically a function of its FOV and flying height. Low altitude systems, such as those used on UAVs, require only moderate roll and pitch measurement accuracy, while high altitude aircraft-based systems require angular accuracy at the milli-degree level. Furthermore, a system with a wide FOV (such as with a 360-degree scanner) will require a much higher heading accuracy measurement versus a scanner with a narrow FOV. Most lidar manufacturers today produce their systems with built-in DG that have been optimized to meet accuracy requirements over the operating range of the sensor.

Calibration parameters for the DG system include the relative positional offsets (also called Lever Arms) of the IMU sensing center with respect to the lidar reference point and the GNSS antenna phase center, and the fixed rotational offsets of the IMU with respect to the scanner housing (boresight angles).

Topographic Lidar Technology Risks

The major risk to all topographic lidar technologies is caused by clouds or fog which impact all optical technologies including topographic and topobathy lidar.

Although topographic lidar is the very best technology for mapping the bare earth Digital Terrain Model (DTM) beneath the vegetation canopy in very dense vegetation, there will be much lower point density on the ground than in non-vegetated areas due to most returns being captured in the canopy. Modern lidar sensors can acquire data with very high point densities to better penetrate dense vegetation. This is the main reason why Florida adopted QL1 lidar (with 8 ppsm) as the state's standard lidar Quality Level, rather than QL2 lidar (2 ppsm) which is standard elsewhere.

The 3rd edition of *Digital Elevation Model Technologies and Applications: The DEM Users Manual* includes Chapter 9 on Lidar Data Processing and Chapter 15 on Quality Assessment of Elevation Data. These chapters are tutorials on how to avoid pitfalls in lidar data processing and Quality Assurance/Quality Control (QA/QC) that impact the success of a lidar mapping program. Whereas modern lidar sensors have few pitfalls of their own, the major risk comes from human errors in lidar data processing and QA/QC.

Photogrammetric Technologies

DEMs can be produced photogrammetrically from stereo satellite imagery, from traditional stereo aerial imagery acquired from high, medium, or low flying heights, and from SfM photogrammetry using low-altitude imagery with heavy forward overlap and sidelap to view the ground from eight or more perspectives – sometimes dozens of different perspectives.

Stereo Photogrammetry

Whether imagery is acquired from satellites or aircraft, stereo photogrammetry requires imagery to be acquired with >50% forward overlap so that the entire terrain area to be mapped can be viewed in stereo, i.e., from two different perspectives, as shown at Figure 9. For nearly a century, stereo photogrammetric principles have been the basis for the first three generations of photogrammetry: (1) analog photogrammetry (1930s into the 1970s), (2) analytical photogrammetry (1970s into the 1990s), and (3) digital photogrammetry (1991 to the present).

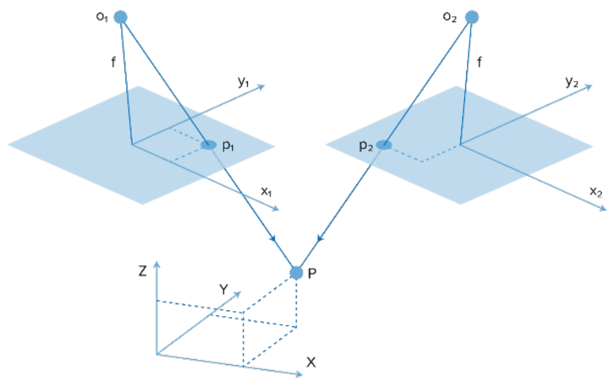

Figure L.9. With correct position and orientation of each photo in space, 2D measurements of points p_1 and p_2 on stereo photos enable the 3D mapping of point P on the ground. Image source: Dewberry.

To reconstruct the 3D geometry that existed when each aerial photo is taken, AT determines the 3D ground-coordinate positions (XYZ) of the camera's focal point and angular orientation (ω/φ/κ) of the camera when each photo is taken. Here X represents the x-coordinate (Easting), Y is the y-coordinate (Northing), and Z is the elevation of each photo's focal point, e.g., o_1 and o_2 in Figure L.9. Omega (ω) is the <u>roll</u> around the x-axis, the direction of flight in the photo coordinate system; phi (φ) is the <u>pitch</u> around the y-axis, horizontally perpendicular to the x-axis; and kappa (κ) is the <u>yaw</u> around the z-axis, vertical and perpendicular to the x-axis and y-axis. Upper case letters (XYZ) represent ground coordinates, ideally in State Plane or Universal Transverse Mercator meters; lower case letters (x/y) represent photo coordinates, typically millimeters in a photo coordinate system.

In Figure L.9, the two photos are shown in the position of image positives, where f is the camera's focal length (e.g., 6" for older film cameras), o_1 and o_2 are the lens' focal points for the camera when photos 1 and 2 were taken; x_1 and y_1 are the photo coordinates of point p_1 on photo 1, and x_2 and y_2 are the photo coordinates of point p_2 on photo 2. In theory, the two lines (light rays) drawn from o_1 through p_1 and from o_2 through p_2 should intersect at point P, enabling photogrammetrists to map the 3D coordinates of point P on the ground. However, without correct position (XYZ) and orientation (ω/φ/κ) of the two photographs, those two light rays will never intersect at point P because ground features cannot be focused in stereo and terrain features cannot be mapped in 3D. Without *relative orientation* between a pair of stereo images, analysts will see "parallax" in the stereo model. Parallax is the displacement amount in x and y at any point (e.g., point P) when the two lines do not intersect and are out of focus when viewed in stereo. Both x-parallax and y-parallax need to be removed for 3D mapping from photogrammetry. Furthermore, without *absolute orientation*, the model will not be scaled and leveled to fit ground control.

Enabling Technologies for Photogrammetric Camera Direct Georeferencing

Airborne photogrammetric cameras on manned platforms or UAVs are typically composed of a single camera looking downward (nadir) or multiple cameras mounted in an oblique configuration. Regardless of the platform or configuration, a DG system integration and the georeferencing workflow remains the same.

The IMU is attached to the camera's structure (usually embedded directly inside) so it can measure the exact motion the camera experiences during flight. The DG system records the IMU and GNSS data plus the mid-exposure pulses of all images in a common time base such as GPS time. The DG post-processing software then computes the position and orientation (also referred to as the Exterior Orientation) of each image at its perspective center at the time of exposure, with respect to a local mapping frame and datum. The data are then used as inputs into the photogrammetric mapping process to generate a DEM without any or with just a few ground control points (GCPs).

Calibration parameters include the lever arm offsets of the IMU to each camera's perspective center, the GNSS antenna phase center, and the IMU boresight angles to each camera. If the camera system is on a stabilized mount, the IMU and camera will rotate with respect to the GNSS antenna that is mounted on the airframe. In this case the angles of the mount (gimbal angles) with respect to the airframe are required as input to the DG system so that the GNSS measurements can be accurately translated from the antenna phase center to the center of rotation of the mount.

Structure from Motion Photogrammetry

The 4th generation of photogrammetry, SfM photogrammetry explained in Chapter 6 of the DEM Users Manual, is more complex than traditional stereo photogrammetry. SfM encompasses a set of computer vision algorithms and techniques that have come into wide usage and gained wide acceptance in surveying and mapping during the past decade. SfM, combined with the proliferation of high-quality, non-metric cameras, small GPS/GNSS chips, and aerial platforms has allowed the generation of high-resolution DSMs and orthoimagery at a fraction of the cost of traditional techniques.

At USGS, SfM has become an integral technique in coastal change assessment. Since 2018, USGS has used Agisoft Metashape Professional Edition Version 1.6 SfM software to develop a workflow that processes coastline aerial imagery collected in response to storms and produced Open-File Report 2021-1039 that details step-by-step instructions to create 3D spatial products from both singular and repeated collections of shoreline aerial imagery.

In most applications today, SfM photogrammetry is used to produce digital orthophotos and to extract DSMs from a series of images collected by a moving aircraft or UAV. Image overlap is key in SfM, as the matching is not performed in a pair-wise sense as in stereo photogrammetry, but rather features must be visible in many images with variable viewing angles as shown in Figure L.10. SfM quality improves with more images and higher levels of overlap and sidelap. It is not uncommon for SfM projects to make use of image sets with 80-90% forward overlap and 60-70% sidelap. For example, with 80% forward overlap and just 50% sidelap, any target area on the ground would be imaged from 10 different look angles on average. With heavier overlap and sidelap, even more look angles would be available.

SfM photogrammetry has its roots in many of the same principles as traditional stereo photogrammetry. However, it differs in one fundamental way. There is no requirement in SfM for any *a priori* knowledge of the camera's interior or exterior orientation or the scene geometry from DG. These quantities are all recovered empirically through a redundant network of matched feature points during the bundle block adjustment process. The ability to derive these quantities sets SfM photogrammetry apart from traditional techniques and allows for the use of lower cost cameras for which the calibration is unknown.

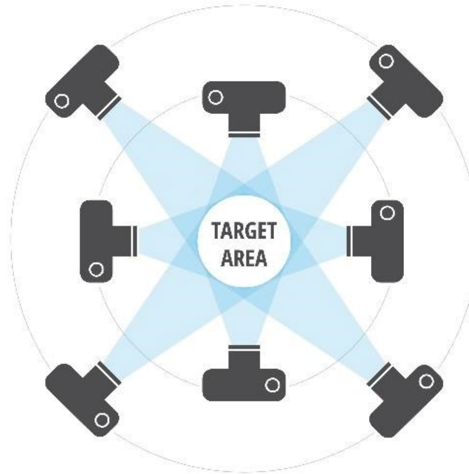

Figure L.10. With SfM, highly redundant image overlap allows for self-calibration of non-metric cameras and mapping in a local coordinate system. Surveyed GCPs are normally added to improve map accuracy. Image source: Dewberry

Scale-invariant feature transform and traditional image matching provides the ability to generate thousands of matched keypoints in image sequences even in the presence of rotations and scale variations. Modern SfM systems can generate millions of high-quality image keypoints with relative ease, based on a consumer-grade camera imaging the same area of interest (AOI) from multiple perspectives. Redundant measurements of thousands of points from multiple perspectives enable the position and orientation of the camera to be determined for each image.

All 3D coordinates from SfM photogrammetry are in their own local coordinate system until some knowledge of real-world coordinates are applied, such as by measuring the location of the photo centers in flight using GPS. Following insertion of GCPs, a 7 degree of freedom (3 translation, 3 rotation, and 1 scale) similarity transformation is typically applied to the local model to transform it to real-world coordinates. The optimization, or local minimization problem, attempts to minimize the overall error across the known camera positions and ground control. This last point makes clear the need for careful collection of GCPs and an understanding of the relative accuracy of all GPS information in an SfM photogrammetric project.

Photogrammetry Technology Risks

Because aerial cameras are optical sensors, clouds and fog are the primary risk to all forms of photogrammetry.

In forests, trees routinely block the ability of photogrammetrists to see the bare earth in stereo, even when the DTM is compiled manually; automated DEM processing typically provides DSMs and not bare-earth DTMs.

The main risk of SfM photogrammetry is that the technology is so easy to use that results will always be provided by the software, regardless of the accuracy or inaccuracy of input parameters.

Without understanding the underlying technology, it is easy for novices to fall into traps and claim accuracies that the data do not support. Currently, ASPRS has not established rigorous processes for SfM photogrammetry.

Synthetic Aperture Radar Technologies

Radar technology can be used to produce DEMs from satellites and from aircraft. Radar sensors utilize wavelengths at the centimeter to meter scale, which gives it special properties, such as the ability to see through clouds. The different wavelengths of Synthetic Aperture Radar (SAR) are often referred to as bands. Most geoscientists refer to SAR systems in terms of their wavelength, λ, denoted by a letter code assigned in World War II for security reasons. The most common wavelengths for SAR remote sensors are labeled K, X, C, L, S, and P, listed in order of increasing wavelength size in Table L.5. Chapter 7 of the 3rd edition of the DEM Users Manual provides explanations for the use of different SAR wavelengths. Most significantly for topographic mapping purposes, X-band is commonly used for aerial and satellite acquisition of DSMs, whereas P-band is better able to penetrate vegetation for mapping of DTMs, though care must be taken as P-band can also penetrate beneath the ground surface, making it inferior to lidar for accurate mapping of DTMs.

Table L.5. SAR band, wavelength, and frequency relationships

SAR Band Identification	Wavelength Range (cm)	Frequency Band (MHz)
Ka	1.13 - 0.75	26,500 - 40,000
K	1.66 - 1.13	18,000 - 26,500
Ku	2.4 - 1.66	12,500 - 18,000
X	3.75 - 2.4	8,000 - 12,500
C	7.5 - 3.75	4,000 - 8,000
S	15 - 7.5	2,000 - 4,000
L	30 - 15	1,000 - 2,000
P or UHF	100 - 30	300 - 900

Airborne Interferometric Synthetic Aperture Radar

Between 2010 and 2020, USGS managed the aerial IfSAR mapping of all of Alaska by the Dewberry team which included Intermap Technologies and Fugro EarthData. USGS required Orthorectified Radar Images (ORI) with 2.5-meter pixels or better, and DSMs and hydro-flattened DTMs with 5-meter point spacing. For vertical accuracy of the DTM, the specification required $RMSE_z$ of 1.85 meters in non-vegetated terrain with slopes between 0 and 10 degrees; larger errors were allowed in steeper and heavily vegetated terrain. The side-looking geometry of IfSAR is shown in Figures L.11 and L.12.

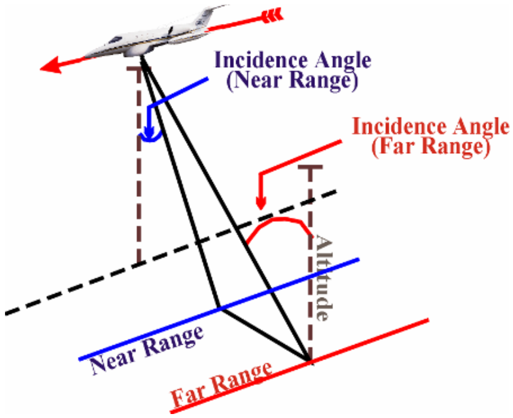

Figure L.11. Rather than mapping downward (nadir), aerial IfSAR maps to the side of the airplane between near range and far range. Image source: Intermap

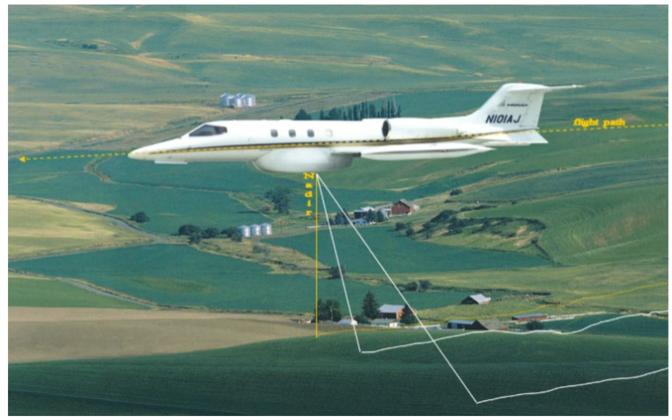

Figure L.12. The incidence angle changes when flying at 18,000' for Type-I 2 m DSMs/DTMs or at 28,000' for Type-II 5 m DSMs/DTMs. Image source: Intermap

As shown at Table L.6, Intermap now offers three Types of IfSAR data, based on DSM/DTM accuracy, not resolution. Orthorectified Radar Imagery is available in three resolutions: 25 centimeters, 50 centimeters, and 62.5 centimeters.

Table L.6. Different types of aerial IfSAR offered by Intermap Technologies

DSM/DTM	**Measures of Accuracy Specifications**		**Pixel Size/Post Spacing**	**Acquisition Altitude**
Product Type	**RMSE**	**LE95/CE95**		
Type I – 2 m	0.5 m	1.0 m	2.0 m	18,000 ft
Type II – 2 m	1.0 m	2.0 m	2.0 m	18,000 ft
Type III – 2 m	3.0 m	6.0 m	2.0 m	18,000 ft
IfSAR DSM, DTM, and ORI previously delivered under USGS Mid-Accuracy Alaska DEM task orders				
Type II – 5 m DSM & DTM	1.0 m	2.0 m	5.0 m	28,000 ft
ORI	2.0 m	4.0 m	0.625 m	28,000 ft

Between 2010 and 2020, Intermap mapped 77% of Alaska in the north and west using their STAR systems with X-band IfSAR only, producing Type-II 5-meter DSMs/DTMs and ORIs with 62.5-centimeters pixels. Although the USGS's mid-accuracy specification was $RMSE_z \leq 185$ centimeters, and Intermap's mid-accuracy specification for Type-II DSMs/DTMs required an $RMSE_z \leq 1$ meter, Dewberry used hundreds of QA/QC checkpoints from JOA Surveys, and Intermap's DTM tested with an $RMSE_z$ of 72 centimeters statewide.

In the western Aleutian Islands where it was too expensive to hire a marine helicopter service to install and survey prism reflectors for control, Intermap provided Type-III 5-meter IfSAR DSMs/DTMs with 62.5 centimeters ORI and used the National Aeronautics and Space Administration's Ice, Cloud, and Land Elevation Satellite (ICESat) lidar to provide minimal control.

Between 2010 and 2020, Fugro mapped the more rugged and heavily vegetated 23% of the state in southeastern Alaska using their Geographic Synthetic Aperture Radar (GeoSAR) system with X-band and P-band IfSAR. Compared with USGS's mid-accuracy specification of $RMSE_z \leq 185$ centimeters, Fugro's DTM tested with an $RMSE_z$ of 166 centimeters, recognizing that Fugro's terrain was more rugged and heavily vegetated.

To keep costs at a minimum, there was no requirement for the IfSAR data to be tide-controlled. Therefore, all IfSAR data from Intermap and Fugro were collected at random tide stages.

In 2017, upon learning of the availability of a USGS lidar dataset of a portion of the Kenai Peninsula along with Fugro's GeoSAR DTM there, Intermap collected Type-I 2-meter and Type-II 5-meter IfSAR data of a small area of the Kenai Peninsula for comparison with the lidar. The Type-I 2-meter IfSAR data was acquired at 18,000 feet. AGL and Type-II 5-meter IfSAR data was acquired at 28,000 feet. AGL. Intermap then used a rasterized binning process to select low-slope areas (0-10 degrees) not highly vegetated (lidar DSM minus lidar DTM <0.5 meters). Statistics were computed for all remaining points in the raster difference surface (IfSAR minus lidar) and the $RMSE_z$ was 46 centimeters for the Type-I 2-meter DSM and 49 centimeters for the Type-II 5-meter DSM, well within USGS's 185 centimeters specifications.

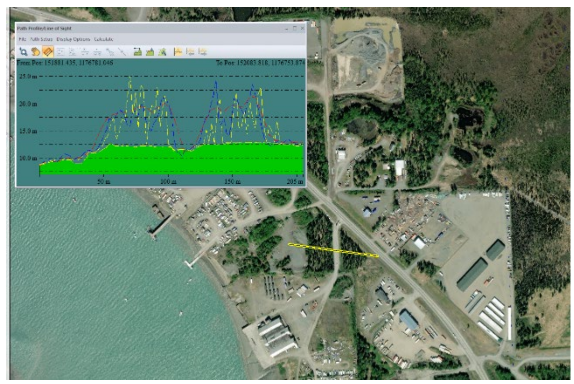

Figure L.13. Image of the test site and a sample profile that compares Intermap's Type-1 and Type-II DSMs to the lidar DSM and DTM. Image source: Intermap

Figure L.13 shows an image of the test site and a sample profile that compares Intermap's Type-I and Type-II DSMs to the lidar DSM and DTM. With X-band IfSAR, Intermap then uses an algorithm to filter out the trees from the IfSAR DSM to produce a bare-earth DTM. Figures L.14, L.15, L.16, and L.17 from Intermap Technologies compare the DSMs and ORIs from Intermap's IfSAR data acquired at 28,000 feet and 18,000 feet.

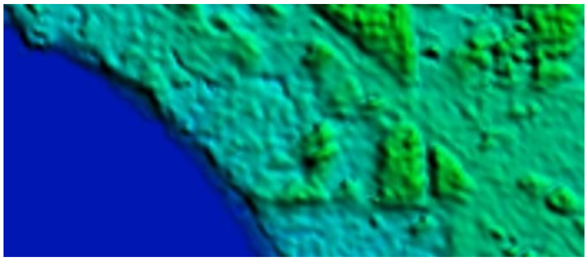

Figure L.14. Type-II 5 m DSM flown from 28,000 feet

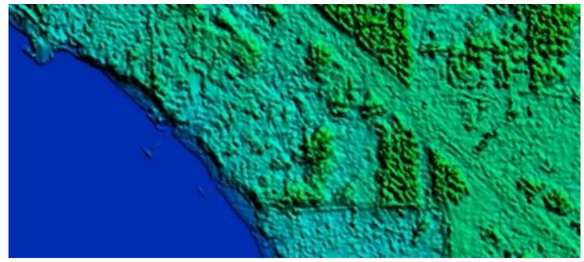

Figure L.15. Type-I 2 m DSM flown from 18,000 feet

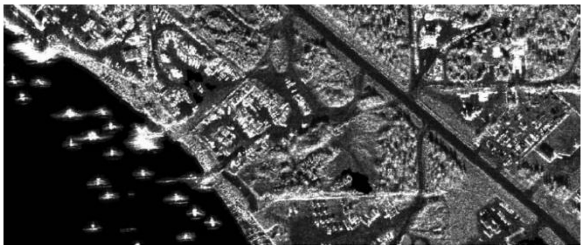

Figure L.16. Type-II 62.5-cm ORI flown from 28,000 feet

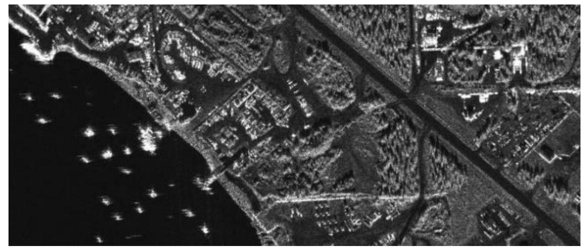

Figure L.17. Type-I 25-cm ORI flown from 18,000 feet

Enabling Technologies for Aerial IfSAR Direct Georeferencing

In an IfSAR system, the DG system is used to compute the relative displacement of the phase center of one SAR antenna with respect to another. The relative displacements are then used to correct the radar phase. This is the equivalent of stabilizing the IfSAR platform against aircraft motion due to maneuvers and air turbulence. The accuracy of the DG system is selected based upon both the absolute orientation accuracy required to produce a specific ground accuracy from a given flying height and the relative orientation accuracy (sample to sample noise) required to produce a sharp radar image.

IfSAR Technology Risks

Weather-related risks are minimized as IfSAR sensors acquire data through clouds, fog, and haze, day or night. However, the main risks would be extreme weather where turbulence may exceed thresholds for mapping data collection. Occasionally, there may be an intense major thunderstorm or hurricane/typhoon that would preclude elevation data collection for a few days. The only other risk involves mechanical issues with either the jet or the sensors.

Satellite Differential InSAR

Interferometric Synthetic Aperture Radar, also called IfSAR, is the measurement of signal phase change (interference) between radar images. When a point on the ground moves, the distance between the sensor and the point changes, producing a corresponding shift in signal phase. This shift is used to quantify the ground movement. Interferograms (Figure L.18) are two-dimensional (2D) representations of the difference in phase values. Variations of phase in an interferogram are identified by fringes, colored bands that indicate the location and magnitude of surface movement.

When InSAR is used to identify and quantify ground movement, the process is referred to as Differential InSAR (DInSAR). In DInSAR, topographic effects are removed by using a DEM of the AOI. The remaining change in phase represents ground movement and can be visualized in the form of a ground Figure L.18 depicts deformation map. DInSAR is useful for providing snapshots of displacement at points in time, identifying the boundaries of areas of movement and observing the spatial variability of movement within the AOI. The main limitations of this approach are that it cannot remove noise introduced by the atmosphere and by potential satellite orbital errors, it does not distinguish between linear and non-linear motion and that measurement precision is at the centimeter level.

DInSAR is ideal for mapping annual rates of isostatic rebound and/or land subsidence. In some parts of the U.S., coastal communities are threatened by sea level rise (SLR) which may be worsened by land subsidence, the magnitude of which is often greater than the magnitude of SLR. In parts of Alaska, fishing villages along streams near the ocean may be threatened by isostatic rebound which could force communities to move further downstream.

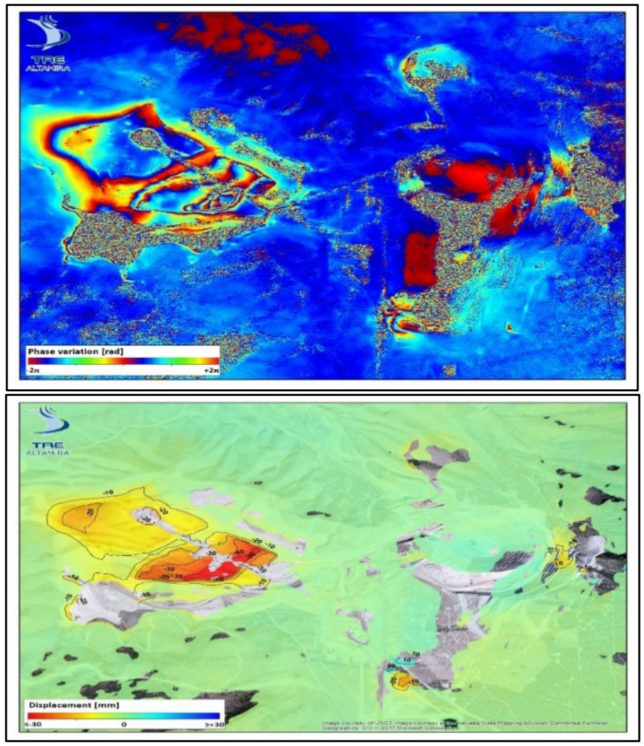

Figure L.18. Interferometric phase and associated displacement data generated by means of DInSAR. Top image: InSAR interferogram with color fringes. Bottom image: the corresponding displacement map. Image source: TRE Altamira

Isostatic rebound, also called post-glacial rebound, is the uplift of land after glacier ice melting and the removal of the huge weight of ice. As reported in the Geophysical Journal International[1], portions of Alaska are uplifting at rates between 10 and 25 millimeters/year, with peak uplifts in the area of Glacier Bay where relative SLR is going down. Isostatic rebound, and the annual rates of isostatic rebound, can be mapped using the very same DInSAR technology used internationally to map subsidence hot spots and annual subsidence rates.

Permanent Scatterer InSAR (PSInSAR®) was developed as an advanced form of DInSAR that uses multiple interferograms created from a stack of at least 15 radar images to overcome the limitations of DInSAR. By identifying persistent or permanent scatterers (PS), which represent reflective objects on the ground surface that consistently reflect the radar signal back to the satellite over time, it is possible to remove atmospheric and orbital errors, and thereby improve measurement precision to the millimeter accuracy level. Further improvements to the PS algorithm have introduced distributed scatterer (DS) types of points, which have increased the spatial coverage of

[1] Geophysical Journal International, Volume 158, Issue 3, September 2004, Pages 1118–1133 https://doi.org/10.1111/j.1365-246X.2004.02356.x

the displacement information to areas with few PS (e.g. rangeland, prairies, sparsely vegetated areas, clearings, etc.), leading to the development of the more recent SqueeSAR® algorithm[2]. These advanced forms of InSAR processing produce outputs in the form of point clouds, where each point (PS or DS) has an associated time series that allows non-linear movement to be measured and characterized.

NOAA's National Geodetic Survey (NGS) hired the Dewberry/TRE Altamira team in 2017 to use DInSAR techniques to map subsidence hot spots and annual rates of subsidence in the Hampton Roads area of Virginia; this included the world's largest naval base at Norfolk, which is subsiding. Figure L.19 shows the result of an image stack of dozens of images at the Norfolk Virginia Beach Expressway, showing a consistent sinking of the land which, when combined with SLR in the area, accelerated the apparent effects of SLR. Figure L.20 mapped the annual subsidence rate of -7 millimeters/year in the Virginia Port Area. This same technology could map post-glacial rebound rates in Alaska and identify hot spots where rebound is more severe. Subsidence rates vary in different areas nearby.

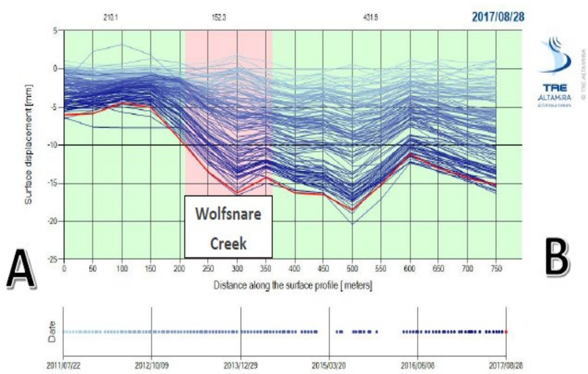

Figure L.19. Surface profile cross-section of the Norfolk Virginia Beach Expressway at Wolfsnare Creek. The red line at the bottom represents displacement at the last image of the archive. Image source: TRE Altamira

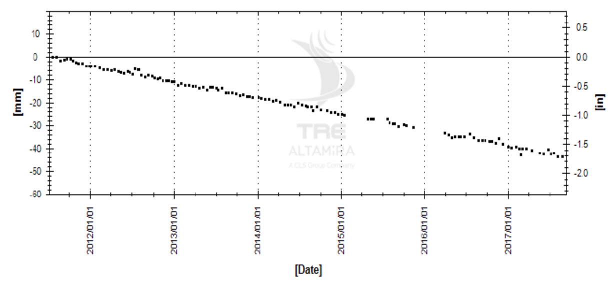

Figure L.20. Subsidence rate of -7 mm/year over a portion of the Virginia Port Area. If this had been an area of post-glacial uplift in Alaska, this graph would have mapped the rate at which the land is moving upward. Image source: TRE Altamira

Figure L.21 compares TRE Altamira's subsidence of an unspecified area using both the Sentinel-1 low resolution (20-meter x 5-meter) C-band SAR imagery which is free, and the commercial higher resolution (3-meter x 3-meter) X-band Cosmo-SkyMed SAR imagery which can be expensive. Table L.7 compares the parameters for these two satellites, as well as the highest

[2] For more information about the SqueeSAR® algorithm, see: https://site.tre-altamira.com/company/our-technology/

resolution (1-meter x 1-meter) TerraSAR-X commercial SAR satellite which is also X-band and even more expensive per square kilometer.

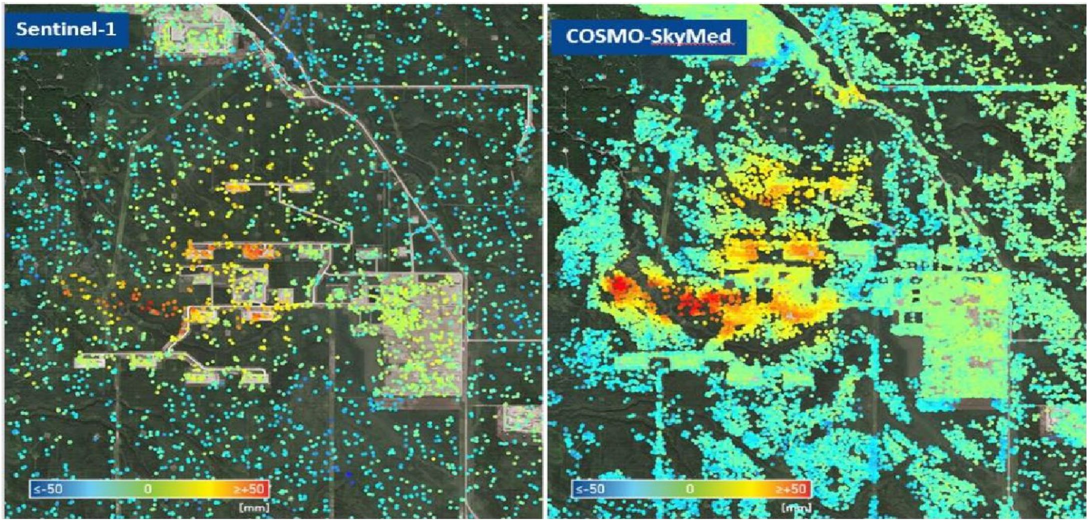

Figure L.21. Example of results obtained from the SqueeSAR analysis of lower-resolution Sentinel-1 radar images and the higher-resolution Cosmo-SkyMed (Stripmap) radar images over the same site. Green points indicate land stability whereas yellow/orange/red points indicate varying degrees of subsidence. If this were Alaska, such maps would show varying degrees of isostatic rebound (uplift) in some areas and subsidence (sinking) in other areas. Image source: TRE Altamira

Table L.7. Comparison of Sentinel-1 (free) and Cosmo-SkyMed and TerraSAR-X (commercial) SAR satellites.

Parameter	Sentinel-1	Cosmo-SkyMed or TerraSAR-X	
Band (Wavelength)	C (5.6 cm)	X (3.1 cm)	
Temporal Sampling	12-day	8- or 11-day	
Pixel Resolution	20m x 5m (65 ft x 15 ft)	3m x 3m (10' x 10')	1m x 1m (3.3' x 3.3')
Area covered by satellite image	250 km x 250 km (155.3 mi x 155.3 mi)	30 km x 50 km (18.6 mi x 31.1 mi)	10 km x 10 km (6.2 mi x 6.2 mi)
Point Density (theoretical maximum)	10,000 pts/km² (28,593 pts/mi²)	111,111 pts/km² (278,784 pts/mi²)	1,000,000 pts/km² (2,589,990 pts/mi²)
Characteristics	• Publicly available data (free) • Regional studies possible with single image stack • Provides high measurement precision	• Provides detailed deformation information for urban applications • Provides high point density • Image acquisitions can be tasked • High XY precision appropriate for urban environments	
Limitations	• Provides lower point density than high-resolution radar satellites • XY precision may be too low for some urban applications	• Higher imagery/data cost • Regional monitoring may require multiple scenes	

DInSAR Technology Risks

Figure L.21 and Table L.7 compare the "trade-offs" between the lower-resolution Sentinel-1 SAR images that are free and the higher-resolution but expensive commercial SAR satellite images. Users need to understand what they are paying for and not expect highly pinpointed subsidence "hot spots" from the lower resolution (but free) SAR imagery.

Advantages and Disadvantages of Topographic Mapping Technologies

Table L.8 summarizes the major advantages and disadvantages of topographic mapping technologies.

Table L.8. Advantages and disadvantages of topographic mapping technologies

Technology	Advantages	Disadvantages
Single Photon and Geiger-Mode Lidar	High altitude, high pulse density. good for broad area mapping.	Does not map through clouds. Some accuracy issues in dense vegetation. Requires extensive ground control targets for calibration. Appropriate for broad area topographic mapping only.
Linear-Mode Lidar	Best bare-earth DTM technology. Can satisfy 5-cm and 10-cm accuracy classes with high point density.	Does not map through clouds. Costs more for narrow corridors with sharp turns.
Aerial Stereo Photogrammetry	Can satisfy 5-cm and 10-cm accuracy classes. Well-established processes by ASPRS.	Does not map through clouds. Difficulties penetrating vegetation. Requires extensive GCPs for AT. Automated processes yield DSMs rather than DTMs.
Structure from Motion Photogrammetry	Inexpensive plane and consumer-grade camera. Easy-to-use by novices. Requires minimal GCPs for control of AT.	Without understanding underlying technology, easy to fall into traps and achieve inaccurate results. Difficulties penetrating vegetation. No ASPRS rigorous processes established.
Satellite Photogrammetry	Large pool of qualified data providers for commercial satellite imagery.	Requires cloud-free imagery. Difficulties penetrating vegetation. Automated processes yield DSMs rather than DTMs. Less accurate than airborne mapping technologies.
Aerial SAR (IfSAR)	Best technology for mapping through clouds, fog, and haze. Now available with 50 cm accuracy class and 2 m resolution.	Small pool of qualified data providers. High mobilization costs. For broad area mapping only. Less accurate compared to lidar.
Satellite Differential InSAR	Best technology for mapping post glacial rebound and subsidence with free (Sentinel-1) imagery	Commercial SAR has higher resolution and accuracy, but expensive. Imagery is seldom archived as required for time-series evaluations.

Inland/Nearshore/Offshore Bathymetry Technologies and Risks

Bathymetry is mapped from both airplanes and boats. Aerial topobathy lidar can map several times the Secchi depth, the depth at which the human eye can no longer see a black and white disk lowered into the water; therefore, topobathy lidar is the preferred technology when waters are reasonably clear. However, where waters are murky, acoustic surveys with echo sounders (sonar) is the only technology that works.

Table L.3 provided the bathymetric Quality Levels used for inland bathymetry. Whereas QL2, in the 10 centimeters vertical accuracy class, is the standard lidar Quality Level for topographic mapping, QL2B is the standard Quality Level for bathymetric charting purposes. QL2B DEMs are in the 15 centimeters vertical accuracy class with point density ≥2.0 ppsm.

Inland Bathymetry Considerations

Topographic lidar systems typically use lasers that produce radiation at 1,064 nanometers , an IR wavelength. Bathymetric lidar systems double the frequency to produce light at 532 nanometers, a green wavelength for penetration of the water column. Topobathy lidar uses lasers with both these wavelengths to simultaneously collect topographic and bathymetric data with both red and green lasers.

As explained in a draft document prepared by Allyson Jason of USGS, bathymetric lidar utilizes an active remote sensing technique that uses lasers with green wavelength to collect 3D point cloud data, processed to provide depths of waterbodies, using techniques also common for shallow-water nearshore bathymetry. When conditions are correct, airborne bathymetric/topobathy lidar is the preferred technology for mapping inland bathymetry – providing highly accurate data on the depths of underwater terrain. Inland topobathy lidar can be merged with topographic lidar data collected through the 3DEP to create topobathy data across the U.S. inland, including streams and lakes.

Bathymetric data have also been collected using wading (manual measurement of water depths to locate survey points or cross-sections for hydrologic modeling of flood studies, for example). Where waters are too turbid for bathymetric lidar, acoustic surveys with sound navigation and ranging (sonar) are performed to collect bathymetry.

Inland bathymetric lidar data collection has been shown to be capable of: (1) completing surveys for the same coverage as wading or sonar but in a shorter timeframe; (2) providing data for rivers and streams of greater depths than is possible for wading surveys; and (3) improving accuracy of inland bathymetric data for features that may be problematic during sonar surveys when waters may be too shallow for a sonar platform to navigate safely. Airborne bathymetric lidar (or topobathy lidar with both red and green lasers) is rapidly becoming the technique of choice if conditions are appropriate.

The successful collection of accurate inland bathymetric lidar has been found to be largely dependent on riverbed medium and substrate, in addition to turbidity, channel geometry, and depth (Miller-Corbett, 2016). A study by Kinzel and others (2012) determined that inland bathymetric lidar results were most accurate for mixed bedrock, gravel, cobble, and sand riverbed mediums; mid-range in accuracy for gravel riverbed mediums; and least accurate for primarily sandy riverbed mediums. This determination was further validated through a study by Wright and Brock (2014) that resulted in similar correlations between accuracy and substrate. Additionally, research by Hobenthal and others (2011) concluded that the most accurate bathymetric lidar data are derived from smooth bedrock surfaces. Riverbed medium and substrate are a general product of a region's unique physiography which is comprised on distinctive geomorphology, subsurface rock type, and structural elements that are characteristic of a specific geographic area, and these are known to vary across the U.S. according to physiographic province (Fenneman and Johnson, 1946).

For determining the suitability of bathymetric lidar (or topobathy lidar) for mapping inland bathymetry, the USGS has taken into consideration a variety of physiographic characteristics as well as water clarity (transparency). Physiographic provinces and sections from Fenneman and Johnson (1946) were assessed in relation to bedrock permeability class (USGS, 2003). Physiographic provinces containing a majority bedrock permeability class of unconsolidated sand and gravel were identified as being unsuitable for inland bathymetric lidar, while physiographic provinces containing sandstone, semi-consolidated sand, basalt, and other volcanic rocks, sandstone, and carbonate rocks, or carbonate rock were determined to be more suitable. In addition, NOAA's water clarity data portal, described below, was used to identify suitable waters for bathymetric lidar. Waterbodies and rivers with higher diffuse attenuation coefficient of light underwater (K_d) values (greater than ~0.8 K_d), which represent smaller attenuation depth and lower water clarity, were primarily located in physiographic provinces determined to be the least promising for accurate inland bathymetric lidar, while waterbodies and rivers with lower K_d values (less than ~0.8 K_d) were located in physiographic provinces determined to have conditions most favorable for inland bathymetric lidar data collection.

Generally, physiographic provinces and sections with low relief and that are known to contain large amounts of sand and sediment were determined to be the least promising for accurate inland bathymetric lidar. These included the Atlantic Coastal Plain, Central Lowland, and Great Plains physiographic provinces. Several sections from the Central Lowland and Great Plains physiographic provinces were identified as being conducive for inland bathymetric lidar because those specific sections were determined to have higher relief, less sand and sediment, and riverbed substrate more suitable for inland bathymetric lidar than other sections in those physiographic provinces. A complete list of physiographic provinces from Fenneman and Johnson (1946) that were determined to have conditions most favorable for inland bathymetric lidar data collection is below (unless specific sections are noted, the following list refers to the entire province):

- Adirondack
- Appalachian Plateaus

- Basin and Range
- Blue Ridge
- Cascade-Sierra Mountains
- Central Lowland – Wisconsin Driftless section
- Colorado Plateaus
- Columbia Plateau
- Great Plains – Black Hills, Colorado Piedmont, Edwards Plateau, Missouri Plateau Glaciated, Pecos Valley, Raton sections
- Interior Low Plateaus
- Lower Californian
- Middle Rocky Mountains
- New England
- Northern Rocky Mountains
- Ouachita
- Ozark Plateaus
- Pacific Border
- Piedmont
- Southern Rocky Mountains
- St. Lawrence Valley
- Superior Upland
- Valley and Ridge
- Wyoming Basin

Nearshore Bathymetry Considerations

For the purpose of this study, nearshore bathymetry is assumed to extend to the 10-meter depth contour. Figure L.22 shows the major advantage of topobathy lidar in shallow water where sonar becomes very expensive.

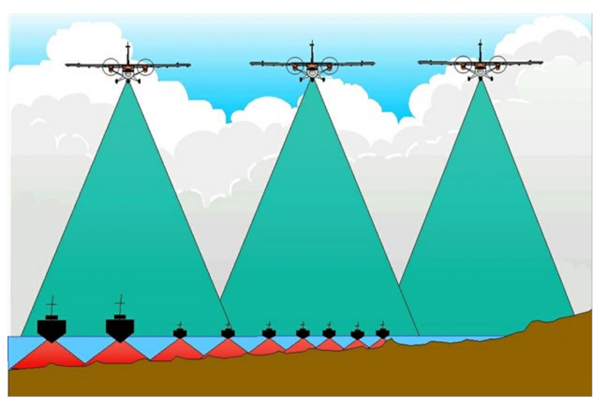

Figure L.22. This image shows why topobathy lidar is most cost-effective in shallower waters where sonar is the least efficient and even dangerous.

Acquisition of nearshore bathymetry is a trade-off between the capabilities and limitations of SDB, topobathy lidar and sonar. SDB is the least expensive and normally also the least effective, largely dependent on water clarity and the quality of available satellite imagery. Topobathy lidar is the most accurate, but also dependent on water clarity and the absence of aquatic or subaquatic vegetation. Sonar is excellent for mapping deeper waters, with or without vegetation, but sonar is limited in its ability to acquire data at depths shallower than the 3.5-meter Navigable Area Limit Line (NALL) for safety of navigation.

For coastal mapping of nearshore bathymetry, Figure L.23 shows how topobathy lidar should first be acquired to determine how deep the area can be mapped with lidar, minimizing the use of the more expensive sonar to map out to deeper waters.

Figure L.24 shows how nearshore water turbidity is the biggest threat to the success of a topobathy lidar project, followed by various forms of surface or submerged aquatic vegetation that causes data voids in the bathymetric surface (Figure L.25).

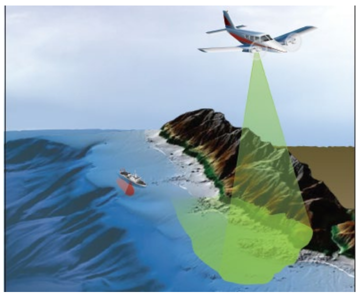

Figure L.23. Topobathy lidar is ideal for mapping the intertidal zone between water and land. Image source: Dewberry

Figure L.24. Water turbidity can severely limit the depth to which topobathy lidar can map nearshore bathymetry: Image source: Alaska ShoreZone imagery

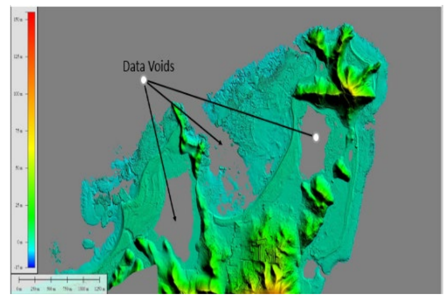

Figure L.25. Data voids will occur with topobathy lidar where there is surface or submerged aquatic vegetation. Image source: Dewberry

Offshore Bathymetry Considerations

Table L.4 lists the IHO Special Publication No. 44 (SP-44) Accuracy Orders for hydrographic surveys. Those Accuracy Orders are explained, going from the least accurate to the most accurate, as follows:

Order 2

This is the least stringent order and is intended for areas where the depth of water is such that a general depiction of the bottom is considered adequate. As a minimum, an evenly distributed bathymetric coverage of 5% is required for the survey area. It is recommended that Order 2 surveys are conducted in areas which are deeper than 200 meters. Once the water depth exceeds 200 meters, the existence of features that are large enough to impact on surface navigation and yet still remain undetected by an Order 2 survey is considered to be unlikely.

Order 1b

This order is intended for areas where the types of surface vessels expected to transit the area is such that a general depiction of the bottom is considered adequate. As a minimum, an evenly distributed bathymetric coverage of 5% is required for the survey area. This means some features will not be detected, although the distance between areas of bathymetric coverage will limit the size of those features. This order of survey is only recommended where underkeel clearance is considered not to be an issue. An example would be an area where the bottom characteristics are such that the likelihood of there being a feature on the bottom that will endanger the type of surface vessel expected to navigate the area is low.

Order 1a

This order is intended for areas where features on the bottom may become a concern for the type of surface traffic expected to transit the area but where the underkeel clearance is considered not to be critical. A 100% feature search is required in order to detect features of a specified size. Bathymetric coverage less than or equal to 100% is appropriate as long as the least depths over all significant features are obtained and the bathymetry provides an adequate depiction of the nature of the bottom topography. Underkeel clearance becomes less critical as depth increases, so the size of the feature to be detected increases with depth in areas where the water depth is greater than 40 meters. Examples of areas that may require Order 1a surveys are coastal waters, harbors, berthing areas, fairways and channels.

Special Order

This order is intended for those areas where underkeel clearance is critical. Therefore, 100% feature search and 100% bathymetric coverage are required and the size of the features to be detected by this search is deliberately more demanding than for Order 1a. Examples of areas that may require Special Order surveys are: berthing areas, harbors, and critical areas of fairways and shipping channels.

Exclusive Order

Exclusive Order hydrographic surveys are an extension of IHO Special Order with more stringent uncertainty and data coverage requirements. Their use is intended to be restricted to shallow water areas (harbors, berthing areas and critical areas of fairways and channels) where there is an exceptional and optimal use of the water column and where specific critical areas with minimum underkeel clearance and bottom characteristics are potentially hazardous to vessels. For this order, a 200% feature search and a 200% bathymetric coverage are required. The size of features to be detected is deliberately more demanding than for Special Order.

Topobathy Lidar Technologies

The best overall reference for topobathy lidar sensors is Chapter 10 of the 3rd edition of the DEM Users Manual. It provides basic concepts of topobathy lidar (water surface, water column, seafloor); system design (laser, scanner, receiver, and ancillary system components); data processing (accuracy standards, system calibration, topobathy lidar point cloud generation, waveform processing, filtering and manual editing, data products, output formats, and deliverables); sensor technology; and operational and planning considerations for topobathy lidar projects. Topobathy lidar was previously called Airborne Lidar Bathymetry (ALB), but "topobathy lidar" is now in common usage.

Topobathy Lidar Sensors

Table L.9 summarizes topobathy lidar sensors used today for mapping shallow and deeper waters in the U.S. These systems, shown in Figures L.26, L.27, L.28, and L.29, each have their own advantages and disadvantages.

Table L.9. Topobathy Lidar System Capabilities

Sensor	Hyperspectral Camera On-board	Red/Green/ Blue/NIR Camera On-board	Shallow Water Capability	Deep Water Capability	Maximum Depth (meters)
Optech CZMIL Supernova	X	X	X	X	4.4/ K_d (deep) 3.0/ K_d (shallow)
Leica Chiroptera 4X		X	X		2.7/ K_d
Leica Hawkeye 4X		X		X	4.0/ K_d
RIEGL VQ-880-G II		X	X		1.5 Secchi depth
RIEGL VQ-840-G		X	X		1.7-2.5 Secchi depth
Fugro RAMMS		X	X	X	3.0/ K_d

The Coastal Zone Mapping and Imaging Lidar (CZMIL) (Figure L.26) topobathy lidar system's deep-water channel provides a diffuse attenuation coefficient of 4.4/ K_d (water column light attenuation coefficient, explained below) enabling this sensor to achieve depths of 80 meters in clear water while providing the best depth penetration in turbid waters compared to other systems listed in Table L.9. The CZMIL's topographic and topobathy data are collected using a single laser at a higher collection rate than other systems. A PhaseOne medium format camera is also on-board to provide multi-band imagery that can also be used to colorize the lidar point cloud data. This sensor can be mounted in a variety of fixed wing aircraft as small as a Piper Navajo.

Figure L.26. Optech CZMIL SuperNova topobathy lidar system. Image source: Optech

Figure L.27. Leica Chiroptera 4X and HawkEye 4X topobathy lidar systems. Image source: Leica

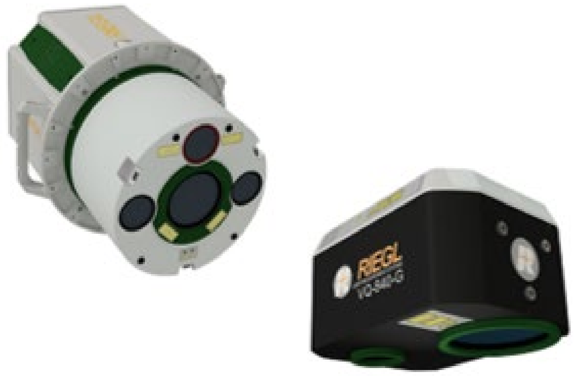

Figure L.28. RIEGL VQ 880-G II and VQ 840-G topobathy lidar systems. Image source: RIEGL

Figure L.29. Rapid Airborne Multi-beam Mapping System (RAMMS). Image source: Fugro

As shown at Figure L.27, Leica Geosystems offers two topobathy lidar sensors, the Chiroptera 4X and HawkEye 4X also listed in Table L.9. The Chiroptera 4X was engineered to survey the coastline and near-shore zone to achieve depths of 25 meters and a bathymetric point density of up to 5 ppsm. The Chiroptera is also equipped with a NIR sensor to acquire topographic data with a point density of at least 10 ppsm. The HawkEye 4X was designed to couple with the Chiroptera 4X to survey waters with depths to 50 meters. These systems are also integrated with an RCD30 medium format multi-spectral camera along with an RGB QA camera to provide simultaneous image capture during the lidar survey. The medium-format imagery can also be used for orthoimagery production and stereo compilation of navigational features not detected by the lidar data.

As shown at Figure L.28, RIEGL offers two topobathy lidar systems designed for inland and nearshore bathymetric surveys. The VQ 880-GII provides simultaneous topographic and bathymetric data capture using NIR (topo) and green (bathy) sensors in one platform. It can achieve depths of at least 1.5 times the recorded Secchi depth. The VQ 880-GII can be installed on fixed-wing aircraft or helicopters and is equipped with a Phase One medium format camera. RIEGL has also developed a compact topobathy lidar system intended for unmanned aerial systems (UAS), such as the VQ-840-G. The depth penetration abilities of this system range from 1.7 to 2.5 Secchi depths depending on the user's preferred laser pulse rate. It is also equipped with an RGB camera for data QA. In addition to UAS platforms, this system can also be installed on small fixed wing aircrafts and helicopters.

As shown at Figure L.29, Fugro's Rapid Airborne Multibeam Mapping System (RAMMS) is a topobathy lidar sensor that can achieve depths of approximately 50 meters. This system uses a push-broom scanner to produce swath width that is roughly equivalent to the flying height of the aircraft.

Regardless of the topobathy sensor, flight lines are normally parallel to the shoreline. NOAA, the USACE Joint Airborne Lidar Technical Center for Expertise (JALBTCX), and the Naval Oceanographic Office currently use different criteria for distance mapped inland and offshore from the shoreline. They are currently working to develop common specifications, with plans to release those specifications in the near future.

Variable Topobathy Lidar Standards and Specifications

Currently, topobathy lidar contractors fly to different standards and specifications when acquiring data for JALBTCX, the NOAA/NGS Remote Sensing Division, or the USGS National Mapping Program. Currently, NOAA specifications have planned point density of 3 ppsm to support a DEM cell size of 1 meter; the 3 ppsm is expected to be met in topographic and shallow bathymetry areas, but falloff in deeper bathymetry is expected and acceptable. Most NOAA projects are expected to adhere to QL2B specifications which are equivalent to the USGS QL2 specifications for topographic lidar, with the addition of a depth-dependent bathymetry accuracy parameter. The NVA is 19.6 centimeters at the 95% confidence level; the VVA is 30 centimeters at the 95^{th} percentile; the bathymetry vertical accuracy is 58.8 centimeters at the 95% confidence level for shallow waters. The absolute horizontal accuracy is 1 meters ($RMSE_r$). The intraswath relative accuracy (within-swath hard surface repeatability) is 6 centimeters; and the interswath relative accuracy (swath-to-swath non-vegetated terrain match) is 8 centimeters. The Joint Airborne Lidar Bathymetry Technical Center of Expertise uses different specifications but is working with NOAA to bring the differing specifications into alignment.

For USGS topobathy lidar of rivers, topographic data are to be collected at 8 ppsm, but submerged topobathy lidar is to be collected at 1.5 ppsm in shallow water (shallow bathymetry maximum depth = 2.4/ K_d (~1.5 Secchi depth) including overlap; three band RGB orthoimagess are acquired during the topobathy lidar data acquisition but may be excluded if acquisition is constrained to night operations.

Topobathy Lidar Technology Risks

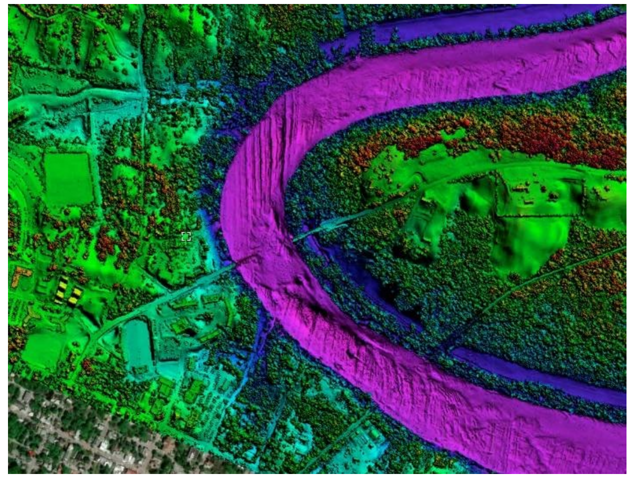

Figure L.30. Highly successful topobathy lidar acquired of the Potomac River near Shepherdstown, MD with a Chiroptera lidar sensor. Image source: Dewberry

Topobathy lidar technology risks include water depth, flow rate, turbidity, and bottom reflectivity. Figure L.30 shows outstanding results in mapping the Potomac River near Shepherdstown, MD. To reduce risks, the data was acquired during low water levels and slow flow rate; whereas the hard bottom is more reflective than murky river bottoms, sandy river bottoms are even more reflective.

Figure L.31 shows where topographic lidar was merged with topobathy lidar of the Lower Withlacoochee River (Florida) for a 22.5 sq. mi. area. The CZMIL topobathy lidar coverage area was 12 sq. mi.. 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 L.32 shows where multi-beam sonar was collected for the deeper parts of the channel (0.3 sq. mi. or 14 linear river miles); and single-beam echo sonar (SBES) with a HyDrone in the two dam spillway areas that were too shallow for multi-beam echo sounder (MBES) and too turbid for lidar. Figure L.33 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 nationwide in order to fully satisfy objectives of the 3D Nation initiative.

Figure L.31. Topobathy lidar mapped portions of the river, but not the deeper tannic waters with mucky bottom. Image source: Dewberry

Figure L.32. Multi-beam sonar mapped the deeper parts of the river not mapped with topobathy lidar. Image source: Dewberry

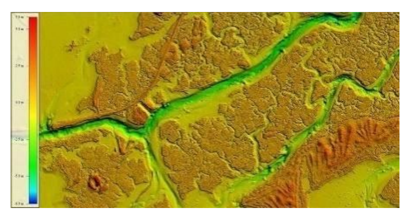

Figure L.33. By merging the two datasets the entire topographic and bathymetric surface was mapped seamlessly. Image source: Dewberry

Sonar Technologies

In the sonar Chapter 11 of the 3rd edition of the DEM Users Manual, the terms “sonar surveys” and “acoustic surveys” are used interchangeably. Both single-beam and multi-beam echosounders use acoustic waves reflecting from the ocean floor to map the bathymetric surface. Sound waves have a physical character that differs from that of other types of electromagnetic propagating waves, i.e. light and radio waves. Whereas both topobathy lidar and satellite derived bathymetry (SDB) are limited by water clarity, because they require light of different wavelengths to penetrate through water, sonar is only marginally affected by water clarity. Acoustic waves are based on vibrations of the actual material of the medium (water) and are manifested as periodic variations of pressure in the water. When a propagating acoustic wave encounters a sudden change in the properties (specifically the product of sound speed and density) of the water, a portion of the acoustic wave will change its direction of propagation. That portion of the acoustic wave that reverses its propagation direction is the echo which echo sounders are designed to exploit for distance measurements.

If the transmission and reception of acoustic energy can be confined to a unique narrow angular sector, the detection of an echo at some time after a pulse is transmitted provides both the range and bearing to the point in space where the echo was generated. Measuring the local configuration of the seabed with acoustics begins this simply: transmit acoustic energy toward the bottom and precisely detect the arrival times and directions of the acoustic energy that returns from the bottom. The measured ranges and 3D directions to points where the echoes were generated can be converted into 3D locations, relative to the transducer, through trigonometric calculations. Finally, it is necessary to geometrically transfer the echo generation locations from the transducer frame of reference into the ship's frame of reference and into the appropriate reference frame for presenting the survey results.

"Choosing the appropriate system for a bathymetric survey"[3] is an excellent reference for comparison of SBES and MBES.

Single-Beam Echo Sounder

Single-Beam Echo Sounders a.k.a. Vertical-Beam Echo Sounders, are primarily designed to produce quantitative information about nadir (vertically below) water depths. An SBES has one, and sometimes two, transducer(s) that are each used for both transmitting and receiving acoustic energy at a given frequency. As shown at Figure L.34, the vertical orientation of the beam(s) means the transmitted acoustic waves will most likely interact with the bottom at near vertical incidence, which will maximize the energy in the echo returns. The received echoes are processed to determine the onset time of the first echo's arrival defined by the "leading edge" of the echo envelope waveform. The time measured by an SBES is associated with the shortest distance from the ship to a point on the seabed. Depending on characteristics of the transducer and the configuration of the local seabed, that distance may not be the depth directly beneath the survey vessel, also referred to as nadir. However, it is generally assumed to be nadir because in shallow depths the error in position is

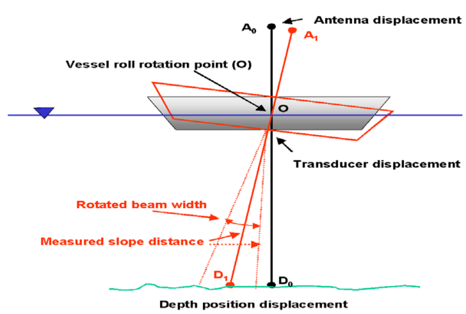

Figure L.34. Horizontal displacement and depth offset caused by roll rotation of the single vertical beam.

[3] https://www.ee.co.za/wp-content/uploads/legacy/positionit_2013/surveying-tech_bathymetric_june13.pdf

likely not great, and in deeper depths the footprint is so large as to include the nadir at nearly all realistic vessel attitudes.

Survey lines are typically perpendicular to the stream centerline or underwater slopes of lakes, and the line spacing depends upon project requirements. Tie lines are perpendicular to the survey lines, but at wider spacing; they serve as a quality control tool for consistency of depths at crossing points. Single-beam echo sounders are used for dredging, port construction, and coastal flood study profiles.

Single-Beam Echo Sounder Technology Risks

Single-beam echo sounders cannot map all the way up to the shorelines of rivers, lakes or oceans, or the survey vessel will run aground. Thus, there is normally an unmapped gap near the shorelines which is best mapped with topobathy lidar.

The major disadvantage is that the SBES does not provide full bottom coverage and can fail to map rocks or obstructions that could cause hazards to navigation.

Multi-Beam Echo Sounder

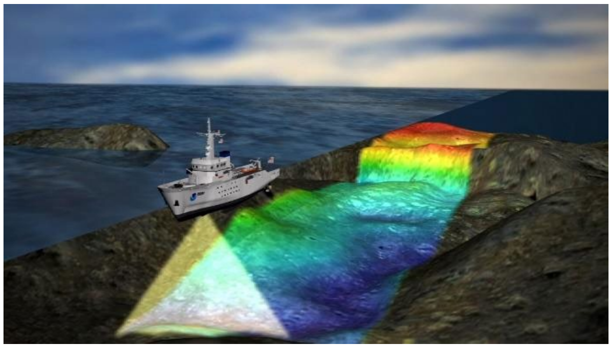

Figure L.35. Multi-beam echo sounders map wide swaths and provide full bottom coverage.

As shown in Figure L.35, an MBES is primarily designed to produce quantitative information about water depth. Multi-beam sonars are first characterized as having significant system response and the ability to measure depths at angles that are non-vertical to the seabed, as well as, at nadir (vertical). An MBES is typically characterized as having separate transducers for transmit and receive. All MBES sonars measure travel times between the echo sounder transducer and the seabed using a transmitted acoustic pulse. One of the major differences between multi-beam and the other types of sonar is the way the sonar processes/interprets the echo waveforms that are received subsequent to the pulse transmission. A conventional MBES measures the acoustic time of flight to the seabed as a function of angle from nadir. Using trigonometric functions, the travel times are converted to a set of points, each with a vertical and horizontal coordinate, relative to the multi-beam transducer (depth and position). Seemingly minor errors in the beam angle relative to nadir can result in unacceptably large depth errors. Because of the non-vertical measurement geometry, it is essential that full roll-pitch-yaw motion sensors be installed and operated on the survey platform along with the multi-beam sonar, with precisely measured accurate time-linkage between the system components.

For each transmitted pulse, there are many locations on the seabed where the projected main lobe of the transmit pulse and the projected main lobe of a computed receive "beam" coincide. Collectively the multiple locations comprise the MBES's entire measurement swath shown in Figure L.35.

Multi-Beam Echo Sounder Technology Risks

Multi-beam echo sounders are at greater risk in shallow water than SBES because the MBES is much more expensive than the SBES and suffer more expensive damages should the survey vessel and equipment run aground. Furthermore, the shallower the water gets, the closer a MBES comes to becoming a high cost SBES.

Silting is a major issue on some rivers. Sean Duffy of the Big River Coalition reports that dredging in the Mississippi River's Southwest Pass to maintain the authorized channel dimensions is usually required during high river periods where the amount of water is overwhelmed by the deposition as the Mississippi River enters the Gulf of Mexico (Figure L.36). "Deposition of up to 5 feet of material in a 24-hour period is not uncommon in the area of Southwest Pass." This is listed as a risk should anyone erroneously assume that bathymetric datasets remain relatively stable for several years. Local managers need to understand how frequently bathymetric surveys of rivers and lakes (especially the Great Lakes) need to be redone.

Figure L.36. Because of rapid silting, dredging is almost a constant operation in some parts of the Mississippi River to maintain required channel depth. Image source: Big River Coalition

Dual-Head Multi-beam Echosounders

A dual-head MBES has advantages for nearshore shallow water surveys from a small boat. For example, the RESON dual-head MBES (Figure L.37) advertises the following benefits[4]:

- All-in-one survey system;
- Single sonar processor for two sonar heads;
- Compact system allows for fast mobilization and low space requirements;
- Clean and ultra-high quality for faster operational surveys and reduced processing time;
- Frequency from 200 to 400 kHz, allowing for improved swath performance and reduced survey time;
- The compressed water column data significantly reduces data volume while maintaining the required information; and
- Normalized backscatter designed specifically for accurate, reliable and repeatable seabed classification.

Figure L.37. The RESON SeaBat Integrated Dual Head T20/50-R is a sonar system that produces 1,024 beams per ping, frequency from 200 to 400 kHZ, allowing for swaths on both sides of small boats in shallow water. Image source: RESON

[4] http://www.teledynemarine.com/SeaBat-IDH-T20-50-R

Curved Array Multi-Beam Sonar

The advantages of curved array multi-beam sonar over traditional linear array multi-beam sonar are explained in a term paper by Robert Sean Galway entitled: "Comparison of Target Detection Capabilities of the Reson Seabat 8101 and Reson Seabat 9001 Multi-beam Sonars".[5]

There are several types of curved array sonars. NORBIT Subsea specializes in ultra-compact wideband multi-beam sonars for subsea and surface platforms. Within their family of sonars is their Winghead i67h (Figure L.38), advertised as a compact ultra-high-resolution curved array broadband multi-beam sonar offering tight integration with a GNSS/INS positioning system designed for use in shallow water environments. There are many other curved array multi-beam sonars on the commercial market.

Figure L.38. NOBIT Winghead i67h curved array multi-beam sonar. Image source: NORBIT

Side Scan Sonar

Whether towed behind a traditional hydrographic survey vessel or hull mounted, side scan sonar is a widely used tool for qualitative observations and supplements other quantitative measurement tools. Side scan sonar provides a detailed presentation of the seabed features and manmade objects that may lie on the surface of the seabed, in the form of a raster image. The first side scan sonar was a shallow water system, and most current versions of this technology are still used in estuaries, lakes, and bays. The fundamental physics are the same as with other sonars; higher resolution requires higher frequency and thus decreased range, so therefore even in deep water a towed side scan sonar must remain relatively close to the bottom to be effective. Side scan sonars are ideal for shallow water surveys.

As in multi-beam sonar and interferometric sonar, a side scan sonar ensonifies the entire measurement swath with the same acoustic transmit pulse. There are two pulses, one transmitted from a continuous line array transducer looking to port and one from a continuous line array transducer looking to starboard. The main lobe of the (port and starboard) transmit transducer is narrow in the along-track direction (horizontal plane) and broad in the cross-track direction (vertical plane), again due to the physics of the array size. Like SBESs, conventional side scan sonars use the same transducer for receive and for transmit. This provides a high degree of confidence, but not an absolute guarantee, that the echoes received by the side scan sonar originated from points that are in the direction that the transducer is pointing. One of the greatest challenges facing the side scan sonar processor is removing multi-path acoustic returns from the primary return. These can be reflections from the underside of the surface-air interface, objects in the vicinity, or even other vessels.

The basic range resolution of a side scan sonar, as well as an SBES and MBES, is determined by the bandwidth of the transmit pulse. In most systems the bandwidth of the transmit pulse is

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[5] http://www.omg.unb.ca/omg/papers/MBSS_TermPaper.pdf

determined by the time duration of a short-transmitted tone burst of a given frequency. However, in some designs the bandwidth is defined by the bandwidth of a long frequency-modulated transmit pulse. These systems are commonly referred to as "chirp" side scan sonars; see EdgeTech 4205[6] example at Figure L.39.

Figure L.39. The EdgeTech 4205 tri-frequency, motion-tolerant side-scan sonar system has improved target positioning and crisp, high resolution "chirp" images. Image source: EdgeTech

In the design of a side scan sonar a high premium is placed on achieving transmit/receive beams that are narrow in the along-track direction to maximize resolution and thus the discrimination of features. Side scan sonars use high frequencies to achieve narrow beam widths with transducers of moderate length. Due to the typically high frequencies of side scan sonar, 455-900 kHz, the useful operating range of a side scan sonar is less than 200 meters to either side of the tow fish. In practical usage, NOAA limits maximum allowable side scan range to 100 meters (2021 Hydrographic Survey Specifications and Deliverables, section 6.1.2.4).

NOAA typically assumes 120-meter set line spacing for side scan sonar operations in 1-20 meters depths along the east coast, Gulf of Mexico, Bering Sea (north of the Aleutian chain), and North Slope of Alaska.

Interferometric Sonar

Traditional hydrographic data acquisition techniques for large-scale shallow water survey projects are typically inefficient and costly. Technological advancements to Phase Differencing Bathymetric Sonar (PDBS) systems, or interferometric sonar[7], have overcome the efficiency and cost obstacles associated with traditional surveying methods. Phase Differencing Bathymetric Sonar systems provide a significantly wider swath in shallow water (depth less than 35 meters) compared to MBES. The increased number of phase detection arrays found in some systems has also proven to significantly improve the accuracy. Additionally, some manufacturers have found methods for closing the nadir gap which has historically plagued the efficiency of these sensors. These recent improvements paired with the wider swath coverage observed by these systems place interferometric sonars at the forefront of acoustic technology. Utilization of these systems allow for fewer sweeps across the survey area resulting in decreased data acquisition time and cost. For many applications, the wider swath coverage eliminates requirements of deploying the survey system close to the shoreline thus increasing keel clearance for safe deployment. Furthermore, some PDBS systems offer a platform for providing simultaneous, co-registered, 3D bathymetry and side scan sonar imagery in a single unit. This considerably improves the integrity of feature

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6 https://www.edgetech.com/product/4205-tri-frequency-motion-tolerant-side-scan-sonar-system/

7 https://www.edgetech.com/wp-content/uploads/2019/07/EdgeTech-Paper-on-6205-presented-at-CHC2014.pdf

detection for navigation and mapping purposes, while reducing processing time for co-registering imagery to the bathymetric data.

The EdgeTech 6205 Swath Bathymetric Sonar System[8] (Figure L.40) is a combined, fully integrated, swath bathymetry and dual frequency side scan sonar system that produces real-time high-resolution 3D maps of the seafloor while providing co-registered simultaneous dual frequency side scan and bathymetric data.

Figure L.40. The EdgeTech 6205 combined interferometric swath bathymetry and side-scan sonar. Image source: EdgeTech

Manufacturers of interferometric sonars state that their systems can typically measure depths over a swath that is up to ten times the depth, or more particularly, the height of the transducer above the bottom. The data density in a beam-formed swath system (multi-beam) and thus cross track resolution will halve if depth is doubled. The data density of a phase measurement swath system (interferometric) is far higher, typically hundreds of times higher, and stays roughly constant with depth. Therefore, the interferometric sonar can afford to average or statistically filter through many real data points and still provide soundings in a high spatial resolution grid. However, they also tend to provide depth measurements that are less accurate and precise than depths measured with beam-formed multi-beam sonar. Factors contributing to the uncertainties in depths from shallow water interferometric sonar are: unraveling the true phase (time) differences in light of the ambiguities in differential phases, interference from multi-path arrivals, and interference due to simultaneous arrival of echoes with different vertical angles of arrival (such as echoes from both the sea surface and seabed). All these factors are exacerbated in nearshore areas, but these are also the areas of greatest interest for interferometry due to the higher potential efficiency versus coverage obtained with directional multi-beam technology.

Motion Sensing Systems for Multi-beam Sonar Bathymetry

A multi-beam sonar generates a fan of listening beams that spans 70-90 degrees. The bottom swath covered by the sonar fan has a width in excess of seven times water depth. The multi-beam sonar provides raw ranges from return echoes along each listening beam, which an online processing computer translates into georeferenced depth images. Figure L.41 shows an example of a sea bottom DEM generated with a multi-beam sonar. This process requires accurate measurement of the position and orientation of the sonar head at high data rates so that the sonar system can interpolate the sonar position and orientation to the time of echo reception.

[8] https://www.edgetech.com/product/6205s-combined-bathymetry-side-scan-sonar/

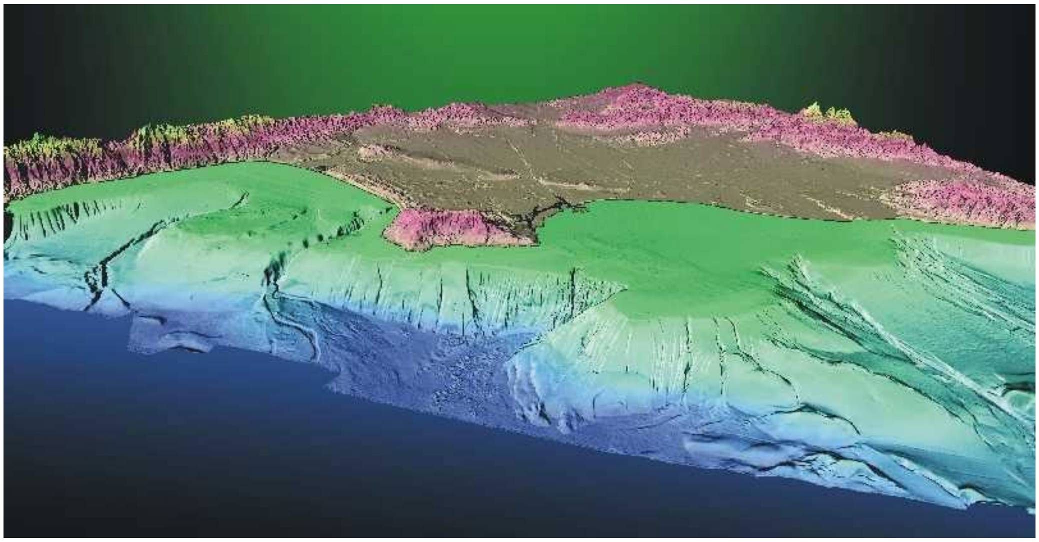

Figure L.41. Greater Los Angeles continental shelf DEM generated with multi-beam sonar. Image source, U.S. Geological Survey

Figure L.42 shows the geometry for a multi-beam sonar motion sensing system. In order to achieve full utilization of a multi-beam sonar, i.e. $\gamma = 0.01$ or 1 percent in the outer beam of a 75-degree fan, the error standard deviation of the measured orientation must be better than 0.05 degrees. Heading error impacts the position error of each pixel in the bathymetry data. In order to obtain a 0.5-meter pixel position error in the outer beam of a 75-degree fan at a depth of 100 meters, the heading error must be better than 0.05 degrees. Consequently, the requirement for a high accuracy multi-beam bathymetry system is 0.5 meters horizontal position error and 0.05 degrees orientation error in all three axes.

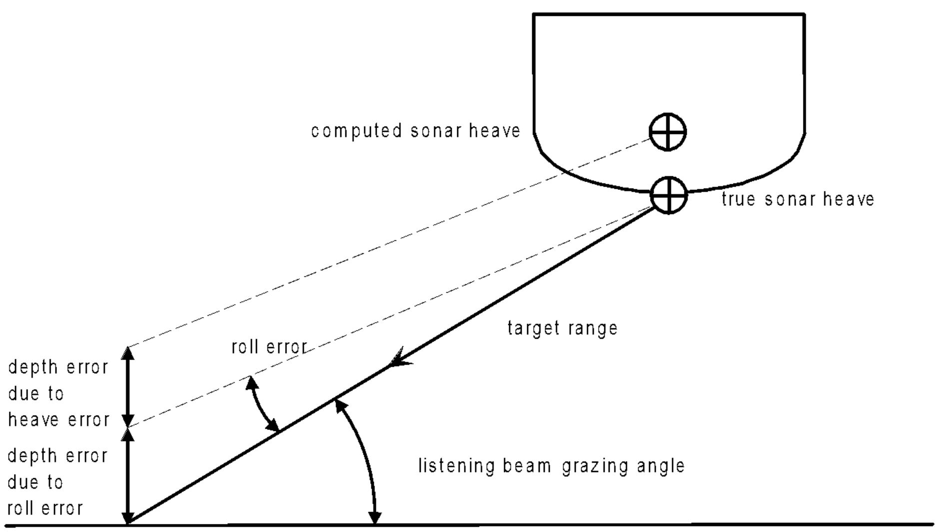

Figure L.42. Bathymetric depth error in a multi-beam sonar

In addition, the heave of the vessel must also be measured to an accuracy of better than 0.1 meters to be consistent with the IHO standard. Absolute measurement of height with this accuracy is currently not feasible in a typical marine survey scenario that is far from the nearest shoreline where a GPS reference receiver or other form of positioning reference can be installed. Furthermore, the datum for mean sea level does not necessarily correspond to a GPS zero altitude measurement. GPS uses the World Geodetic System 1984 ellipsoid as the reference for positioning and an undulation model to compute height with respect to an approximate mean-sea level reference called the geoid. Consequently, vessel heave for marine survey is specified as a relative displacement with respect to an assumed vessel waterline in calm water. Any offset between the assumed heave datum and true mean sea level is removed during the final map generation. A heave sensor is thus required to measure the non-constant or high frequency vertical displacement of the vessel, which is an approximately sinusoidal displacement with frequency given by the wave encounter frequency of the vessel. A simple heave sensor comprises a vertical accelerometer and a heave filter that performs a combined double integration and a high-pass filtering action on the measured vertical acceleration. The high-pass filter blocks the nearly constant accelerometer bias from reaching the double integrator, which in turn computes the vertical displacement of the vessel in the filter pass band. The heave filter must be tuned so that it provides the required accuracy in a pass band that includes the lowest expected wave encounter frequency when the vessel is moving downwind.

A roll-pitch-heave (RPH) sensor provides basic measurements of vessel roll, pitch and heave. It is typically a single unit that contains triads of accelerometers and gyros and a processor that implements a vertical gyro (VG) algorithm and the previously described heave filter. The VG algorithm computes roll and pitch with respect to an apparent vertical reference assumed to be the gravity vector. If the vessel does not accelerate, then the accelerometers will measure only the gravity vector that defines the true vertical. The VG algorithm computes the short-term roll and pitch motion with respect to the apparent vertical using the gyro data. It uses a complementary filter to block high frequency accelerations due to wave motion in the apparent vertical estimation and block low frequency gyro biases in the roll and pitch propagation. If the vessel experiences a sustained horizontal acceleration during a turn, then the apparent vertical will shift away from the true vertical and the computed roll and pitch will contain offsets. Once the sustained acceleration ends, the VG algorithm will exhibit a transient that decays within the complementary filter’s settling time. A vessel that uses an RPH sensor must therefore allow a settling time (typically less than five minutes) at the beginning of a survey line following a turn before using the RPH data.

The state-of-the-art in high accuracy marine motion sensors is a GNSS-Aided Inertial Navigation System (AINS). This technology provides all the required motion data at the required accuracy to provide full utilization of a wide swath multi-beam sonar. The GNSS-aiding provides for initialization, alignment and full accuracy motion sensing independent of vessel motion, as well as continuous refinement of the alignment and calibration of the inertial sensors. The GNSS-AINS delivers full accuracy in any vessel dynamics, including sharp turns and severe accelerations and decelerations. It has no requirement to maintain a straight trajectory or to allow for a settling time after a turn, as does a VG-based RPH sensor. The IMU provides the vertical acceleration measurement for the heave filter. The heading accuracy is achieved with a dual-antenna azimuth aiding system.

Sonar Technology Risks

NOAA would prefer to have topobathy lidar collect bathymetry out to the deepest waters possible because that would reduce the need for more expensive sonar surveys. NOAA's goal would be to collect topobathy lidar out to **at least** the 3.5-meter depth contour for the NALL, the limit to which most MBES surveys can be safely performed, but even this is difficult to achieve in some areas with water clarity and turbidity issues.

For safety purposes, MBES surveys are normally performed in waters deeper than the NALL; the shallower the water, the MBES essentially becomes an expensive SBES. Dual head MBES, curved array MBES, side scan sonar, and interferometric sonar are better for waters shallower than the NALL, but they too have risks that the platform could run aground.

While side scan sonar provides a detailed presentation of the seabed features and manmade objects that may lie on the surface of the seabed in the form of a raster image, side scan sonar does not map bathymetric depths.

Bathymetric Sonar Platforms

Crewed Surface Vessels

There are literally hundreds of different types of crewed surface vessels performing single-beam and multi-beam sonar surveys in the U.S. One such example is at Figure L.43.

Figure L.43. Typical crewed hydrographic survey vessel used for mapping of inland bathymetry. Image source: TerraSond

Figure L.44 shows a large survey vessel designed for deeper water surveys; this vessel, while surveying in deeper waters, can also serve as a mothership for the CW5 Uncrewed Surface Vehicle (USV) shown in both Figures L.44 and L.45 which more-safely surveys in waters shallower than the 3.5-meter NALL unsafe for the mothership.

Figure L.44. Larger vessel (mothership) used for traditional MBES surveys in deeper water and CW5 USV (yellow) used for shallow-water surveys. Image source: TerraSond

Figure L.45. With the mothership in the background, the CW5 is a proven USV platform for nearshore bathymetric surveys with a variety of sonar sensors. Image source: L3-Harris

eTrac

eTrac has developed a method of economically extending the footprint of a multi-beam swath system by leveraging a force multiplication autonomy model. The base of the operation begins with a mothership that is staffed with traditional hydrographic personnel (captain and technician). One or several autonomous vessels are then networked to the mothership through the integration of a wireless mesh radio network. With the network established, each vessel in the system has visibility of every other vessel. This visibility includes positional and depth information from each vessel. Through the application of proprietary SwathSync™ Technology, eTrac has achieved the ability to "virtually tow" an autonomous vessel behind a mothership with the only user input to the system being the desired percent overlap between swaths (Figure L.46).

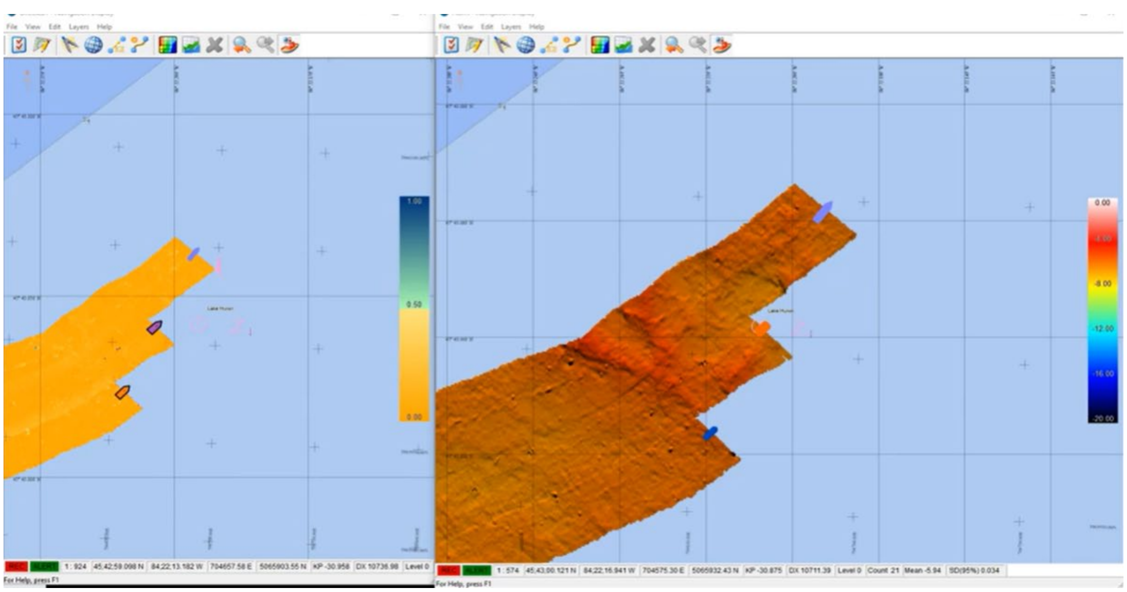

Figure L.46. The eTrac mothership is trailed by Autonomous Surface Vessels that are “virtually towed” and controlled for the correct overlap between swaths.

Currently eTrac has one 70-foot live-aboard vessel that would operate as a mothership to several optionally manned vessels or Autonomous Surface Vessels (ASV)/USVs; eTrac currently has five vessels within its fleet that can be operated remotely and used in the SwathSync follow mode.

Overall capacity is much larger than this as eTrac currently leverages partnerships with larger vessel leasing companies as well as ASV/USV vendors; eTrac currently has many assets and regularly performs work worldwide.

Uncrewed Surface Vessels

There are many USVs on the commercial market that are suitable for inland bathymetry. Three popular examples are at Figures L.47, L.48, and L.49. Platform selection should be based on velocity of streams or rivers to be surveyed with SBES or MBES. These can be controlled by an operator on land or from a mothership at sea. Many are programmed to operate on planned survey tracks, preplanned for selected overlaps.

Figure L.47. The HyDrone is ideal for hydrographic surveys of lakes and ponds. Image source: Seafloor Systems

Figure L.48. Similarly, the Z-Boat is not powered to operate in waters with waves and strong currents. Image source: Teledyne Marine

Figure L.49. The EchoBoat-160 is advertised for MBES surveys in “choppy inland waters” but not for ocean waves. Image source: Kuker-Ranken

Shallow Surveyor by SeaSat

The SeaSat Shallow Surveyor (Figure L.50) is optimized for performing shallow water surveys. At the shallowest depths between 1 and 2 meters, it surveys with an SBES producing high resolution single-beam survey tracks as close as 1 meter apart; although this is not full bottom coverage, this comes reasonably close. The 3-meter survey line spacing with 15 meters tie line spacing (Figure L.51) is more common. SeaSat offers many options for SBES line spacing for survey lines and tie lines to validate consistency in different tidal stages of the acquisition.

With its small size and light weight, a SeaSat Shallow Surveyor can be transported on a small plane and launched manually by a single person from a dock, ramp or beach and controlled from anywhere. This makes the Shallow Surveyor ideal for many remote locations where it would be too expensive to bring in a traditional hydrographic survey vessel with or without USV.

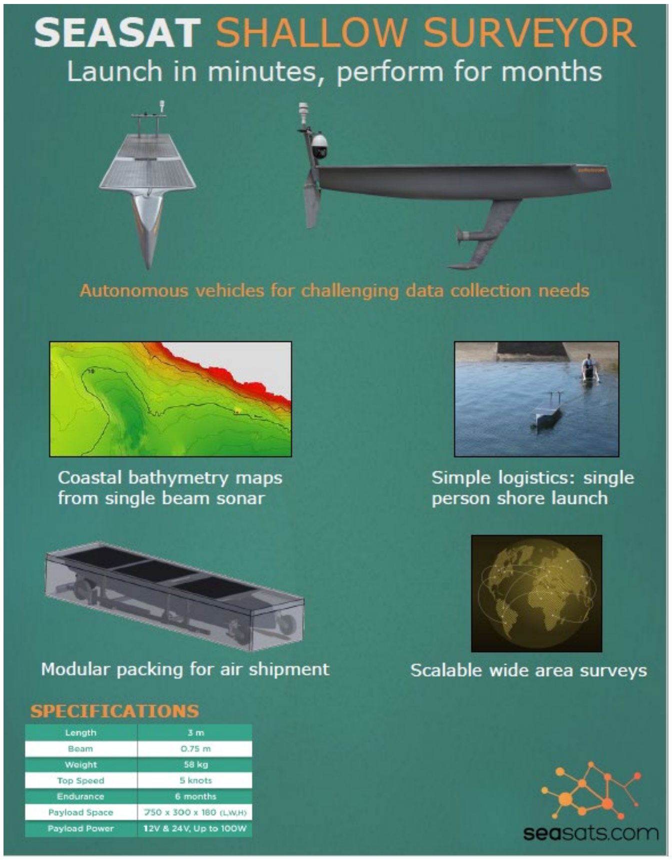

Figure L.50. The Shallow Surveyor can be flown into remote airfields on small planes to map the community's shallow bathymetry. Image source: SeaSat

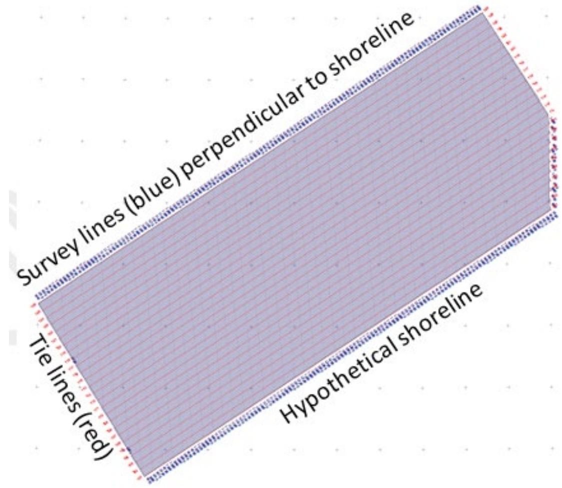

Figure L.50. With variable line spacings offered by SeaSat, narrowly spaced survey lines are programmed to survey SBES tracks perpendicular to the shoreline, and widely spaced SBES tie lines are programmed parallel to the shoreline. Elevations at the intersection points between survey lines and tie lines are used to compare their consistency using RMSDz statistics.

Autonomous Surface Vessels

To increase productivity, autonomous hydrographic survey capabilities have long been a goal for NOAA, monitored by data link from large distances. There are several innovative options for mapping Offshore Bathymetry for major portions of ocean waters.

XOCEAN XO-450


Figure L.51. XO-450 ASV. Image Source: XOCEAN

XOCEAN provides a full suite of coastal survey services and uses ASVs at high water and UAVs at low water to create seamless, high resolution topographic and bathymetric datasets.

The XO-450 ASV (Figure L.52) is a 4.5-meter catamaran ASV, operated by XOCEAN. The ASV features a fully automated hybrid power plant consisting of solar harvesting, lithium-ion battery, intelligent control system and auxiliary micro diesel generator. Continuous electrical load capacity of 3kW is available to power the vessel systems and sensor payload. The ASV has low emissions (~0.02 tons CO_2/day), which is 0.1% of the carbon emissions of a traditional crewed vessel.

The ASV has a shallow draft (less than 1 meter) with MBES installed and has been designed to provide a highly flexible platform for integrating multiple sensors. This includes experience with sonars from NORBIT, Kongsberg, R2Sonic and EdgeTech. Other commercially available and leading equipment is used during survey operations, including an Applanix POS MV IMU (Position and Orientation System for Marine Vessels, Inertial Measurement Unit), and Quality Planning Software from QINSy (QPS QINSy), a Microsoft Windows based software package to acquire the data and to provide information to the ASV's autopilot to steer it along the survey lines. Bathymetry, several imagery and backscatter outputs, and other weather and oceanographic observations (depending on the configured payloads) are acquired.

XOCEAN's ASVs offer full uncrewed 'Over-The-Horizon' operation using satellite communications. Each ASV sends real time images and situational awareness data to XOCEAN's Control Room in Ireland where a team of qualified Pilots keep watch and control the vessels 24/7 to ensure safe operation. The situational awareness information includes real-time 360-degree vision from the cameras on the ASV, and Automatic Identification System (AIS) is integrated into the XO-450 CyberDeck cloud-based platform. The online surveyor also monitors the real time DTM map which is rendered in such a way that when it reaches an assigned value it turns blue. The blue color is essentially a safety contour for the ASV, enabling safe but efficient data collection.

XOCEAN uses senseFly eBee UAVs equipped with RGB and multispectral cameras to acquire the topographic data, and extract bathymetry in the very shallow water. This is done using the QPS Qimera SfM refraction algorithm to enable it to match the ASV bathymetry. The datasets from the

ASVs use Post-Processing Kinematic positional imagery which is then processed using Pix4D Mapper.

XOCEAN has successfully completed several projects in complex coastal zones (Figure L.53. A dynamic DTM surface is created using both the cleaned multi-beam data and the UAV files. During data cleaning, it is possible to view the two datasets together either colored by file or preferably, colored by RGB. This gives a photorealistic point cloud of the UAV data with the ASV multi-beam data colored white, making it easy to see what was rock and what was noise in these splash zone areas in the intertidal zone.

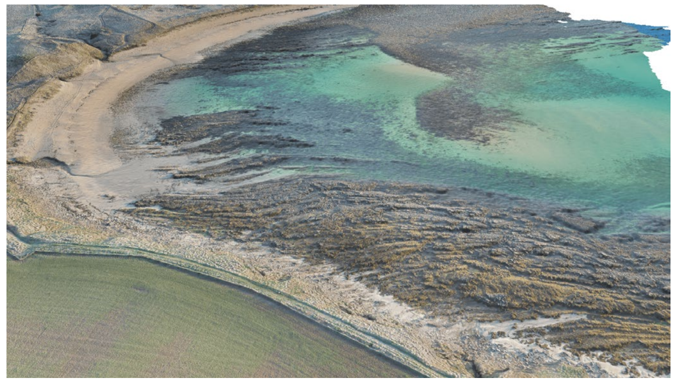

Figure L.52. XOCEAN coastal survey example. Image source: XOCEAN

A support vessel capable of survey and research activities, safely operating in areas such as the Bering Sea, and with sufficient open deck space to launch, recover and maintain two ASVs, is used for survey operations. By using a support vessel, logistics will be improved for the ASVs to: (a) reach the survey locations, (b) be efficiently launched and recovered, and (c) have maintenance performed by vessel crew and convenient access to spare parts if needed. Launch and Recovery Systems (LARS) allow the ASVs to be safely lifted and housed on a vessel. The floating LARS (Figure L.54) has similar buoyancy to the ASV to limit contrary motion, and the ASV is driven into the LARS where there is fendering to protect it. The rigging design allows the LARS to be angled forward for lifting onto the vessel deck. The ASV is housed in the LARS when on the vessel.

Figure L.53. XO-LARS (Launch and Recovery System) and XO-450 ASV during recovery. Image source: XOCEAN

The ASV provides the Pilot in the Operations Center with multiple information feeds with which to make decisions, to include: (a) AIS displayed on a moving map; (b) four fixed visible light cameras facing forwards, to port, to starboard and aft, each with a 90° field of view; (c) a thermal camera that continuously sweeps through 360° and sends images to the operator regarding poor visibility (mist, fog, rain); (d) vessel conspicuity equipment and methods (Class B AIS transmissions, navigation lights, radar reflector, operator controlled sound signals, and superstructure painted yellow); extensive vessel stability design and testing; primary satellite connection via an Inmarsat Fleet Broadband link with worldwide coverage; and a highly flexible platform for integrating multiple sensors.

Whereas XO-450 ASVs can operate autonomously over-the-horizon to map shallow waters, a fleet of XO-450 ASVs can also be deployed to map offshore bathymetry for large areas. XOCEAN operates a fleet of 12 USVs with an additional six vessels in production, so they are capable of mapping large areas with their sizeable fleet (Figure L.55) with continuous, real-time 24/7 monitoring and control in Sea State 5, and they do this with a small carbon footprint, i.e., <5 gallons of diesel per day. Data are processed while mapping operations are ongoing.

Figure L.54. X-OCEAN operates a fleet of 12 XO-450 USVs with an additional six vessels in production.

Saildrones

Saildrone Inc. operates fleets of wind-powered USVs/ASVs in three classes:

- The Saildrone Explorer with SBES, is designed for reconnaissance;
- The Saildrone Voyager with MBES is designed for coastal mapping out to a depth of 700 meters – including but well beyond the 10-meter depth specified for nearshore bathymetry in this study; and
- The Saildrone Surveyor with MBES is designed for offshore bathymetry out to depths of 7,000 meters.

The smaller Saildrone Explorers (Figure L.56), with an SBES, or the larger Saildrone Voyagers or Surveyors with an MBES, operate autonomously over-the-horizon, and they are remotely monitored by Saildrone Mission Control 24/7 located thousands of miles away in Alameda, CA. Missions can be adapted or adjusted on-the-fly. Saildrones are wind and solar powered, the most carbon neutral of all options, and can operate continuously for up to a year without servicing or refueling. Saildrone has the advantage of simultaneously collecting many other ocean and atmospheric data through their 20+ onboard sensors.

Figure L.55. Saildrone has a fleet of 100 Explorers of which 12 can be outfitted with SBES.

The 2020 Arctic Mapping mission[9] was an SBES mission supporting NOAA's effort to provide modern, accurate mapping data of the Bering Sea and Alaska's North Slope. Using a fleet of Explorer Saildrones with SBES (Figure L.57), the goal was to identify the 20-meter and 50-meter depth contours delineating a virtual lane to be mapped for safe passage of commercial vessels (Figure L.58).

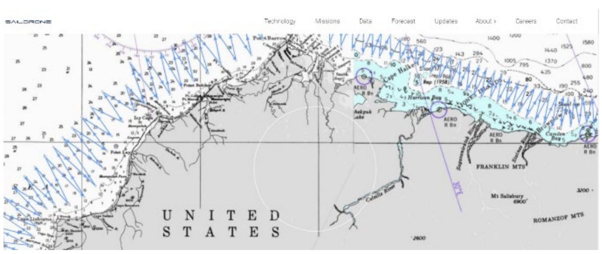

Figure L.56. For the Arctic in 2020, a fleet of Explorer Saildrones using SBES mapped a zig-zag pattern with a spacing of no more than five nautical miles between passes to delineate a corridor between the 20-meter and 50-meter contours for safe navigation of commercial vessels. Image source: Saildrone

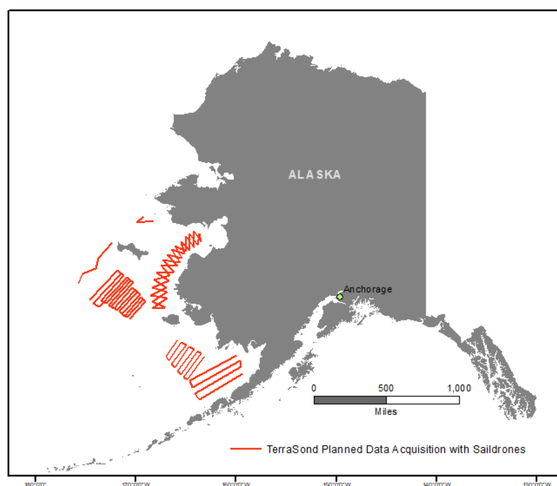

Figure L.57. In 2021, Saildrone and TerraSond mapped Norton Sound and Bristol Bay. Image source: TerraSond

Like the 2020 mission, a 2021 Bering Sea SBES[10] mission was executed with TerraSond/Saildrone (Figure L.59). Larger Voyager Saildrones with MBES sensors are planned for 2022. All types of Saildrones, with either SBES or MBES, will operate in waters deeper than the NALL – 3.5-meters below the Mean Lower Low Water chart datum.

[9] https://www.saildrone.com/news/national-ocean-service-arctic-bathymetry-mission
[10] https://storymaps.arcgis.com/stories/224ea9d51804433c84ec5b86f5bb2852

Figure L.60 compares the Saildrone Explorer, with the larger Voyager and Surveyor Saildrones equipped with MBES, making them ideal for executing major portions of the National Strategy for Ocean Mapping, Exploring, and Characterizing the United States Exclusive Economic Zone (NOMEC Strategy). Figures L.61 and L.62 show schematic diagrams of the Voyager and Surveyor.

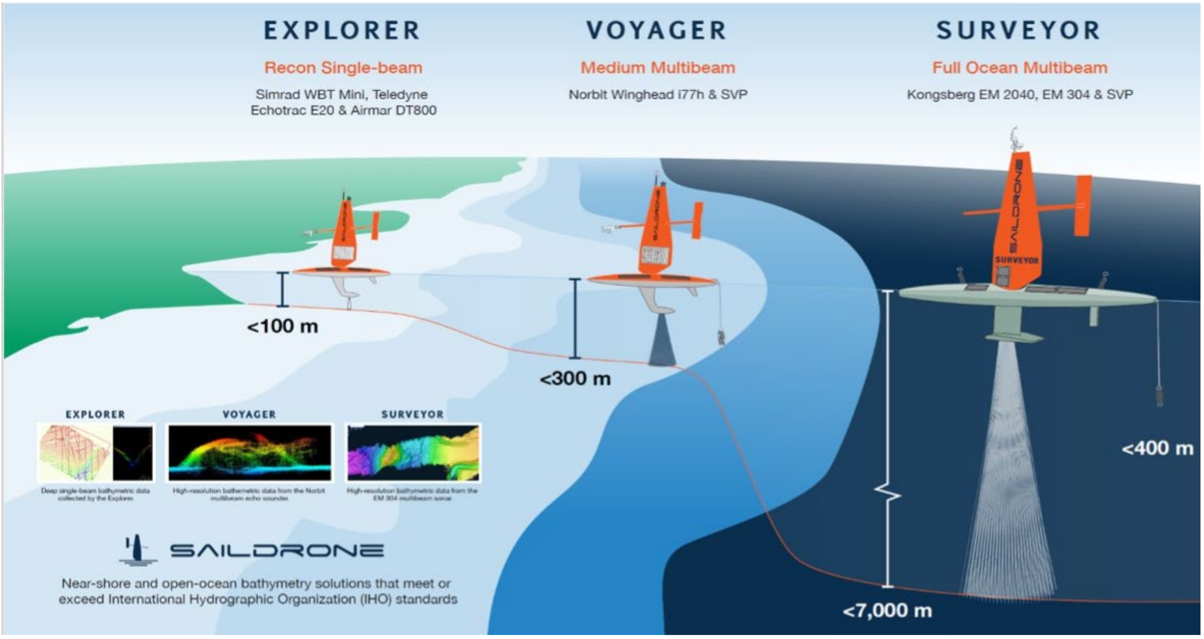

Figure L.58. The three major types of Saildrones.

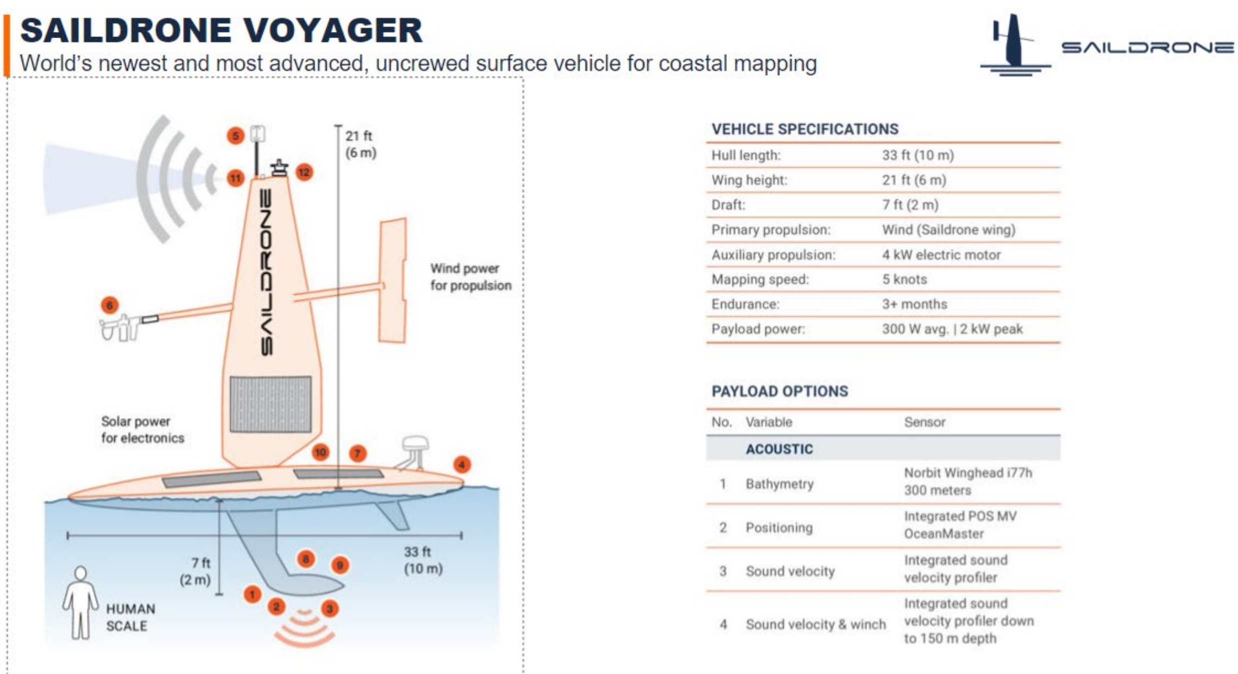

Figure L.59. The Saildrone Voyager with MBES is designed for coastal mapping. Saildrone has one Voyager now, with eight more planned for 2022, plus 20+ additional units in outlying years. Image source: Saildrone

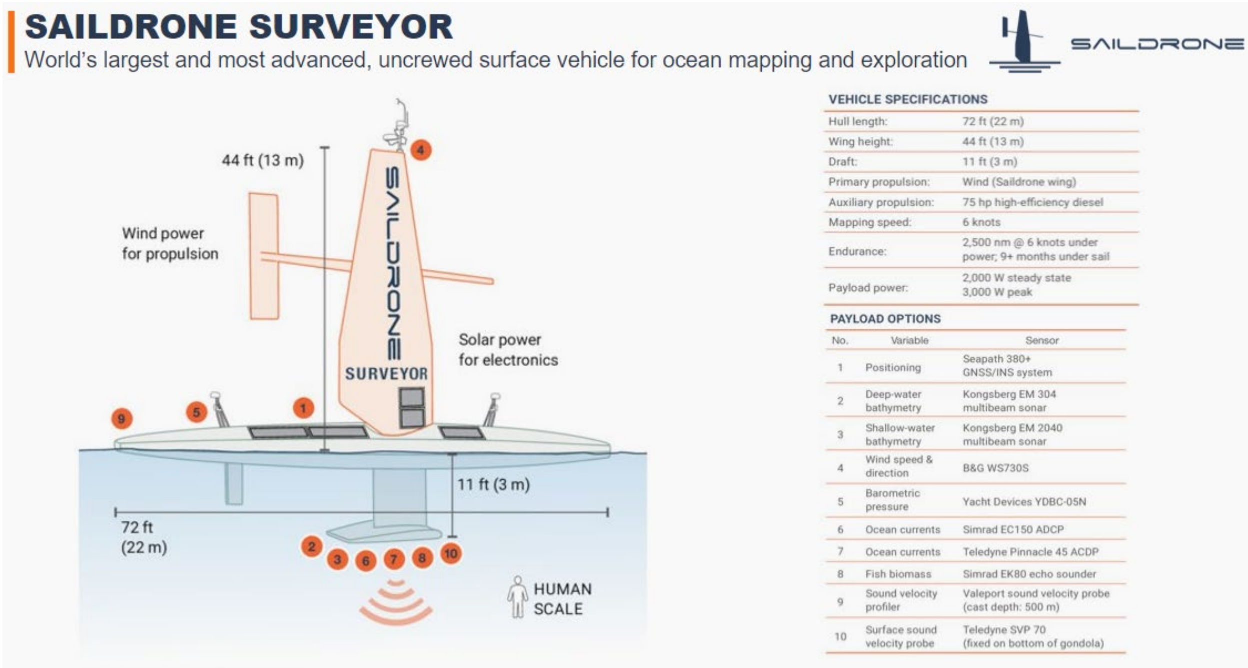

Figure L.60. The Saildrone Surveyor is designed for ocean mapping and exploration and will be the most capable for executing major portions of the NOMEC Strategy. Saildrone has one Surveyor now, with two more planned for 2022 and 10+ additional units in outlying years. Image source: Saildrone

Satellite-Derived Bathymetry

With permission from TCarta, this section is largely quoted from a TCarta Marine posting, entitled Satellite Derived Bathymetry[11], February 24, 2021, which provides an overview of SDB technology.

SDB relates the surface reflectance of shallow coastal waters to the depth of the water column. This process has been greatly refined and developed in recent years. Although SDB will never rival multi-beam and lidar in terms of accuracy, precision and resolution, it can be used as a reconnaissance tool for planned bathymetric surveys as well as a method for filling gaps in existing survey data coverage. In certain situations, SDB is a more viable option than traditional methods for surveying coastal environments. The following are typical steps for SDB data acquisition and processing:

1. Imagery Collection. A remote sensing analyst first decides the type of imagery product that best suits the AOI, considering factors like spatial, temporal, spectral, and radiometric resolutions. Next, candidate imagery is visually investigated for desirable qualities such as having minimal cloud cover, haze, turbidity/waves, and sun glint. Imagery used is always within the past five years unless historic imagery is desired by the customer.
2. Pre-Processing. In most instances, the collected imagery already comes radiometrically and geometrically corrected from the provider. Digital Number values from the satellite

[11] https://storymaps.arcgis.com/stories/03992a3d4ea44f0995b8ad95c117a3e9

sensor are converted to top of atmosphere radiance values then further to water surface reflectance. In this process, atmospheric correction is undergone to adjust for scattering and absorption effects, while de-glinting is done as needed. Land, clouds, whitecaps, and vessels are masked out by thresholding the NIR band.

3. Bathymetry Creation. A physics-based radiative transfer, random forest or band ratio algorithm, which incorporates satellite observed surface reflectance and properties of the water column, is used to produce the bathymetry products.

4. Multi-image Composites. To eliminate, reduce or mitigate the effects of turbidity, cloud cover, sun glint or other image quality attributes that detract from SDB outputs, a multi-image composite technique is deployed to programmatically assess candidate images pixel by pixel to identify and combine clear water pixels with suitable conditions for SDB calculation.

5. Post Processing. An outlier detection and smoothing filter is applied as needed to remove signal noise, and the bathymetry output is evaluated in a 3D environment to remove all erroneous data points. Additionally, any artificial objects, which cause inaccurate depth readings, are cleaned up. Examples of such include algae blooms, raised sediment, dredging channels, waves/turbidity, boats/docks, underwater cables, building/cloud shadows, and dark vegetation.

6. Quality Assurance/Quality Control. TCarta's final step is to compare its SDB product against any and all in situ data for the study area and assign an uncertainty level (e.g., 10, 20 or 30%) to the SDB output. SDB is then delivered to the customer.

TCarta summarized the advantages and disadvantages of SDB in Table L.10.

Table L.10. Advantages and disadvantages of SDB

Advantages	Disadvantages
Can be done completely remotely	Not suitable for regions with persistent turbidity
No environmental impacts or risks to personnel and equipment	Coarse resolution compared to MBES or lidar (2-meter vs. centimeter level)
No permitting or mobilization required	Not Safety of Life at Sea (SOLAS) compliant and can't be used for official safety of navigation
Cost effective and time efficient	No official IHO standards exist for SDB yet
Useful for change detection	None

TCarta states: "It is very difficult to validate SDB in some regions due to a lack of available ground truth data. However, as a participant in the Applied User's program for ICESat-2, TCarta has developed methods to extract highly accurate space-based laser bathymetry from ICESat-2's data products."

Note: ICESat-2 collects space-based photon-counting lidar at both 532 and 1064-nanometers wavelengths, with 56-foot swath width, along tracks that are 3.3 kilometers apart. The 532-nanometers wavelength is standard for topobathy lidar and the 1064-nanometers wavelength is standard for topographic lidar. Thus, it could be used to validate all inland and nearshore bathymetric mapping technologies in this paper, but only along these widely spaced tracks. ICESat-2's greatest value may be for QA/QC purposes and/or in sampling, during different months, whether SDB may be viable, or whether SDB may be unsuitable because of persistent turbidity.

In NOAA's prior attempts to utilize SDB in Alaska, for example, projects failed because of persistent turbidity, so ICESat-2 could be used to determine if SDB is more likely to work with satellite imagery collected in May, June, July, August, or September, for example. ICESat-2 data products are available free from the National Snow and Ice Data Center. An additional source of ICESat-2 data is available through OpenAltimetry. This website allows the user to view 2D profiles of ICESat-2 data, thus making it easier to validate the existence of bathymetric bottom returns.

Satellite Derived Bathymetry Technology Risks

Table L.10 summarizes the risks of SDB.

- SDB technology is not suitable for regions with persistent turbidity;
- SDB data have coarse resolution (typically 2 meters) compared with fine resolution (centimeters) from topobathy lidar and sonar;
- SDB data are not SOLAS compliant; SDB data cannot be used where safety of maritime navigation is an issue; and
- There are no official IHO standards for SDB.

Turbidity Risks for Topobathy Lidar and Satellite Derived Bathymetry

Turbidity, the amount of suspended sediment and organics in the water column, is the single most important consideration for success of a topobathy lidar project. If the water has a high content of sediment and/or organic particles, the photons in each laser pulse will be scattered and/or absorbed to such an extent that an insufficient amount of light returns to receivers in the aircraft to make an accurate depth determination. Local knowledge of turbidity and its drivers in the survey area is key to scheduling a topobathy lidar survey with the greatest chance of success. Turbidity can be highly variable depending on the day or the season. Similarly, water turbidity is the major risk to success of SDB.

Water clarity is a general term describing the combined scattering and absorption properties of the water column and is the primary limitation for depth performance from topobathy lidar. If the water is too turbid or has a high fraction of suspended sediments, bubbles, or organic material, the backscatter from the water column will be greater than the bottom return resulting in no returns from the bottom.

Data voids are gaps in the lidar point data coverage, caused by surface non-reflectance of the lidar pulse, instrument or processing anomalies or failure, obstruction of the lidar pulse, or improper collection flight planning or execution. Topobathy lidar projects will almost always have data voids to some degree, even in waters generally deemed to be clear.

Performance of topobathy lidar systems is often described in terms of Secchi depth, an old and intuitive measure of water clarity based on the depth at which a standard black and white disk, deployed over the side of a boat, is no longer visible to the human eye. Topobathy systems often specify performance of 1 to 1.5 times the Secchi depth, without specifying scattering or absorption, but Secchi depth is not a particularly good predictor of topobathy lidar performance because its relationship to the proper optical parameter, the diffuse attenuation coefficient, varies with the scattering-to-absorption ratio of the water column.

NOAA's Water Clarity Climatology K_d Viewer

Sentinel-3 is a multi-instrument mission to measure sea-surface topography, sea- and land-surface temperature, ocean color, and land color with high-end accuracy and reliability. The mission supports ocean forecasting systems, as well as environmental and climate monitoring. Sentinel-3A was launched in 2016 and Sentinel-3B joined its twin in orbit in 2018.

The data used to create NOAA's Sentinel Viewer are monthly composites of Ocean and Land Color Instrument (OLCI) Sentinel-3 daily imagery at a resolution of 300 meters. The OLCI is a visible imaging push-broom radiometer with 21 spectral bands from 400 to 1,200 nanometers. K_d is a measure of how light dissipates with depth in water. Sentinel-3 has three color channels that are impacted differently by turbidity. K_d, an indicator of turbidity, is determined by using the relative intensity information from these color channels, calibrating them and calculating a total value that approximates the amount of scattering particles in the water column. The K_d Rhos color bar is shown in Figure L.62. In general, the dark blue represents ideal conditions near shore for SDB and topobathy lidar while dark red represents substandard conditions.

NOAA's Sentinel Viewer is based on historical satellite image records, to identify patterns in time and space to maximize potential for SDB or topobathy lidar along the Atlantic, Gulf, Pacific, and Alaska coasts and the Great Lakes. Figure L.62 displays K_d values for July of 2021.

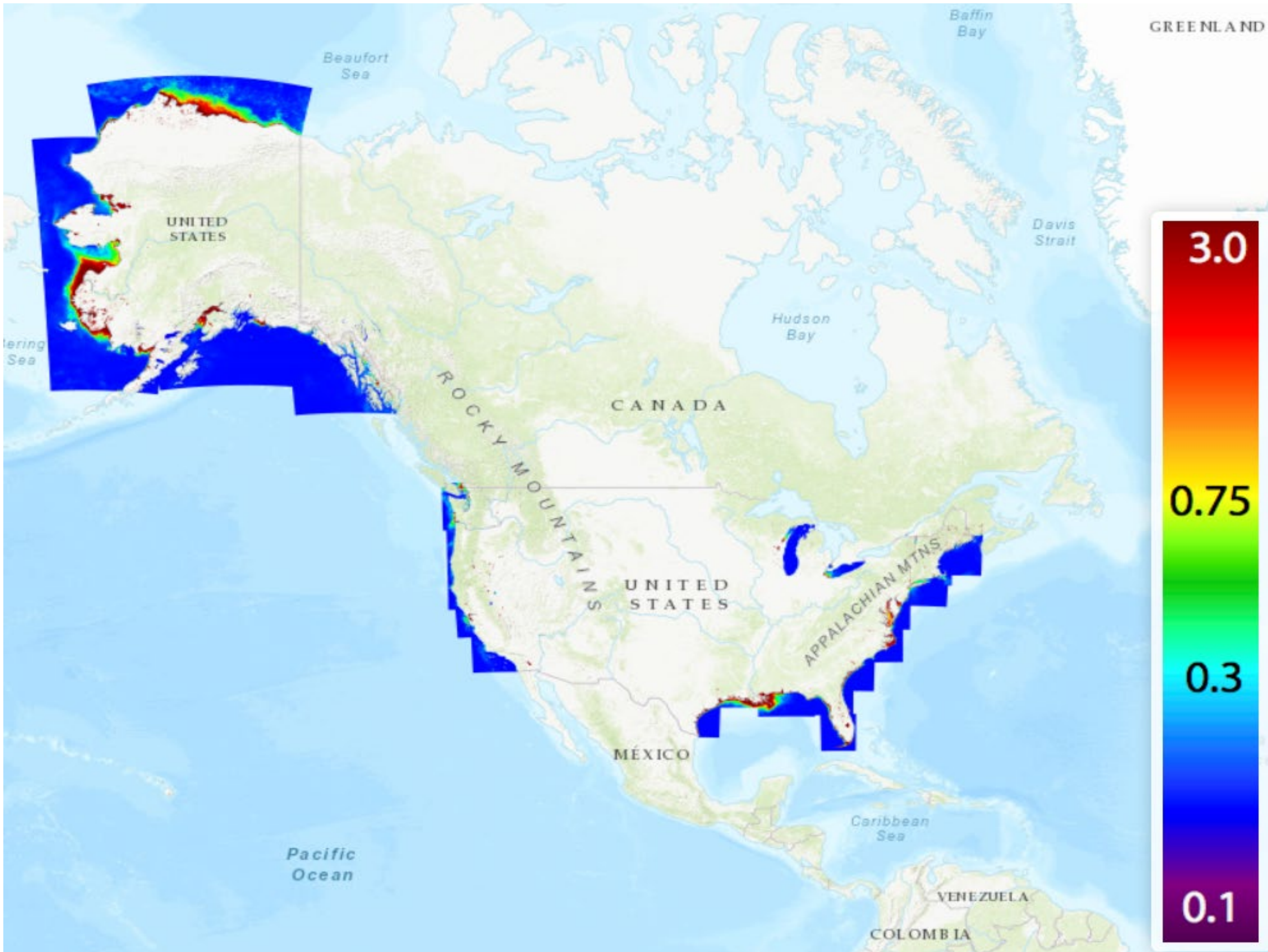

Figure L.61. Sentinel Viewer K_d values for July 2021. Image source: NOAA

Advantages and Disadvantages of Bathymetric Mapping Technologies

All bathymetric mapping technologies enable scientists to know water depths and understand the shape of the seafloor to improve safety of marine navigation and support other marine activities, such as the blue economy, security and defense, and environmental protection.

Table L.11 summarizes the major advantages and disadvantages of technologies for mapping bathymetry.

Table L.11. Advantages and disadvantages/risks of bathymetric mapping technologies

Technology	Advantages	Disadvantages/Risks
Topobathy Lidar	When waters are clear, maps rivers and the intertidal zone including topo and bathy surfaces.	Bathymetric mapping success is dependent on water clarity and limited by depth.
Single-Beam Echo Sounder	Not dependent on water clarity. Maps shallow water bathymetry.	Uses a single transducer to transmit/receive acoustic data, producing a narrow data swath.

Technology	Advantages	Disadvantages/Risks
Multi-Beam Echo Sounder	Not dependent on water clarity. Ideal for deeper water and high-resolution bathymetry.	Time consuming operations in shallower water environments.
Satellite Derived Bathymetry	This technology is useful for general mapping purposes only but does not produce a high quality/high accuracy product.	Bathymetric mapping success depends on water clarity when satellite imagery was acquired. Accuracies can vary significantly.

Topobathy Lidar

Topobathy lidar can provide the highest accuracy data to map the entire intertidal zone, but it is totally dependent on the turbidity of the waters being mapped.

Sonar Technologies

Multi-beam echo sounders , integrated with high quality motion sensors, are best for providing accurate full bottom coverage of the ocean floor. A large selection of MBES sensors are available commercially. The main question is to determine the best platforms for acquiring the vast quantities of offshore bathymetry required. Sonar's major advantage is that it accurately maps bathymetry regardless of water clarity. Its main disadvantage is that sonar is very expensive in shallow waters, and it is also expensive in deeper waters when mounted on crewed survey vessels that are very costly to mobilize to a project area and costly to operate.

Crewed Survey Vessels

Crewed hydrographic survey vessels have been the mainstay for collecting bathymetry for many decades. The main advantages are that traditional sonar mapping technologies and platforms are tried, proven, and reliable. The main disadvantage is the relative high cost of such surveys. Fortunately, innovative and lower-cost solutions are now available to execute the NOMEC Strategy.

Crewed hydrographic survey vessels with various types of sonar sensors can be hull mounted or towed to use a wide array of sonar sensors, each with their own advantages and disadvantages. Crewed vessels are typically very expensive because of personnel costs, not just during the surveys but during sometimes-long mobilization to arrive on site. Crewed survey vessels can also serve as "motherships" for USVs.

Uncrewed Surface Vessels

Uncrewed Surface Vessels have greatly increased productivity, enabling a single operator on a mothership, for example, to control multiple USVs collecting MBES data simultaneously. But the operator is normally required to maintain line-of-sight to USVs to ensure they do not run aground, and the mothership provides other support roles in deploying the USVs, but mothership operations can be expensive.

USVs can be controlled from a “mothership” in remote waters or by a controller on land, normally maintaining line-of-sight with one or more USVs. USVs can be very efficient in acquiring nearshore bathymetry in waters shallower than the 3.5-meter NALL. There are many different USVs available commercially, with different levels of suitability for mapping in waters with waves and currents; they offer significant potential for addressing national needs for nearshore bathymetry. Some USVs can be programmed to operate autonomously along pre-planned routes, negating the need for full-time operators/observers. The CW5 is an example of a popular USV. The Shallow Surveyor by SeaSat is an example of a USV that does not require a mothership.

Autonomous Surface Vessels

Autonomous Surface Vessels have further increased productivity, operating over-the-horizon with or without a support vessel, with a single operator controlling multiple ASVs from a remote command center thousands of miles away. X-OCEAN’s XO-450 ASV requires a Launch and Recovery System and support vessel but can then operate autonomously for up to three weeks without servicing. The three types of Saildrones do not require support vessels and can operate autonomously for over a year without servicing. Large fleets of such ASVs are seen as the most cost-effective way to execute the NOMEC Strategy.

Some are powered by small diesel engines and solar energy (e.g., XO-450), and some are powered by combinations of diesel, solar and wind energy (e.g., Saildrone). XOCEAN advertises that their fleet of XO-450 ASVs can operate autonomously for multiple weeks without being serviced, whereas Saildrone advertises that their fleet of drones can operate autonomously for up to a year without being serviced.

With the large number of USVs and ASVs mapping the oceans and collecting huge amounts of data, there is expected to be a shortage of qualified data processing capacity in the U.S. It is recommended that the University of New Hampshire, University of South Mississippi, University of South Florida and/or other universities in support of NOAA, establish curricula for training personnel from geospatial data processing firms to process such data in formats required by NOAA.

Satellite Derived Bathymetry

SDB is useful for general mapping purposes only but does not produce a high quality/high accuracy product. It is totally dependent on water clarity and the quality of satellite imagery.