Avoiding Rock Bottom: How Landsat Aids Nautical Charting

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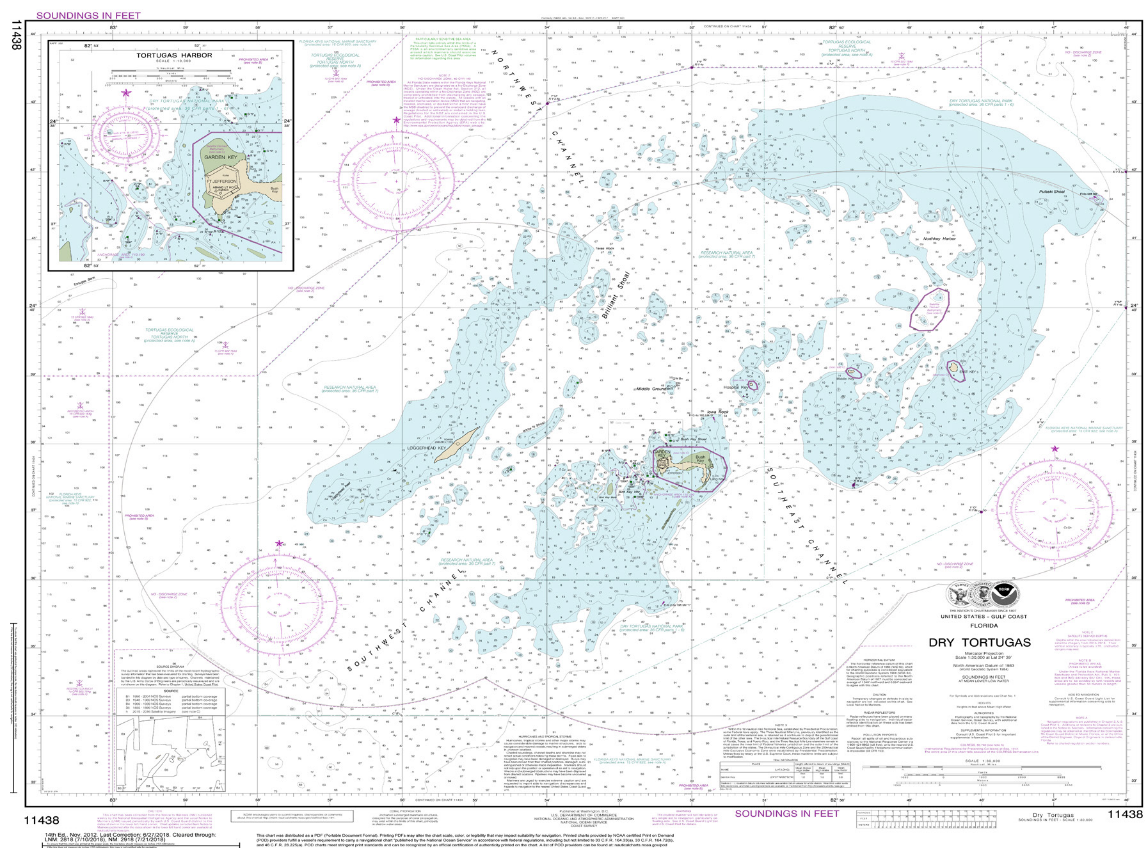
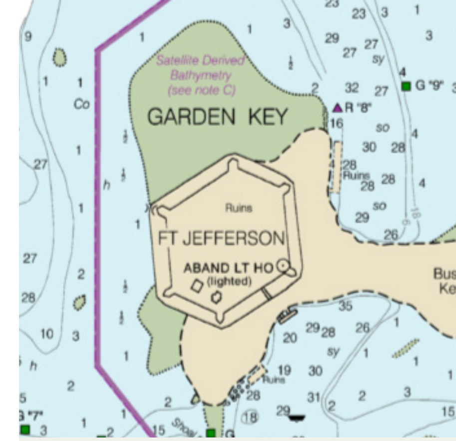
On the most recent nautical chart of the Dry Tortugas, a grouping of islands that lies seventy miles west of Key West, Florida, Landsat data provided the estimated water depths for areas too shallow and difficult to be reached by the National Oceanographic and Atmospheric Administration's (NOAA) surveying ships.

It was sometime between 1840 and 1939 that the sections of water surrounding the islands were last formally surveyed. Since that time, Dry Tortugas National Park was established and the park—along with its hundreds of shipwrecks, pristine beaches, and clear water—has become popular with recreational boat cruisers. Recent and accurate depth information is essential for boaters, especially in the shallows. Using bathymetry measurements made from Landsat between 2015 and 2016, NOAA was able to provide sailors updated depth estimates in five locations, including the area around Garden Key where the historic Fort Jefferson, a popular destination, is located. As the National Park Service tells visitors to its website, NOAA's chart of the area is "indispensable for safe boating on these waters."

In NOAA's Office of Coast Survey, the Marine Chart Division is responsible for updating the suite of over 1,000 nautical charts that keep mariners in U.S. waters safe. Their mandate covers all U.S. territorial waters in the U.S. Exclusive Economic Zone (EEZ), a combined area of 3.4 million square nautical miles that extends 200 nautical miles offshore from the nation's coastline. The U.S. has the largest EEZ of all nations in the world but, as of 2015, it ranked behind 18 other nations in the number of vessels with hydrographic surveying capabilities (the ability to measure and map water depths). The job is sizable and expensive. While the Army Corps of Engineers is responsible for maintaining the depth of shipping channels, providing bathymetry everywhere else in U.S. waters is NOAA's duty. ▸





Above: Chart inlay of Tortugas Harbor which surrounds Garden Key where Fort Jefferson is located. The depth measurements around the key (within the thick purple line) were made using Landsat data.

In-page: The most recent NOAA nautical chart of Florida's Dry Tortugas (Chart 11438). The purple polygons, including the area around Garden Key where Fort Jefferson is located, indicate chart regions that use Landsat-derived bathymetry as source data.

Opposite: Recreational boaters anchored off of Fort Jefferson. The fort, located on Garden Key in the Dry Tortugas National Park, Florida, is a popular destination for cruisers. Photo credit: Varina Patel

Above: Close-up of Bechevin Bay from NOAA Chart 16520: "Unimak and Akutan Passes."

Keeping waterways safe is a massive undertaking

The responsibilities of NOAA's Marine Chart Division are immense. Charged with providing accurate charts for mariners, NOAA cartographers need to know when existing charts are out-of-date. To determine if charts are current, they employ lots of tools. They monitor navigation hazard reports submitted by mariners; they watch ship traffic patterns using vessel positioning information (via the Automatic Identification System); and, more and more, they are turning to satellites like Landsat for information.

The field of Satellite Derived Bathymetry (SDB), has been around for nearly a half century, but the advent of free Landsat data in 2008 together with the 2013 launch of the more-advanced Landsat 8 satellite, and a shift in thinking about SDB products, have led to a reinvigorated use of satellite data in NOAA's Marine Chart Division.

The concept of SDB is that shorter wavelengths of light penetrate water to differing degrees. The smaller wavelengths (e.g. blue and green light) penetrate water more than longer wavelengths (e.g. near infrared, shortwave infrared). When water is clear and the seafloor bottom is bright (e.g. sandy), estimates of depth can be made by modeling the depth of light penetration based on the amount of reflectance measured by the satellite. And when multiple visible-wavelength spectral bands are used together, the effects of seafloor reflectance variability and water turbidity are lessened. However, these modeled depth measurements typically do not meet hydrographic accuracy standards, so in the past SDB measurements were eschewed.

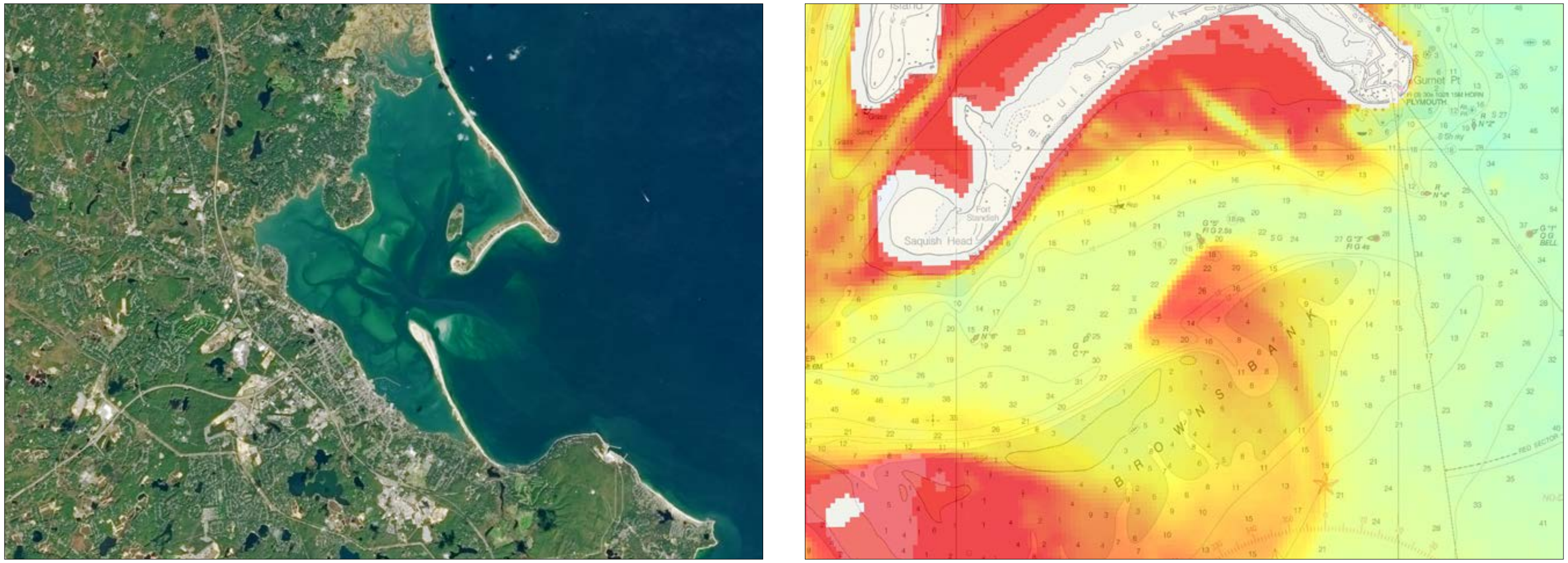
"There's been a shift in the way we think," explained Lieutenant Anthony Klemm, an Operations Officer on the NOAA hydrographic surveying ship *Thomas Jefferson* and a former NOAA Corps Officer with the Office of Coast Survey's Marine Chart Division. "In the past, if a measurement wasn't made by the Army Corps or a NOAA survey ship, we didn't want to use it, but now we are opening up to other technologies to evaluate the health of our current chart suite."

Because of this sea change in thinking and faced with the daunting job of deciding which charts were most in need of updating, NOAA hydrographers revisited the use of SDB using freely available satellite data such as Landsat as a viable tool to help them do their jobs.

"NOAA has now been using Landsat imagery for chart adequacy assessment and mission planning," said Shachak Pe'eri, Branch Chief of the NOAA Chart Standards Group and a Research Professor at the Joint Hydrographic Center at the University of New Hampshire.

The Joint Hydrographic Center, a think-tank of researchers investigating technology and mapping challenges in NOAA's Office of Coast Survey, realized that Landsat SDB could be an important reconnaissance tool. A single Landsat image is about 100 nautical miles across and affords a wide overview of a coastal area. Maps of SDB can be compared with existing nautical charts. Places where depth patterns do not match are more closely examined. Has the seafloor changed in this area? If an area looks shallower than what is presented in the chart and if there is a reasonable amount of vessel traffic or corroborating mariners' reports in the area, the chart location is tagged as a higher-priority candidate for hydrographic mapping—i.e. sending out a hydrographic ship to make depth measurements using sonar (multi-beam or single-beam).

Multi-beam sonar provides very accurate and comprehensive bathymetry, but for the amount of water NOAA is responsible for charting, these expensive ships are in short supply. ▸



A Landsat 8 image showing the location of Massachusetts' Plymouth Bay (left). The right image shows Satellite Derived Bathymetry measurements overlaid on a chart of Plymouth Bay. The red indicates shallow waters. Here, the SDB indicates that the shoaling of Brown's Bank has shifted since the chart's creation.

Klemm, who is currently onboard a hydrographic vessel, knows well the amount of time and effort that goes into gathering bathymetry information. He is excited about the prospect of formally incorporating Landsat SDB into his workflow.

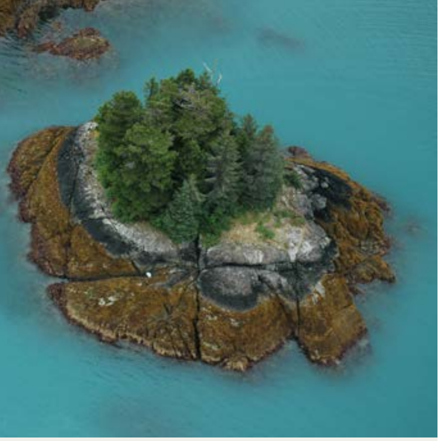
"SDB products to evaluate the current state of existing bathymetry representation is pretty amazing because of the temporal resolution of the satellite data—a little over every two weeks and you get a new shot of an area," Klemm described. Landsat 8's orbit places it back over a given location every sixteen days. Because satellites like Landsat can provide "quantifiable information related to the amount of change since the last hydrographic survey," as Pe'eri wrote, SDB information can figure prominently into the determination of where new hydrographic surveys are most needed.

Pe'eri and Klemm helped to craft NOAA's policy on the use of SDB. They outlined how to use SDB to prioritize hydrographic surveys using a chart adequacy assessment procedure they developed. They also helped formulate a policy on how to update charts with features found using satellite imagery, like the process used to updated the Dry Tortuga chart.

"These charts are considered intermediary, but they can be made publicly available and used until a proper hydrographic survey can be performed," Pe'eri explains.

Landsat is good at identifying new shoals and mapping shallow areas where survey vessels cannot go. NOAA thinking is that it is better to amend charts to tell mariners that satellites indicated a shoal, even though exact depths cannot be provided until the next hydrographic survey. ▸

Above: Visiting Fort Jefferson on Garden Key in the Dry Tortugas, a family poses for a photo on top of the nineteenth-century fort, with the shallow turquoise Gulf waters stretching out behind them. Photo credit: Andrzej Sienko, National Park Service



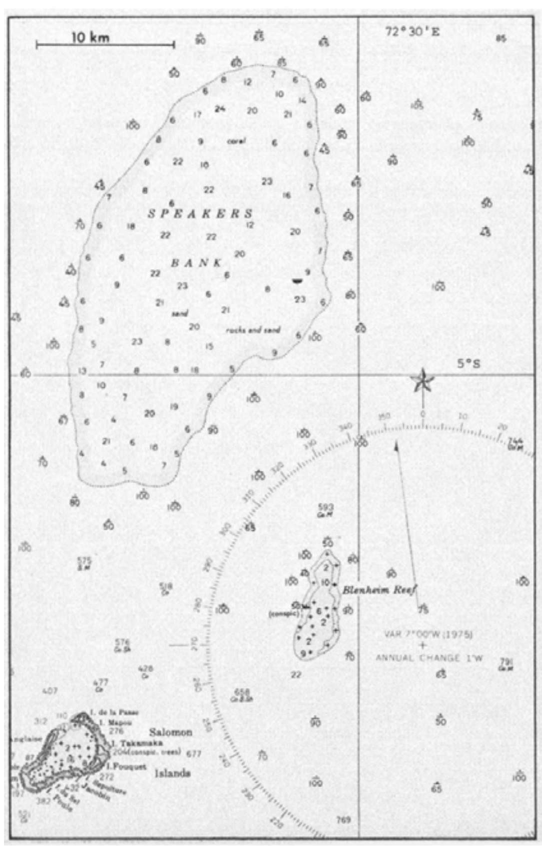
Above: This circular islet is in a section of Alaska's Prince William Sound known as Dangerous Passage. Accurate nautical charts are indispensable for safe sailing. Photo credit: Mandy Lindeberg, NOAA

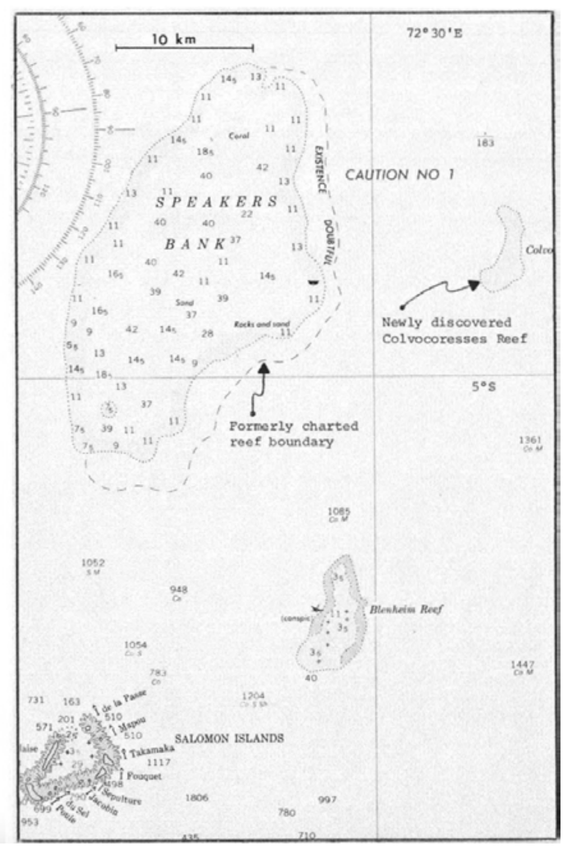
In-page: The second (left) and third (right) editions of Defense Mapping Agency chart 61610. The third edition, released on August 28, 1976, shows the newly discovered Colvocoresses Reef and the adjusted position of Speakers Bank. Landsat provided the information needed for both chart adjustments.

Deriving bathymetry with Landsat for 46+ years

Uncharted shoals have sunk many ships. In the late 1960s, research groups began to experiment with remote bathymetry using multispectral airborne data in an effort to make measurements over large tracts of coastal waters in search of navigational hazards and shifting bathymetry. With the launch of Landsat 1 in 1972, these newly developed methods could be used with data collected by the satellite's Multispectral Scanner System and its 100 nm-wide images—satellite derived bathymetry was born.

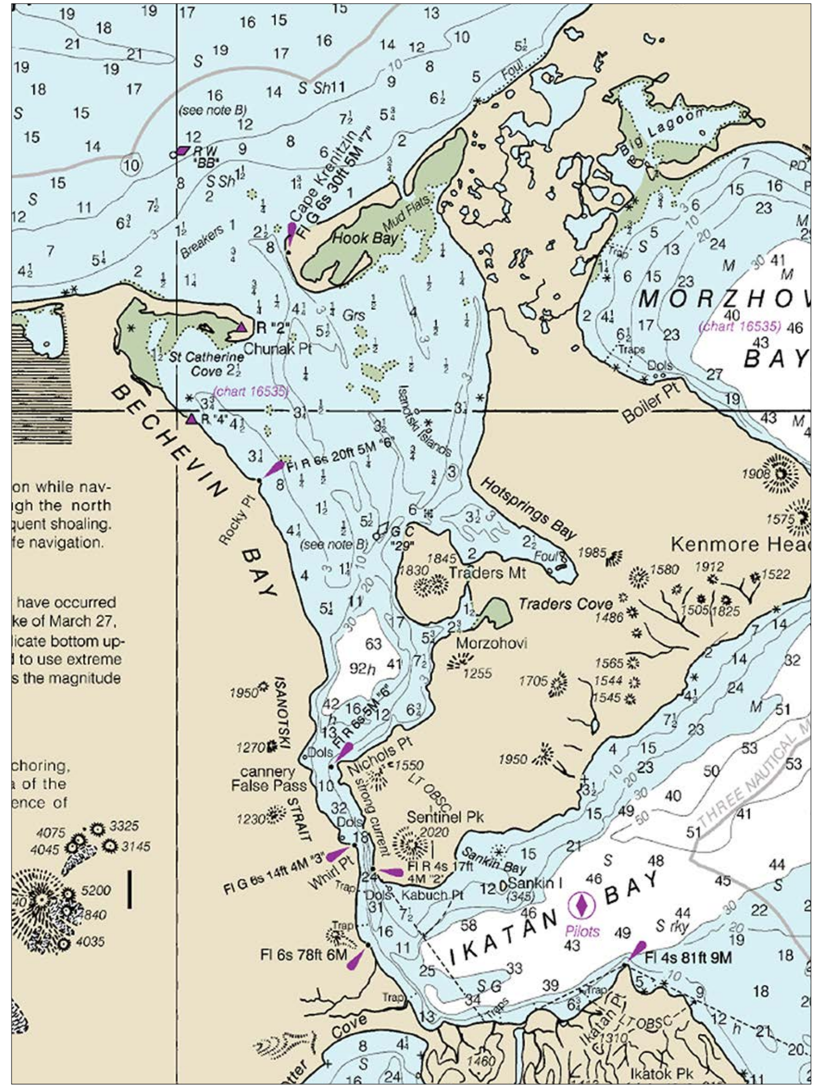
In 1975, NASA teamed with famed oceanographer Jacques Cousteau to conduct an ocean bathymetry experiment using Landsat data to measure water depth in the Bahamas and off of Florida's eastern coast. Cousteau's ship, Calypso, anchored over a study site as Landsats 1 and 2 collected data from overhead, while they simultaneously took depth measurements using the ship's sonic depth finder. In this pre-GPS timeframe, LORAN-C radio measurements were used for locating the boat position. Divers also plunged to the seafloor to take in situ reflectance measurements with a submarine photometer. This early experiment proved the feasibility of mapping shoals in clear water to depths equal to or greater than those needed for safe shipping.





The International Hydrographic Office, an intergovernmental organization concerned with making the seas navigable, had once classified shoals as navigational hazards between 0 and 17 meters (56 feet) below the surface, but with the advent of supertankers with drafts of over 20 meters (65 feet) and the capacity to carry massive amounts of oil, shoal definitions had to be broadened.

A year later, a Landsat 2 image acquired on March 29, 1976, revealed a major uncharted 8-km-long reef in the Indian Ocean's Chagos Archipelago: "There was a major reef or bank where the chart showed safe, deep water and some banks appeared to be out of position by more than 15 km relative to the nearest land," wrote James Hammack, a participant in the NASA/Cousteau experiment and a cartographer with the Defense Mapping Agency's Hydrographic Center (DMA)(now part of the National Geospatial-Intelligence Agency). Within a few months, the newly found reef—named Colvocoresses Reef after ▸



the USGS cartographer who identified the feature on the Landsat image—was added to DMA nautical chart 61610. In the interim, Notice to Mariners were sent out to warn sailors in the region.

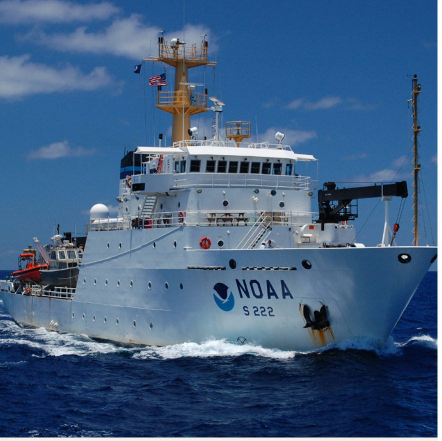
Based on the success of the NASA/Cousteau and Chagos Archipelago experiments, DMA requested that Landsat data be collected globally over coastal areas. This data was used to "augment the completeness" of its nautical chart products. DMA also used Landsat data to visually verify ship-reported navigational hazards.

Some other documented cases of Landsat data providing critical information to navigation include a safe deep passage through Papua New Guinea's Star Reefs, which was first discovered using Landsat imagery. The Australian Royal Navy ship Flinders confirmed this passageway, which enabled ships to more quickly travel from Australian ports to East Asian ones. Likewise, British Admiralty Chart 322 of the Red Sea near Al Qunfidha had to be completely revised after it was compared with Landsat data.

In 2006, 75 shallow-water features such as reefs, shoals, and seamounts were discovered or found mislocated with the use of Landsat 7.

Above: Anthony Klemm, a NOAA Corps Officer, in New York Harbor, aboard the NOAA Ship *Thomas Jefferson*, a hydrographic survey ship based out of Norfolk, VA. Photo credit: NOAA

In-page: Landsat 8 image of In Bechevin Bay, the easternmost passageway between the Gulf of Alaska and the Bering Sea (left). This natural color, pan-sharpened image was acquired on May 14, 2014. Image credit: Joshua Stevens and Jesse Allen, NASA Earth Observatory. NOAA nautical chart of Bechevin Bay (right).



Above: The NOAA hydrographic surveying ship *Thomas Jefferson* at sea in 2010. Lieutenant Anthony Klemm is currently an Operations Officer on this vessel. Photo credit: NOAA

Opposite In-page: A natural-color Landsat 8 image of the Beaufort Sea near Point Barrow, Alaska. Researchers are developing ways to estimate seafloor depth in turbid waters by combining suspended sediment swirl analyses with multi-date satellite-derived bathymetry measurements. Image credit: NASA Earth Observatory

Landsat aids hydrographic offices around the world

The International Hydrographic Organization (IHO) and the United Nations' Intergovernmental Oceanographic Commission jointly create an authoritative, publicly available, global bathymetry map known as the General Bathymetric Chart of the Oceans, or GEBCO. GEBCO charts have been published since 1903. Despite this heritage, only about a tenth of the ocean floor has been mapped.

GEBCO is no stranger to SDB. They have been aware of its capabilities for decades. But now that Landsat data are publically and freely available, Landsat is being used more often—as is data from the European Space Agency's Copernicus Sentinel-2 satellites, with spectral bands similar to Landsat 8.

NOAA, as a major Landsat user, has been sponsoring international GEBCO students from around the world and teaching them how to use SDB to update charts in their home offices. NOAA's fourth SDB training was held in July 2018 as part of the Chart Adequacy Workshop. The 2018 workshop participants—from Madagascar, Mexico, Nigeria, Peru, Australia, Greece, Ireland, Japan, Latvia, Poland, St. Vincent and the Grenadines, Trinidad and Tobago, and Taiwan—learned about SBD and how to find land-water boundaries with satellite imagery, among covered topics.

The GEBCO companion how-to guide for creating bathymetric charts, called The GEBCO Cookbook, includes a chapter on using Landsat to derive bathymetry. For cash-strapped national hydrographic offices, using free Landsat data to assess the adequacy of existing charts is essential, allowing them to allocate scarce resources with maximum impact to mariner safety. GEBCO students also use the European Space Agency's Copernicus Sentinel-2 data and some commercial WorldView imagery. Students often like to use Landsat data because of its deep archive, which they use to produce time series showing shoreline and shoal trends over decades. SDB alone does not meet IHO accuracy standards, but its use as a complementary prioritization and planning tool is key.

SDB measurements can also "be used to infill regions in remote or inaccessible areas where no (or poor) bathymetry data exists," shares Stephen Sagar, an Aquatic Remote Sensing Scientist with Australia's National Earth and Marine Observation Group.

NOAA: thinking big about SDB

Water clarity has been a limiting factor when it comes to SDB. If waters are too turbid (full of sediments that obscure light reflectance from the seafloor), then bathymetric measurements cannot be made.

The inability of longer wavelengths, such as shortwave infrared light, to deeply penetrate water allows hydrographers to map shoreline change. But when concentrations of suspended sediments are great enough to thwart penetration by shorter wavelengths, SDB by definition suffers. But in NOAA's Marine Chart Division, researchers are thinking outside of the SDB-box.

Pe'eri, in a collaborative study with NOAA and the U.S. Coast Guard, has pioneered turbidity mapping as a proxy for bathymetric measurements. In enclosed waterbodies with strong currents, such as bays and sounds, turbid channels show up on Landsat imagery—and these turbid channels illuminate where currents are carving deeper channels that are safe for boat passage.

In the Arctic, where near-shore changes occur rapidly because of seasonal sedimentation and erosion, new SDB techniques like turbidity mapping are preventing maritime mishaps. In Bechevin Bay, where the easternmost passageway between the Gulf of Alaska and the Bering Sea provides fisherman with a shortcut for three ice-free months a year, the location of sand bars can shift significantly because of melting ice in this narrow passage. With the help of Landsat SDB turbidity maps, the new locations of these sandbars can be estimated. Recently, this has led to the discovery of a new, straighter, and more geologically stable channel.

"SDB estimated from Landsat turbidity maps can help guide NOAA charting craft when they are mapping the channel each year and placing channel marking buoys. This saves time and it makes the process safer," Pe'eri said. "With insufficient knowledge of sandbar locations, the NOAA craft risk running aground and crew can be thrown overboard when that happens."

Pe'eri's team has also developed a multi-image method to help separate clear and turbid waters using Landsat data. Techniques such as turbidity mapping will grow increasingly important for navigation planning as warming waters enable more industrial development of the Arctic and set the stage for international shipping routes.

NOAA's Marine Chart Division has made Landsat a prominent tool in their charting toolbox—especially Landsat 8 with its new deep blue band, improved signal-to-noise, and greater dynamic range (12-bit).

"Landsat 8 is overwhelmingly better," Pe'eri shared, citing the new satellite's additional cirrus band which helps him better account for atmospheric noise that can compromise accurate SDB and Landsat 8's better radiometric resolution (which means more signal, less noise, and more measurement fidelity). After Landsat 9 launches in late 2020, Pe'eri and others will evaluate its data and once it checks out, will add it to their toolbox. But it's not just SDB that this innovative office is utilizing.

They are also watching traffic patterns using the Automatic Identification System (AIS) and even light communication from recreational boaters, fishermen, tugboats, and larger vessels, and—together with bathymetry measurements—they are prioritizing which charts are in perilous need of revision.

"We're making charts safer up there," Klemm said, talking about the work done in Alaskan waters, "and that's so exciting." ■

This article was originally published on July 23, 2015 on the NASA Landsat Science website. Updates to the article were made in August 2018.

Satellite Data Requirements:

- 16-day revisit
- 30 m resolution
- Vis, NIR, SWIR
- Global coverage
- Archive continuity & consistency
- Free, unrestricted data
- Geolocation ≥ 15 m
- ≤ 5% radiance calibration
- 12-bit data digitization