Looking across Isanotski Strait from above the town of False Pass on Alaska's Unimak Island. For three ice-free months a year, this is the easternmost passageway between the Gulf of Alaska and the Bering Sea.

Credit: Shishaldin

How Landsat Helps: BATHYMETRY
Avoiding Rock Bottom: How Landsat Aids Nautical Charting

Laura E.P. Rocchio

On the most recent nautical chart of the Beaufort Sea where the long narrow Tapkaluk Islands of Alaska's North Slope separate the sea from the shallow Elson Lagoon (Nautical Chart 16081) a massive shoal is immediately noticeable just west of the entrance to the lagoon. On the chart it looks like a massive blue thumb jutting out into the sea. The National Oceanographic and Atmospheric Administration (NOAA) identified this prodigious, 6-nautical mile-long, 2-nm-wide shoal using Landsat satellite data.

It was sometime around 1950 that a hydrographic survey ship last plied these waters taking water depth measurements along its path using a single-beam echo sounder and visual navigation. These data points were laboriously merged with shoreline and hazard information to create this chart, Alaska-Arctic Coast, Scott Pt. to Tangent Pt. Given the low ship traffic in the region, updating this chart was lower priority than other high-traffic areas. But things change—fishing and water-commuting traffic have risen in the area, as has marine tourism; but that's not all: bottom depths have changed too as currents, erosion, and sediments have worked together to sculpt the seafloor.

In NOAA's Office of Coast Survey, the Marine Chart Division is responsible for updating the suite of over 1000 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 it ranks behind 18 other nations in the number of vessels with hydrographic surveying capabilities. Their job is sizable and expensive. While the Army Corps of Engineers is responsible for maintaining shipping channel depths, providing bathymetry everywhere else in U.S. waters is NOAA's duty.
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 Charged with providing accurate charts for mariners, NOAA cartographers need to know when existing charts are out-of-date.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 satellite information, especially Landsat data.

The field of Satellite Derived Bathymetry (SDB), has been around for nearly a half-century now, 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 different wavelengths of light penetrate water to differing degrees. The smaller the 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 (sandy for example) 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. 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,” Lieutenant Anthony Klemm, a NOAA Corps Officer in the Office of Coast Survey’s Marine Chart Division, explains, “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 Landsat data as a viable tool to help them do their jobs.

“NOAA has now been using Landsat imagery for chart adequacy assessment and mission planning,” Shachak Pe’eri, a Research Professor at the Joint Hydrographic Center at the University of New Hampshire, says.

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.
Klemm has been out on hydrographic voyages, and 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 describes. Landsat 8’s orbit puts 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 have been working on a NOAA policy about the use of SDB. They are outlining how to use SDB to prioritize hydrographic surveys using a chart adequacy assessment procedure they have developed. They are also working on a policy of how to update a chart with features found using satellite imagery.

“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, like that big 12 nm thumb-shaped shoal off of Alaska’s North Slope. And 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.
Deriving bathymetry with Landsat for 43 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, the 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. They also dove 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 inter-government 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 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 (now part of the National Geospatial-Intelligence Agency). Within a few months, the newly found reef, named Colvoocoreses 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.

Second and third editions of a nautical chart showing Landsat-based adjustments to Speakers Bank and the newly found Colvoocoreses Reef.
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 where discovered or found mislocated with the use of Landsat 7.
Landsat aids hydrographic offices around the world

The International Hydrographic Organization 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 it is getting more and more use—as no doubt the European Space Agency’s Sentinel-2A, with spectral bands similar to Landsat 8, will as well.

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. SDB alone does not meet IHO accuracy standards, but its use as a complimentary 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, as a major Landsat user, has been sponsoring international GEBCO students from around the world (Kenya, Sri Lanka, Ecuador, Philippines, etc.) and teaching them how to use SDB to update charts in their home offices. From July 14–16, 2015, NOAA hosted a workshop to share this knowledge in the confidences that using SDB will make mariners worldwide more safe. Hydrographers from 11 countries attended. The workshop was a big success and more workshops are planned.

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. Péeri, 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.

Back 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,” Péeri says. “With insufficient knowledge of sandbar locations, the NOAA craft risk running aground and crew can be thrown overboard when that happens.”

Péeri’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,” Péeri says citing the new satellite’s additional cirrus band which helps him better account for atmospheric noise that can counter accurate SDB and Landsat 8’s better radiometric resolution (which means more signal, less noise, and more measurement fidelity). 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 are prioritizing which charts are in perilous need of revision.

“We’re making charts safer up there,” Klemm says talking about the recent Beaufort Sea chart revisions, “and that’s so exciting.”

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.

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 bit data digitization
The Synoptic View of California’s Camp Fire: A Scorching Reality of Today’s Fires

Feb 19, 2019 • As 2018 closed, Discover Magazine blogger Tom Yulsman posted to his ImaGeo blog about the most gripping image he’d seen during the year. The “particularly compelling” one he chose was a Landsat 8 image of the Camp Fire in northern California.

The specific Landsat image of the Camp Fire that Yulsman selected was created by independent blogger and geojournalist Pierre Markuse, using Landsat 8 data collected on November 8, 2018.
Inception

The Landsat 8 data behind this image, which made repeated appearances in the media, told a striking story of both the extent and the speed of the blaze. Landsat 8 acquired the image on Thursday, November 8 at 10:45 a.m. local time, a mere four hours after a small fire off Camp Creek Road had started the conflagration. It would become California’s deadliest fire, killing 86 people and burning more than 14,500 homes and businesses in the foothill town of Paradise.

NASA Earth Observatory provided a heavily used version of the Landsat 8 image of the Camp Fire in Northern California. USGS, universities, and environmental companies all provided versions of this image as well. The open Landsat data archive allowed anyone who wanted the data to get it. Image credit: Joshua Stevens, NASA Earth Observatory/Landsat

The Landsat image revealed that half of Paradise was already burning that morning. The fire’s extent was visible through the smoke because of data the satellite collects from wavelengths
beyond human range of sight (namely the shortwave infrared (SWIR) and Thermal Infrared (TIR) regions).

Smoke obscures the ground in the visible color Landsat 8 image on the left (created using the red, green, and blue bands—bands 4,3,2). The image on the right was created using one of Landsat 8’s thermal infrared bands, one of its shortwave infrared bands, and its blue band—bands 10,6,4). The shortwave and thermal infrared data show the active fire front and hotspots below the smoke cover. Image credit: Matt Montanaro and Aaron Gerace/Landsat.

The Camp Fire burned more structures than any before in California’s history (18,804 in total when including support structures like sheds and garages). Flames consumed nine out of every ten homes in Paradise, in what is now recognized as the deadliest fire in America since 1918.

As Yulsman wrote in his initial blog post two days after the fire began:

“In all the many years that I’ve covered wildfire, I don’t believe I’ve encountered anything like what we’ve seen with the Camp Fire blazing in California’s northern Sierra Nevada mountains. What really shocked me was the speed with which this cataclysmic inferno progressed.”

At UC Berkeley, geography professor Jeff Chambers used this Landsat 8 image to calculate the speed of the fire. Given the known start time of 6:30 a.m. and the collect time of the satellite, he calculated that the fire had been traveling 3 mph during those first four hours, stoked by dry easterly winds tearing across California’s Sierra Nevada mountains from the warm deserts of Nevada. Winds speeds that day were 30 mph with gusts up to 50 mph.
Chambers and other fire specialists also used this Landsat data to verify the “leapfrog” behavior of the fire. Embers blown by the dry winds started spot fires along the western front, jumping 2.5 miles ahead of the main fire front. The Landsat image captures the fire behavior behind this devastating disaster.

As Chambers told Berkeley News, “It’s astonishing. You can see the fire burning right through the city.”

In nearby Chico, California, Zeke Lunder, a pyrogeographer and founder of Deer Creek GIS, used the Landsat image together with topographic data and road overlay information to create a number of 3D renderings of the fire.

Lunder used the Landsat 8 image of the campfire together with topographic and road network data to create this image. This image and others created with Landsat 8 were used in public safety meetings and were featured in the Wildfire Today publication. Image credit: Zeke Lunder, Deer Creek GIS/Landsat/Google Earth

Lunder and his team used the Landsat image to create fire perimeter and progression maps. He used the maps in public meetings to, as he explained, “help people understand how the fire spread in its initial stages.”
Deer Creek GIS often uses Landsat to do regular landscape-scale fire hazard assessments, but the timing of this Landsat 8 image and what it showed was astonishing to even Lunder:

“We rarely are able to find images such as this, which capture the peak burning period of a major fire we are working. The size of the spot fires, distance the spot fires were ahead of the main fire, the hot spots—each a burning home—the width of the flaming front, and the fire’s impingement on all of the major evacuation routes, all tell a crazy story, capturing a remarkably dramatic and traumatic point in time.”

The town of Paradise is nestled into the foothills of the Sierras, situated on a ridge between two canyons. It’s a gorgeous geography, but one with limited escape routes. The Landsat 8 image captured how horrifyingly fast the fire spread, and why there was little or no time for evacuations. The Guardian interviewed 50 Camp Fire survivors from Paradise and their story paints a vivid picture of just how terrifying this fire was to live through.

It took more than 2,000 fire fighting personnel and nearly three weeks to finally quell the flames.

Map showing the mix of vegetation types that were within the Camp Fire perimeter. Image credit: Allie Weill, using CALVEG and CAL FIRE data.
**Fueling the Fire**

In interview after interview in the days after the fire started, fire researchers commented that the dry conditions accompanying our changing climate have shifted the nature of fires, increasing their ferocity.

Sprawling urban fires that once regularly plagued civilization were thought to be a thing the past—the Camp Fire let us know they are back.

Why was the Camp Fire so fierce, so aggressive? The drought conditions and the strong winds were factors, as was the “fuel,” i.e. what was burning.

After some mischaracterization, the Camp Fire was clarified as a wildland fire—a fire burning a mix of grasses, shrubby vegetation, and forest. It was this patchwork of vegetation that fueled the Camp Fire—a mix of vegetation that, after years of drought conditions, had become a dry fuel load.

As fire ecologist and science writer Allie Weill wrote for *KQED Science* prior to the Camp Fire, “Fuel Matters” and firefighters must pay close attention to land cover because it effects how a fire behaves.

Weill created a number of land cover maps for her article showing the different types of vegetation, or fuel, that was found where some of California’s worst fires were located. To create the maps she used open CALVEG data along with fire perimeter information from CAL FIRE, the California fire protection entity.

The **CALVEG dataset** is today derived from a mix of Landsat data, aerial data and field information, but the data set has a long association with Landsat. Its acronym stands for Classification and Assessment with Landsat of Visible Ecological Groupings. The U.S. Forest Service created the initial dataset using first generation Landsat data in the 1970s.
Prevention and Preparedness in the New Age of Mega-Fires

With a repeat cycle of every sixteen days it is rare for Landsat to image a fire within hours of its onset, as it did for the Camp Fire. But the mission’s long archive and well-calibrated data set makes it essential for fire management in other ways.

In addition to informing land cover data sets such as CALVEG, Landsat is integral to a number of fire management programs including LANDFIRE, an interagency endeavor that provides vegetation fuel data for the entire U.S.; Monitoring Trends in Burn Severity, or MTBS, a program that uses Landsat to map burn severity and fire extent, watching for fire behavior trends, and the Burned Area Emergency Response program, which puts teams on the ground armed with Landsat-based burn severity maps immediately following fires to aid in post-fire remediation efforts.

NASA uses Landsat alongside its other space-based Earth-observing resources to provide data to fire managers before, during, and after a fire as part of its Disasters Program. Landsat also helps inform NASA’s RECOVER program that provides online mapping tools with spatially relevant data that fire managers need.

Meanwhile, the European Space Agency is test-piloting a Fire Detection Service that processes Landsat data in real time, scanning for any fire signatures and alerting responders when a fire is detected.

As the Camp Fire has forced us to recognize, the trend towards bigger and faster wildfires cannot be ignored, especially as cities grow towards wildland areas.

In California, five of the state’s most destructive fires have happened within the last two years, and 15 of the top 20 have occurred since 2000. The cleanup of the Camp Fire is still ongoing in Paradise. As NPR correspondent Kirk Siegler reported, federal disaster officials say the work there is the worst toxic debris removal job the U.S. has faced since 9/11.

Good information about the land cover that gives fuel to fires like the Camp Fire is part of any strategy to limit such staggering wildfire tragedies in the future. As landscapes change along with the climate, Landsat and other satellites are giving fire managers valuable insights that can translate into a better chance to protect people.

As Lunder put it, “Landsat is an invaluable tool for people working in our field of community wildfire safety.”
Smoke from the Camp Fire at sunrise. Photo credit: InciWeb

Related Reading:
+ [USGS, EROS Offer Insights to National Fire Strategy Discussion](https://inciweb.gov), USGS EROS
+ [Early warning for wildland fires? There could be an app for that](https://www.berkeleynews.com), Berkeley News [added May 1, 2019]

References:
+ [My pick for the most compelling — and scary — remote sensing image of 2018](https://www.discovermagazine.com/imaGeo), Discover Magazine/ImaGeo
+ [Stunning satellite images and animations offer a sobering perspective on California’s raging infernos](https://www.discovermagazine.com/imaGeo), Discover Magazine/ImaGeo
+ [New satellite view of Camp Fire as it burned through Paradise](https://www.berkeleynews.com), Berkeley News
+ [Experts weigh in on how to prevent another Paradise-like catastrophe](https://www.dailydemocrat.com), The Daily Democrat
+ [Fueling the Fire](https://www.slate.com), Slate
+ [Last day in Paradise: the untold story of how a fire swallowed a town](https://www.theguardian.com), The Guardian
+ [NASA Disasters Program: California Wildfires in Fall 2018](https://science.nasa.gov), NASA
+ [NASA Mobilizes to Aid California Fires Response](https://jpl.nasa.gov), NASA Jet Propulsion Lab
+ [Fuel Matters: Why Wildfire Behavior Depends on What’s Burning](https://www.kqed.org), KQED Science
+ [California’s Deadliest Fire Is Seen Engulfing Paradise in ‘Astonishing’ Satellite Images](https://www.livescience.com), Live Science
+ [2018’s Billion Dollar Disasters in Context](https://www.weather.gov), Weather Nation
Story by Laura E.P. Rocchio, NASA Landsat Communication and Public Engagement Team

This entry is filed under Disasters, Feature-FrontPage, Fire, News.
Discovering New Thermal Areas in Yellowstone’s Dynamic Landscape

By: R. Greg Vaughan, U.S. Geological Survey Research Scientist for the Caldera Chronicles

Map of thermal areas in Yellowstone National Park. Most of Yellowstone’s more than 10,000 thermal features are clustered together into about 120 distinct thermal areas (shown in red). Lakes are blue. The Yellowstone Caldera is solid black and the resurgent domes are dotted black. Roads are yellow. The orange box shows the location of the Tern Lake thermal area. Image credit: USGS

Apr 8, 2019 • Yellowstone’s thermal areas are the surface expression of the deeper magmatic system, and they are always changing. They heat up, they cool down, and they can move around. A recent spectacular example was the September 2018 emergence of a new thermal feature and eruption of the long-dormant Ear Spring in the Upper Geyser Basin, near Old Faithful. Even more impressive was the expansion of heated ground in the Back Basin of the Norris Geyser
These sorts of changes are part of the normal life cycles of thermal areas in Yellowstone National Park.

Recently, we have discovered another phenomenal example of thermal change—the emergence of an entirely new thermal area, which has taken place over the past 20 years.

First, a little background. A thermal area is a contiguous geologic unit that includes one or more thermal features (like fumaroles, hot springs, or geysers) surrounded by hydrothermally altered ground, hydrothermal mineral deposits, geothermal gas emissions, heated ground, and/or a lack of vegetation. There are more than 10,000 thermal features in Yellowstone, most of which are clustered together into about 120 distinct thermal areas (like Upper Geyser Basin and Norris Geyser Basin). One such area is called the Tern Lake thermal area and is located in the central part of the Park along the northeast margin of the Sour Creek resurgent dome. It is named after nearby Tern Lake and West Tern Lake. This area is deep in Yellowstone’s back county, about half a mile (0.8 kilometers) from the nearest trail, and about 11.2 miles (18 kilometers) from the nearest trailhead; therefore, few people have visited this site. Indeed, many of Yellowstone’s thermal areas are located in remote and inaccessible areas of the Park. This is why YVO scientists use satellite-based thermal infrared remote sensing to help map the locations of thermal areas and their changes through time.

Landsat-8 nighttime thermal infrared image from April 2017 showing the Tern Lake area. In Yellowstone, temperatures are extremely cold at night in the winter, and most lakes are frozen (dark pixels). West Tern Lake seems to be thawing here—perhaps it receives some thermal waters from nearby hot springs. The patch of bright (warm) pixels between West Tern Lake and the Tern Lake thermal area has emerged over the last 20 years. Lakes are outlined in blue; the
The boundary of the Sour Creek resurgent dome is in black; known thermal areas are outlined in red; and the red triangles are individual thermal features that have been mapped. Image credit: USGS

Landsat 8 nighttime thermal infrared image from April 2017 showing the Tern Lake area. In Yellowstone, temperatures are extremely cold at night in the winter, and most lakes are frozen (dark pixels).

West Tern Lake seems to be thawing here – perhaps it receives some thermal waters from nearby hot springs. The patch of bright (warm) pixels between West Tern Lake and the Tern Lake thermal area has emerged over the last 20 years. Lakes are outlined in blue; the boundary of the Sour Creek resurgent dome is in black; known thermal areas are outlined in red; and the red triangles are individual thermal features that have been mapped.

**Landsat 8** thermal infrared images are a great resource for examining thermal areas—especially when the temperature-sensitive images are acquired at night when the contrast between thermal areas and unheated ground is highest. Analysis of a Landsat-8 nighttime thermal infrared image acquired in April 2017 revealed an unexpected warm area between West Tern Lake and the previously mapped Tern Lake thermal area. This mysterious patch of bright pixels in the thermal infrared image did not match any previously mapped thermal areas. Could it be a lake? At night, lakes are warmer than the surrounding land and stand out in thermal infrared images, but only if they are liquid (i.e., not frozen).

All of Yellowstone’s lakes without significant thermal input stay frozen throughout the winter, but the lakes can start to thaw in April. In fact, this appears to be the case in the April 2017 image—some of the lakes are clearly frozen (dark pixels in the thermal infrared), but West Tern Lake appeared to be starting to thaw. This may have been because the lake was receiving thermal water from nearby hot springs. But that new bright area between West Tern Lake and the previously mapped Tern Lake thermal area was not a lake. What was it? High-resolution airborne visible images held the answer.

The **National Agriculture Imagery Program (NAIP)**, administered by USDA’s Farm Service Agency, acquires high-resolution (0.5 to 1-m pixel) aerial imagery over the continental U.S. every few years. The most recent image of the Tern Lake region, from 2017, reveals a large area of dead trees and bright soil, rather like a thermal area. The NAIP imagery from 2006 shows a smaller zone barren of vegetation and the beginnings of a tree kill zone with many reddish-brown trees among healthy green ones. The 1994 air photos, while black and white and lower spatial resolution, clearly show that this was once an area of healthy trees with no hint of a thermal area. Other historical imagery that have been analyzed indicate that this thermal area started forming in the late 1990s or early 2000s. It is also notable that between 2006 and 2017 there was an increase in the size of the tree kill zone on the north side of the previously mapped Tern Lake thermal area.
High-spatial-resolution airborne images of the Tern Lake area from 1994, 2006, and 2017. The area of bright pixels identified in the Landsat-8 thermal infrared image corresponds to a newly emerging area of warm ground and tree kills about 32,500 m² (8 acres, or 4 soccer fields) in area. The air photo from 2006 shows the beginnings of a tree kill zone. The black and white air photo from 1994 shows no evidence of a newly emerging thermal area. Lakes are outlined in blue; known thermal areas are outlined in red; and the red triangles are individual thermal features that have been mapped. Photo credit: USDA and USGS

From all these satellite and aerial images, we conclude that a new thermal area has emerged in the past 20 years! The newly emerging thermal area, located at 44.6635° N latitude, 110.279° W longitude, can be seen using Google Earth. In fact, using the time slider tool in Google Earth, one can see how this area has changed since 1994—you can see the changes in the vegetation and the emergence of the thermal area yourself!

The recognition of the new thermal area is a great example of the importance of satellite thermal infrared imaging—especially images acquired at night—for mapping Yellowstone’s thermal areas (including both the discovery of new hot spots and changes in existing areas). This is exactly the sort of behavior we expect from Yellowstone’s dynamic hydrothermal activity, and it highlights that changes are always taking place, sometimes in remote and generally inaccessible areas of the park. We will continue to keep an eye on Yellowstone using satellite imagery and report on any changes we see in future Caldera Chronicles articles. And if you’re really interested, you can check out the Landsat-8 data and airborne NAIP images for yourself! All images are freely available from https://earthexplorer.usgs.gov. Have fun!