

National Aeronautics and
Space Administration



ICESat-2

MEASURING THE HEIGHT
OF EARTH'S ICE
FROM SPACE

Ice, Cloud, and land Elevation Satellite-2 mission: icesat-2.gsfc.nasa.gov

ICESat-2 Science Objectives

The ICESat-2 mission is designed to accomplish four science objectives:

1. Quantify how much melting ice sheets in Greenland and Antarctica contribute to sea level changes.
2. Quantify how ice sheets and glaciers are gaining or losing mass at a regional level, to help researchers understand the mechanisms behind those changes.
3. Estimate the thickness of sea ice and monitor any changes.
4. Measure the height of vegetation in forests and other ecosystems worldwide.

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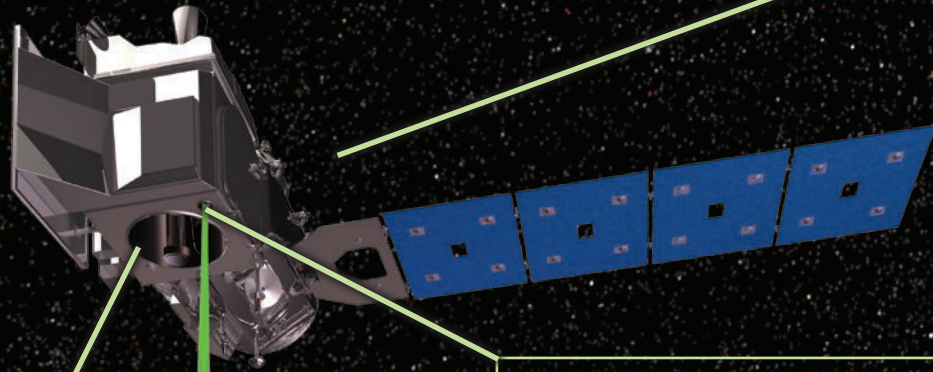
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Photo credit: Eric Fignoa/NASA

ICESat-2

NASA's new Earth-observing satellite will measure the height of our planet's ice in unprecedented detail.



Telescope

The ATLAS receiver telescope collects the handful of photons from each laser pulse that return to the satellite. Every second, the instrument records data from 60,000 returning photons. Each photon's flight time is measured with a precision of 800 picoseconds.

Laser

ICESat-2's ATLAS laser instrument pulses 10,000 times a second, each pulse sending 300 trillion bright green laser photons to the ground. Scientists calculate height by using the time it takes individual photons sent from the laser to bounce off Earth's surface and return to the satellite.

Spacecraft

The ICESat-2 spacecraft orbits Earth at 15,660 mph at an altitude of 310 miles. Every 91 days, it completes 1,387 unique orbits. The mission collects a terabyte of data daily.

Land Ice

Glaciers and ice sheets form as snowfall accumulates over centuries and millennia. As more land ice melts into the ocean, global sea level rises. ICESat-2 will measure the annual rise or fall of ice sheets to within a fraction of an inch.



Credit: Nathan Kurtz/Operation Icebridge/NASA

Sea Ice

Sea ice forms when ocean water freezes, and in the Arctic Ocean forms a brightly reflective cap that helps regulate Earth's temperature. The ICESat-2 mission will calculate the thickness of sea ice by measuring the freeboard—the difference between the top of sea ice and the ocean surface.



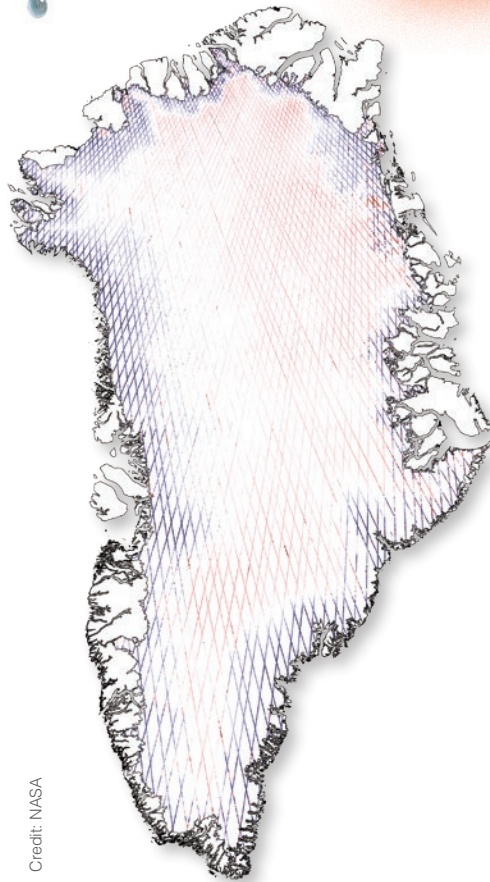
Credit: Jeremy Harbeck/Operation Icebridge/NASA

ICESat-2

Measuring the Height of Ice from Space

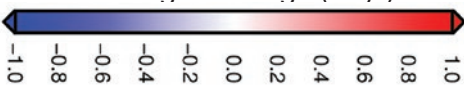


Earth's ice is shrinking.



Credit: NASA

Greenland
Ice Height Change (m/yr)



[Above] This image was created using data from the original ICESat mission. Blue denotes decreases in ice height per year from 2003-2009 (when ICESat was in operation), while red denotes increases in ice height per year. More recently, between 2002 and 2016, about 280 gigatons of ice melted from Greenland each year, causing annual global sea level rise of 0.03 inches (0.8 millimeters). Scientists are using height changes to calculate the mass loss of ice.

Ice is being lost across the globe, especially in the polar regions. The continental ice sheets of Greenland and Antarctica are shedding ice to the oceans and raising sea level. Arctic sea ice is less than half its 1980s volume. Fundamentally changing the Arctic, this ice loss may also be affecting North American and global weather.

NASA is launching the Ice, Cloud and land Elevation Satellite-2 (ICESat-2) to measure changes in Earth's ice and improve forecasts of the global impacts. With its fast-firing laser, the satellite will collect information enabling scientists to calculate—to within fractions of an inch—how much the vast ice sheets of Antarctica and Greenland rise or fall each year.

ICESat-2 will take measurements across the globe and provide an incredibly precise height map of our planet in unprecedented detail. Its focus will be on Earth's poles, including the Arctic region where temperatures are rising faster than at other latitudes.



Photo credit: NASA/Operation IceBridge

[Above] The calving front of the Kangerlussuaq Glacier, on Greenland's east coast. When glacier ice calves and melts into the ocean, it contributes to sea level rise. Scientists estimate global sea level could rise between 0.66 to 6.6 feet (0.2 to 2.0 meters) higher by 2100, compared to the first decade of this century.

Global land-ocean temperature index for 2017 relative to the 1951-1980 average:

↑ +0.9°C

Greenland ice mass change since 2002:

↓ -286 gigatons/year

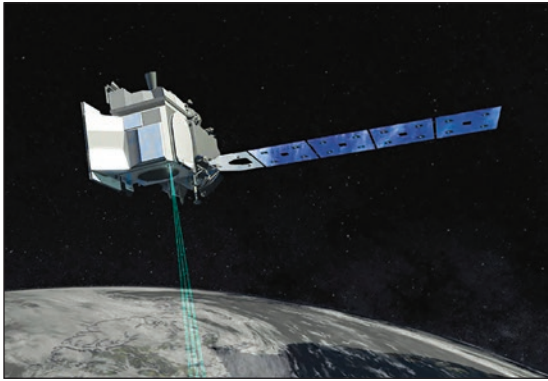
Greenland ice loss 2002-2018:

↓ 4,576 gigatons

Antarctic ice mass change since 2002:

↓ -127 gigatons/year

Credit: NASA



ICESat-2 is poised to capture changes in the planet's ice in unprecedented detail, shedding light on rising sea levels and shifting ocean currents.

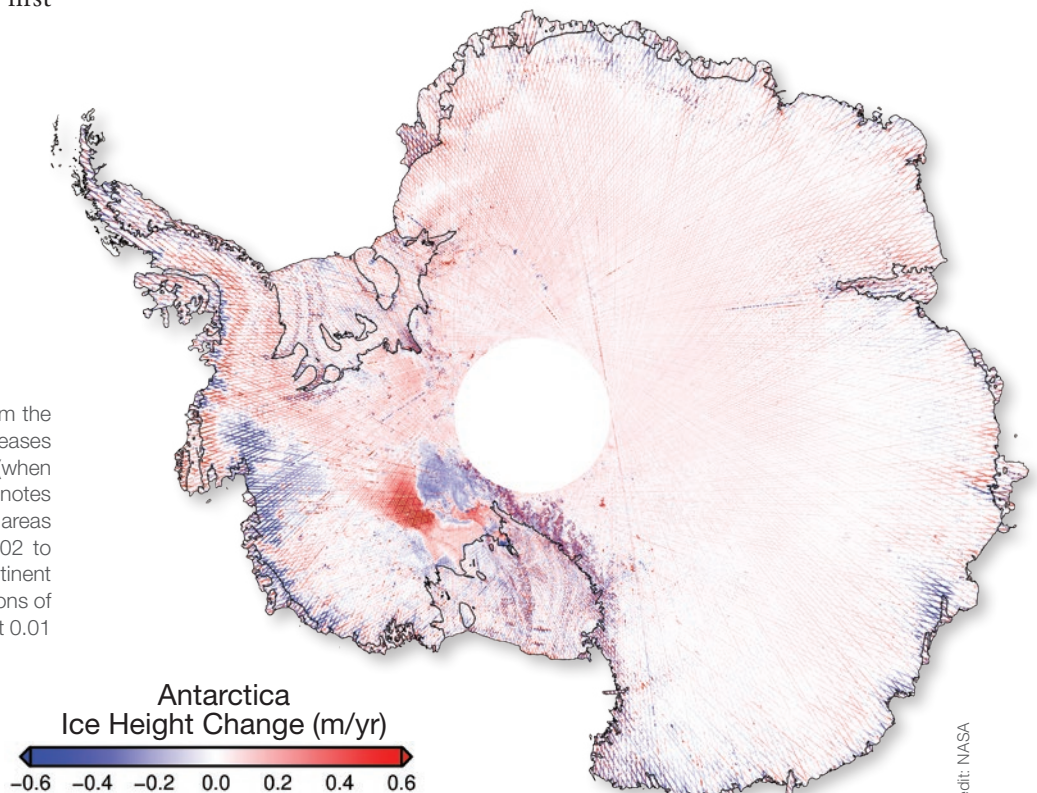
Hundreds of billions of tons of land ice melt into the oceans annually, raising sea levels worldwide. In recent years, meltwater from the ice sheets on Greenland and Antarctica alone has raised global sea level by more than a millimeter a year, and the rate is increasing. Based on computer simulations and satellite data, global sea level could be anywhere from 0.66 to 6.6 feet (0.2 to 2.0 meters) higher by 2100 than in the first

decade of this century. ICESat-2 data documenting the ongoing height change of ice sheets will help researchers narrow that range of possibilities to forecast sea level rise with greater certainty, allowing communities to be better prepared.

Floating sea ice doesn't change sea level when it melts, just like melting ice cubes don't overflow a glass of water. But sea

ice loss has a different suite of global consequences. The bright Arctic ice cap reflects the Sun's heat back into space. When white ice melts away, leaving dark waters, the ocean soaks up that heat. This alters wind and ocean circulation patterns that span the globe, affecting Earth's weather and climate.

[Right] In this image, created using data from the original ICESat mission, blue denotes decreases in ice height per year from 2003-2009 (when ICESat was in operation), while red denotes increases in ice height per year. While some areas gained ice from 2003-2009, data from 2002 to 2016 show that overall the ice from the continent is melting, sending approximately 125 gigatons of ice into the ocean and raising sea level about 0.01 inches (0.35 mm) per year.



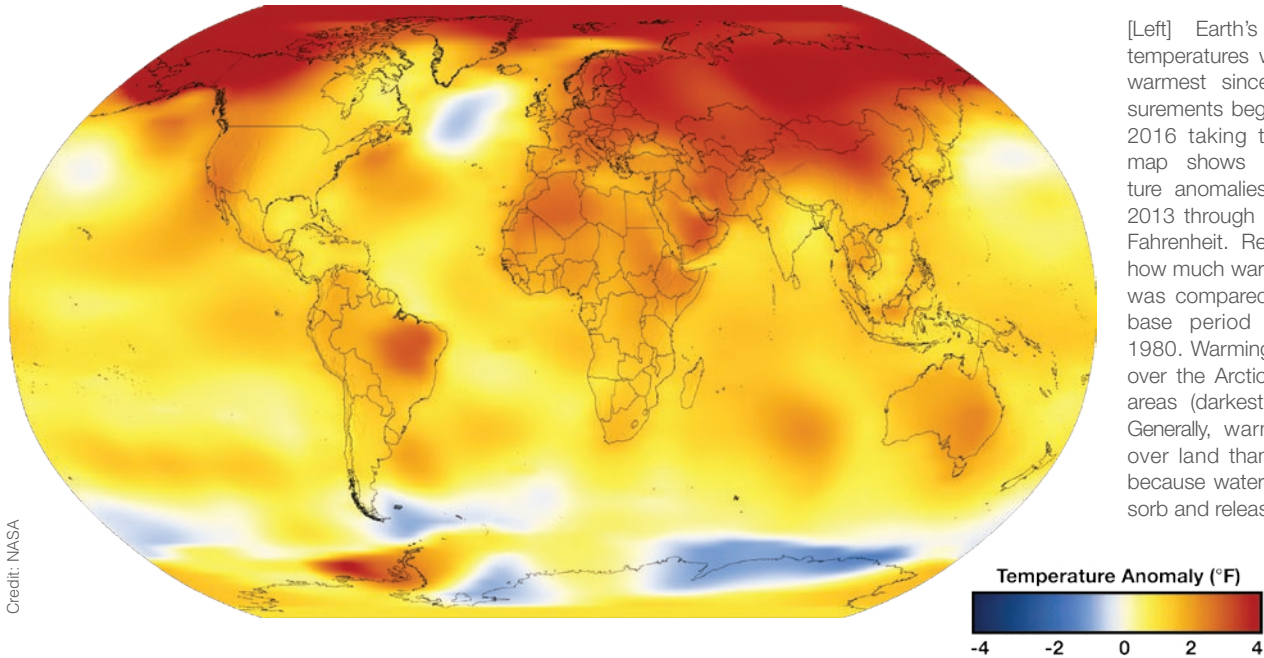
Credit: NASA

Antarctic ice loss 2002-2018:
↓ 2,032 gigatons

Arctic sea ice loss since 1980:
↓ ~40%

**Arctic sea ice minimum
relative to the 1981-2010 average:**
↓ -13.2 %/decade

Sea level rate of change 1993-2018:
↑ 3.2 millimeters/year



Credit: NASA

[Left] Earth's 2017 surface temperatures were the second warmest since modern measurements began in 1880, with 2016 taking the record. This map shows global temperature anomalies averaged from 2013 through 2017 in degrees Fahrenheit. Red shades show how much warmer a given area was compared to an averaged base period from 1951 to 1980. Warming is concentrated over the Arctic and some land areas (darkest shades of red). Generally, warming is greater over land than over the ocean because water is slower to absorb and release heat.

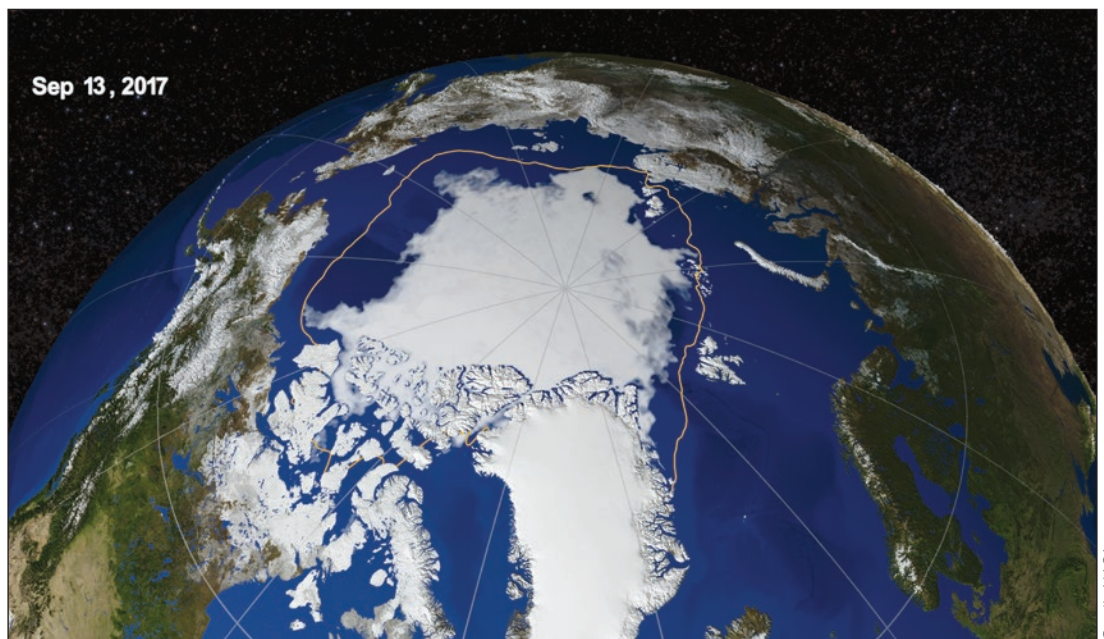
Shrinking sea ice cover also disrupts traditional ways of life for native Arctic communities, and changes habitats for wildlife such as polar bears and whales. While scientists routinely measure sea ice coverage from satellite images, they lack region-wide sea ice height measurements that would allow them

to derive thickness and volume—height measurements that ICESat-2 will provide.

In the blink of an eye—half a second—ICESat-2's laser altimeter will fire 5,000 times, sending trillions of photons to the ground in six beams of green light. The instrument, called the Advanced Topographic Laser Altimeter System

(ATLAS), measures height by timing how long it takes individual photons to travel from the spacecraft to Earth and back—and does so with a precision better than a billionth of a second. In the course of three months, ATLAS will cover the globe with 1,387 individual orbits, collecting billions of measurements to create a three-dimensional portrait of our planet.

[Right] In 2017, Arctic sea ice reached its lowest extent for that year on September 13, according to NASA and the National Snow and Ice Data Center (NSIDC). Since satellites began continually monitoring sea ice in 1978, researchers have observed a steep decline in the average extent of Arctic sea ice for every month of the year. With ICESat-2 data, scientists will be able to track the thickness of the sea ice in addition to the extent.



Credit: NASA

Arctic sea ice extent has consistently shrunk below the 1980–2010 average since 2011.

Between 2003 and 2009, Arctic sea ice declined in thickness by more than **23.6 inches (60 centimeters)**.

As the satellite orbits, it will also measure the height of the ocean and land. Researchers investigating vegetation, clouds, and more will be able to use the satellite's terabytes of data to study the planet's temperate and tropical latitudes.

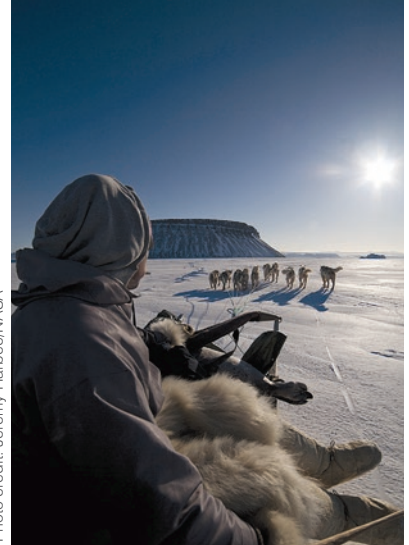
Beyond the poles, ICESat-2 will measure the heights of the world's forests. ATLAS is designed to measure both the tops of trees and the forest floor below, which—combined with existing datasets on forest extent—will help researchers estimate the amount of global vegetation.

Even prior to launch, potential data-users have been working with ICESat-2 to con-

nect the mission science to societal needs. ICESat-2 measurements of reservoir heights could help local governments plan for flooding or drought, for example. Forest height maps, showing tree density and structure, could improve computer models that firefighters use to forecast wildfire behavior. Sea ice measurements could be integrated into forecasts the U.S. Navy issues for navigation and sea ice conditions.

The full potential of ICESat-2's data is unknown; the mission's profile of Earth will open the door for discoveries not yet imagined.

Photo credit: Jeremy Harbeck/NASA



[Above] Changes in ice cover directly impact the lives of people who live north of the Arctic Circle in Greenland and Canada.

Sea Ice Versus Land Ice

Earth's frozen poles are dominated by different forms of ice. The North Pole lies in the Arctic Ocean, which is mostly covered by sea ice, while the South Pole is on the Antarctic continent, covered by land ice.

Sea ice forms when salty ocean water freezes. Some sea ice lasts for decades and can grow to 15 feet (4.5 meters) thick. Some sea ice forms and melts yearly. Just as melting ice cubes do not cause a full glass of water to overflow, melting sea ice does not change sea level. However, melting sea ice can change ocean circulation patterns and influence the global climate.

Arctic



Credit: NASA

Antarctic



Credit: NASA

Land ice, such as the ice sheets in Greenland and Antarctica or glaciers in the Himalaya, builds up from centuries' worth of snowfall. It can be miles thick. The Antarctic ice sheet has a mean thickness of 1.6 miles (2.2 km), for example, and reaches a maximum of almost 3 miles (4.8 km) thick. When ice on land melts, it can flow into the ocean and raise sea level.

Since 1870, sea level has risen about
↑ 8 inches (20 centimeters).

ICESat-2 will collect data within a swath width of 56 feet (17 meters).

NASA's View of Our Frozen Earth

From space, satellite observations of ice show rapid change.



Credit: NASA

[Above] The Nimbus-7 spacecraft (1978-1994) began a continuous satellite record of sea ice measurements that now covers 40 years and has revealed dramatic changes to the Arctic climate.

NASA's ICESat-2 mission will extend a continuous data record on the height of Earth's ice. This record started in 2003 with the original ICESat mission and continued in 2009 with NASA's Operation IceBridge. IceBridge fills the data gap between ICESat and ICESat-2, with airplanes flying a suite of scientific instruments over the Arctic and Antarctic. The airborne campaign has provided essential information to improve sea ice forecasts and has charted the decline of several Antarctic glaciers and ice shelves, among many other accomplishments.

With ICESat-2's advanced laser technology, NASA will provide even more detailed, more precise and more dense datasets on land and sea ice.

The Frozen Ocean Sea Ice

Arctic sea ice fluctuates with the seasons, but on average covers an area the size of the United States. This ice cap acts as a cooling system for the rest of the globe.

A C-130 Hercules
flown by Operation IceBridge

**NASA's
Ice-Measuring
Lidars**

1993: NASA's Airborne Topographic Mapper begins surveys of Greenland's ice

2003: The original ICESat launches; ends mission in 2010

In 2009, NASA began a campaign called

Operation IceBridge

the world's largest airborne survey of polar ice to continue the data record started by ICESat.

When heat from the Sun hits the Arctic Ocean, ice cover makes a difference. Solar energy that hits bright, white sea ice is reflected back into space, while solar energy that hits the dark ocean is absorbed, warming the water and keeping the heat on Earth.

Sea ice also acts as insulation for the ocean. The Arctic air is often far colder than the Arctic Ocean, and open water easily loses heat into the atmosphere.

Changes in sea ice extent can therefore have a significant effect on the temperatures of the ocean and atmosphere. This, in turn, can lead to alteration of global ocean and atmospheric circulation patterns—patterns that determine the climate in more temperate parts of the world.

NASA and other organizations have been monitoring sea ice extent from polar-orbiting satellites for more than four decades, beginning operationally with the Nimbus-7 satellite in the late 1970s. Some satellites carry passive microwave instruments that allow scientists to monitor the daily reach of the sea ice, even through clouds. With infrared instruments like the Moderate Resolution Imaging Spectroradiometer



Photo credit: Chris Larsen/UAF

(MODIS) and NOAA's Advanced Very High Resolution Radiometer (AVHRR), researchers can measure the surface temperature. The Landsat series of satellites has collected images of the polar ice for decades as well. Scientists have charted the annual variations in sea ice and documented the decline in the ice's extent in recent years. Since 2011, Arctic sea ice extent has consistently shrunk below the 1980–2010 average.

[Above] This DHC-3 Otter is flown in NASA's Operation IceBridge-Alaska surveys of mountain glaciers in Alaska. Over the past few decades, Alaskan glaciers have lost about 75 billion tons of ice per year.

[Below] Young sea ice in the Chukchi Sea, north of the Bering Sea, as seen by Operation IceBridge in March 2017. IceBridge measures ice thickness along its flight lines. ICESat-2 will provide the most comprehensive measurements yet of sea ice thickness and how it is changing.

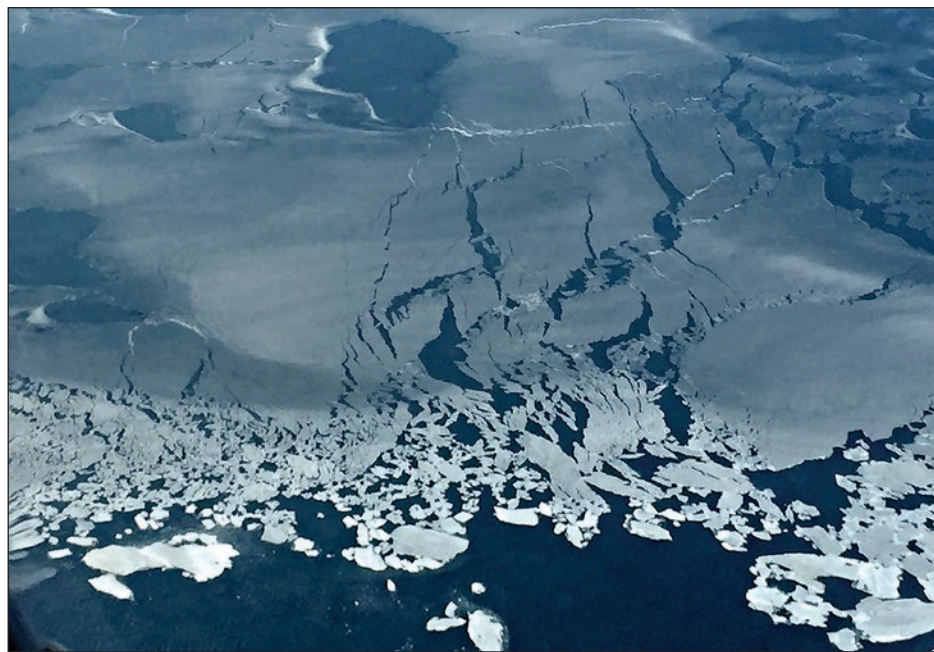


Photo credit: Operation IceBridge/NASA

2007: NASA's Land, Vegetation, and Ice Sensor begins airborne Greenland surveys

2007: The National Research Council's Decadal Survey recommends a second ICESat mission

2009: NASA's Operation IceBridge begins annual airborne campaign over the Arctic and Antarctic with the Airborne Topographic Mapper and the Land, Vegetation, and Ice Sensor

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ICESat-2 will measure the distance between the top of sea ice and the ocean surface to provide unprecedented sea ice thickness data.

Sea ice that has built up over years can be 5 meters (15 feet) thick and is tougher to melt than the relatively thin ice that forms annually. The first ICESat mission, in operation from 2003 to 2010, demonstrated that between those years Arctic sea ice thickness declined overall by more than 60 centimeters (2 feet).

ICESat-2 will provide a wealth of detailed sea ice thickness data. The satellite's instrument will measure *freeboard*—the distance between the top of the ice and the ocean surface. From that, computer programs can use the ratio of ice above water to ice below water to calculate the thickness of the floating ice.



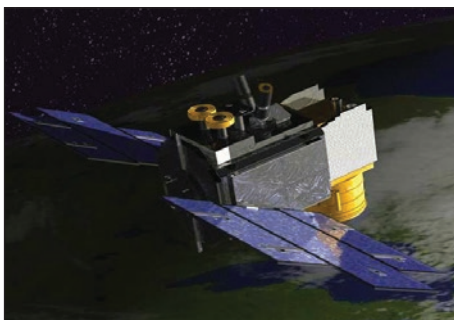
Photo credit: Andy Mahoney/NSIDC

[Above] Sea ice is changing in different ways in the Arctic and Antarctic, and ICESat-2 will help scientists investigate this variation.

Massive Stores of Ice Ice Sheets

The ice that covers Greenland and Antarctica may seem as stationary as cement. But it is in flux. New ice forms as snow falls on top of the ice sheet over decades, compacted into layers of ice over thousands of years. Along the Greenland and Antarctic coasts, glaciers calve icebergs, which eventually melt into the ocean and contribute to sea level changes. Some ice, especially in Greenland, melts directly from the ice sheet into the ocean.

If the ice sheets are in balance, the amount of snowfall and the amounts of ice lost through calving and melt are equal. But satellite data show that has not been the case in this century. ICESat demonstrated that the margins of ice sheets were dropping in height, in some places by 3.3 feet (1 meter) or more a year.



Credit: NASA

[Above] The first ICESat spacecraft (2003-2010)

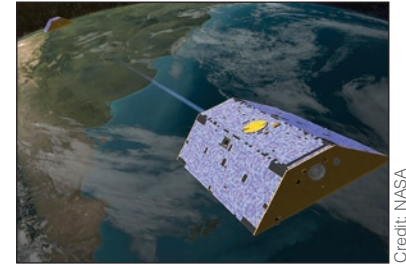
2012: The Multiple Altimeter Beam Experimental Lidar (MABEL) begins flights for ICESat-2 algorithm development.

2014: Engineers begin integrating and testing the ATLAS laser altimeter at NASA Goddard.

2016: ATLAS instrument assembly completed, instrument undergoes environmental testing.

2017: Engineers install ATLAS flight lasers.

The GRACE mission allowed scientists to detect a significant trend of ice loss in Greenland and West Antarctica over 15 years.



Credit: NASA

[Above] The twin GRACE spacecraft (2002-2017)

From satellites such as GRACE, the Gravity Recovery and Climate Experiment, scientists have found that Greenland is losing more than 250 gigatons of ice each year. Antarctica is losing more than 125 gigatons of ice each year. To put this into perspective, one gigaton of water is enough to fill 400,000 Olympic-sized swimming pools, and it would take more than four summer days for one gigaton of water to flow over Niagara Falls.

Those 375 gigatons of melt from ice sheets make up roughly a third of the

current observed sea level rise. Globally, sea level has risen about 8 inches (20 centimeters) since the beginning of the twentieth century and more than 2 inches (5 centimeters) in the last 20 years alone. A 2017 study suggested that sea level rise is accelerating and projected that by 2100 sea level will rise 26 inches (65 centimeters).

ICESat-2 will be able to detect centimeter-level rises or falls in the height of the ice sheets, which will give researchers more data on the precise location, and amount, of ice loss. The sheer number

of data points ICESat-2 will collect, together with the laser's small footprint size of about 56 feet (17 meters), means that researchers will have information on the changes in ice height on the scale of individual glaciers—in Greenland and Antarctica, as well as other parts of the globe. This, in turn, will allow scientists to better understand the current situation and better predict how much sea level will rise and the impacts to coastal communities globally.

[Right] This view from a NOAA P-3 Orion aircraft shows the calving front of Sermeq Kujatdleq glacier, located on the west coast of Greenland. ICESat-2's measurements will allow scientists to calculate the elevation of glaciers such as this in unprecedented detail and to track changes over time. Glacial ice melt is a major contributor to global sea level rise.

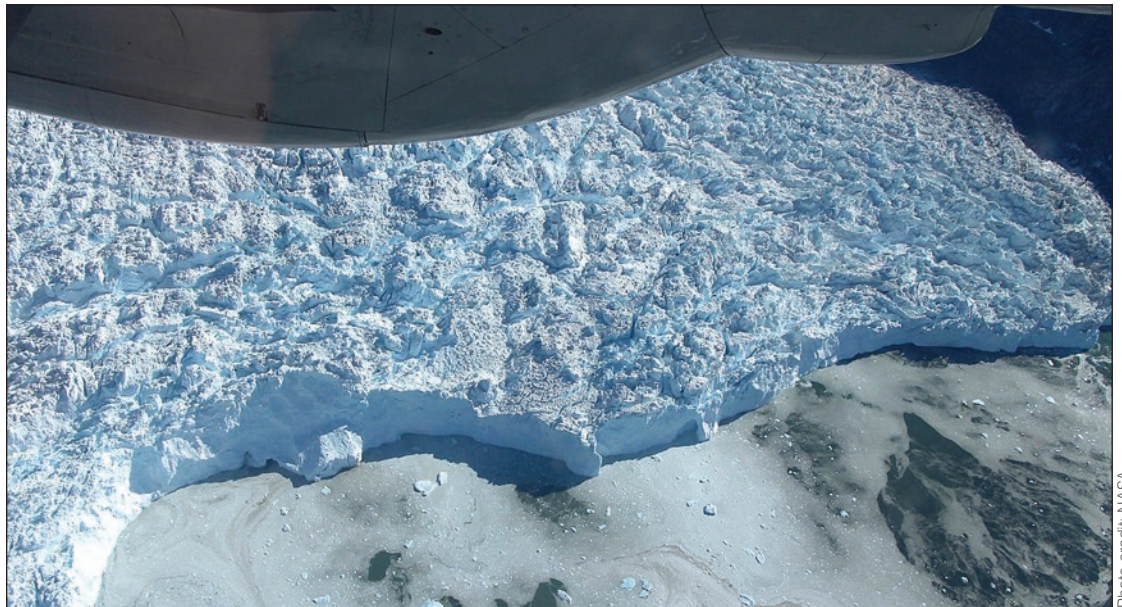


Photo credit: NASA

2017/18: ICESat-2 scientists collect Antarctic elevation measurements to assess future satellite data.

Early 2018: ATLAS ships to Northrop Grumman facility in Gilbert, Arizona, for spacecraft integration and testing.

June 2018: Integrated ICESat-2 satellite ships to Vandenberg Air Force Base.

Fall 2018: ICESat-2 launch scheduled.

Instrument Overview

The Advanced Topographic Laser Altimeter System

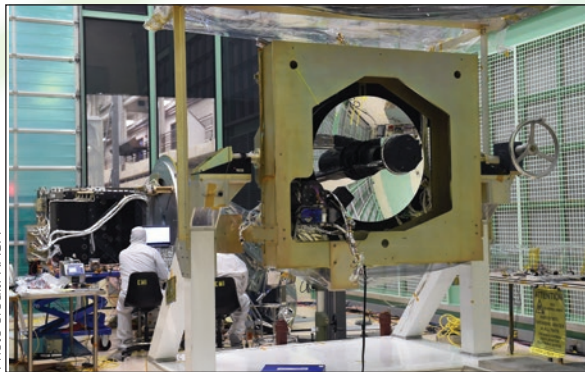
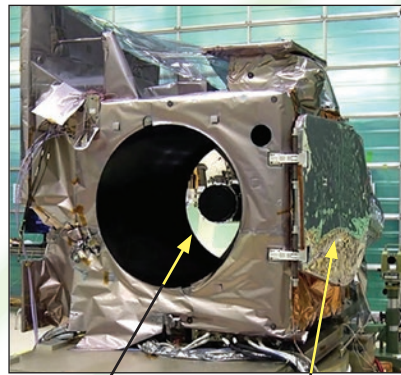


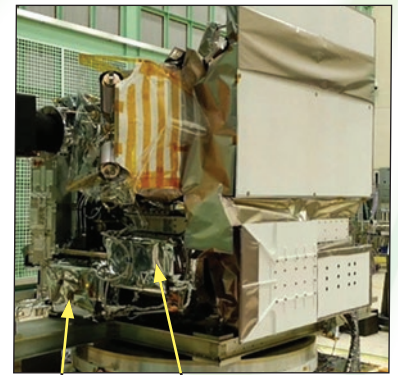
Photo credit: NASA

[Above and Right] These photos show the ATLAS instrument inside a cleanroom at NASA's Goddard Space Flight Center where the instrument was assembled. The instrument will carry a backup laser in case the primary laser fails.



Telescope

Door



Laser 1

Laser 2

To precisely time how long it takes a pulse of laser light to travel from space to Earth and back, you need a really good stopwatch — one that can measure within a fraction of a billionth of a second. Nothing available met ICESat-2's exacting requirements, so the team behind the satellite's Advanced Topographic Laser Altimeter System (ATLAS), built one themselves. It, and other ATLAS components make it one of the most advanced space lasers ever flown.

ATLAS has three major tasks: send pulses of laser light to the ground (while precisely determining where the laser is pointing), collect the returning photons in a telescope, and record the photon travel time. To do this, ATLAS will release 10,000 laser pulses a second. The light from the lasers, built by

Fibertek, is at 532 nanometers—a bright green on the visible spectrum. As a pulse is fired, ATLAS splits the single laser beam into six. The multiple beams from ATLAS are designed to cover more ground than the first ICESat's GLAS instrument, which used only a single beam. The six beams are arranged in three pairs, designed to allow scientists to gauge the *slope*, or gradient, of the terrain in one pass. With its incredibly fast pulse rate, ATLAS can take measurements every ~2.3 feet (70 centimeters) along the satellite's ground path. The footprint of each pulse is ~56 feet (17 meters) in diameter. In comparison, GLAS took measurements every 170 meters.

About 300 trillion photons leave ATLAS with each pulse; only about a dozen from each beam are detected upon returning to the satellite's beryllium telescope. To ensure that the telescope is aligned to catch those returning photons, ATLAS engineers have designed and built a Laser Reference System. This system picks up a fraction of the laser light

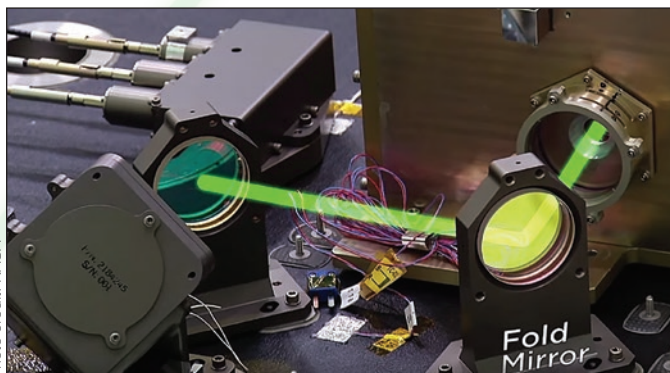


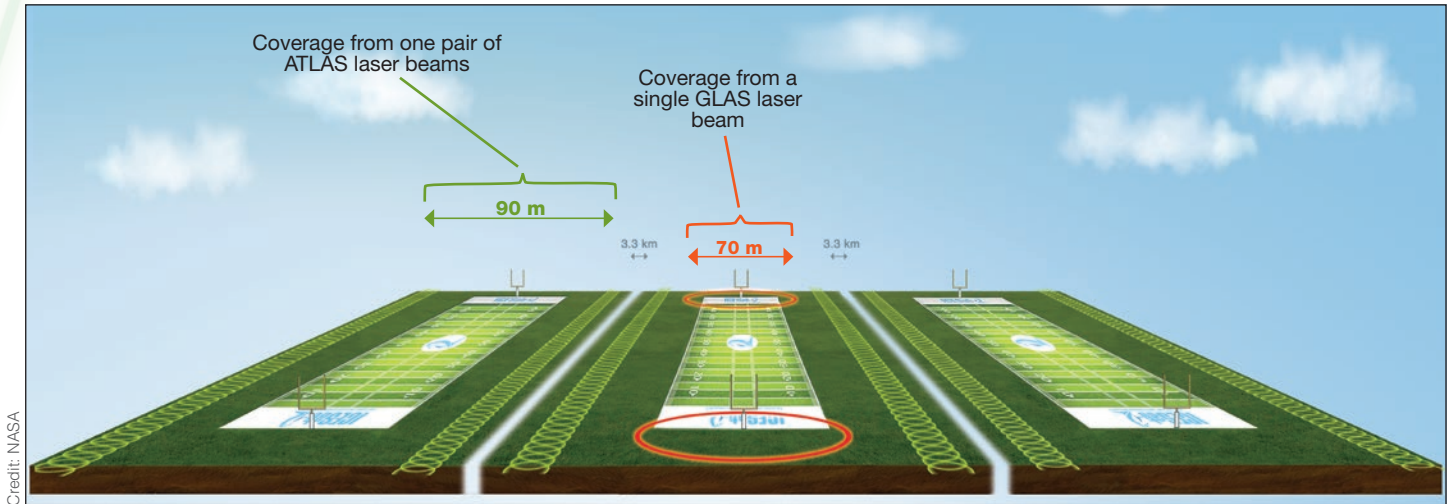
Photo credit: NASA

[Left] ICESat-2's laser beam has to make several turns as it travels through ATLAS, as seen in this illustrated image. Shown here, the pulses of light travel through a series of lenses and mirrors before beaming to the ground. This pathway along the optical bench serves to start the stopwatch on the timing mechanism, check the laser's wavelength, set the size of the ground footprint, ensure that the laser and the telescope are perfectly aligned, and split the laser into six beams, divided into three pairs.

Laser wavelength:
532 nanometers

Transmitted pulse width:
1.5 nanoseconds

Pulse repetition rate:
10 kilohertz



[Above] The high-frequency laser on ATLAS allows for nearly continuous coverage under its orbit. If it flew over a football field, the GLAS instrument on the first ICESat would have taken a measurement in each end zone (two red circles); ATLAS will take measurements within each yard line (green circles). ATLAS also creates a tighter footprint than GLAS did, providing more certainty of where on Earth's surface the photons are reflecting off of. And while GLAS had one laser beam, ATLAS will have three pairs of beams, or six beams total—which means at the same time two laser beams are collecting data on one field, the other two pairs of beams can gather data on two parallel football fields 2.1 miles (3.3 kilometers) apart.

before it leaves the satellite to check the aim. If it's not aligned, ATLAS can steer the laser to correct it.

The photons that return to the ATLAS telescope are focused on six fiber optic cables that correspond with where the six laser beams will return. From those fibers, the photons pass

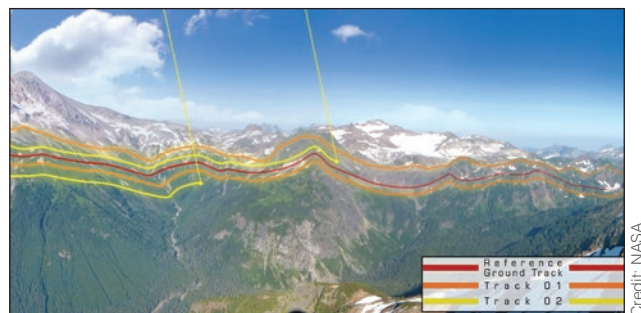
through a series of filters, which only let through light that is at precisely 532 nanometers. When an individual photon makes it through the filters, it triggers a detector and its time is recorded. ATLAS can measure the time of flight of a photon to within 800 picoseconds (0.000000008 seconds).

Slope Versus Elevation Change

Scientists analyzing data from the original ICESat mission were faced with a problem. As the satellite made multiple passes over an area, it was difficult to tell whether the ice had melted over time, or if the laser beam was simply pointed a bit off the path and down a hill. To be sure, they had to gather data on a particular site several times to first estimate the slope and then estimate ice loss.

ICESat-2 can determine the slope across the laser's path on a single pass. The updated satellite uses pairs of beams that straddle the reference ground track. Then, on subsequent passes, even if the two beams end up slightly upslope or downslope from where they were on the first pass, scientists can use the ground track to calculate elevation change.

[Right] This image depicts how one pair of laser beams will track on Earth as ICESat-2 passes overhead. The red line denotes the reference ground track, while the two orange lines represent ICESat-2's first pass and the two yellow lines represent beams from a later pass. Each time ATLAS collects data along a particular track, onboard software aims the laser beams so that the reference ground track is always between the two beams, as shown in the image at right. This allows scientists to combine the elevation and slope information from two different passes to determine elevation change along the same reference ground track.



Number of beams:
6 beams, organized in 3 pairs

Beam spacing (across track):
295 feet (90 m) within pairs, 2.1 miles (3.2 km) separating the pairs

Illuminated spot diameter:
< 57.4 feet (17.5 meters)

Telescope aperture diameter:
2.6 feet (0.8 meters)

The time-tagged data about each returned photon is communicated to the electronics and communication system on ICESat-2's spacecraft, before the data are sent to a ground station. Computer programs can use that travel time, laser pointing direction, and precise satellite position to determine the distance the photon traveled and the height of the surface. However, one data point isn't sufficient to determine

elevation with the required precision; therefore, hundreds of data points, averaged over different intervals, are needed.

The number of data points collected over a given area will determine how precise the elevation measurements will be for a particular area. With more data points collected, the data-analyzing software can better identify the surface. For example, over large areas such as the Greenland and Antarctic ice sheets, ICESat-2 will gather enough data points to estimate the annual elevation change within 0.16 inches (4 millimeters). Over smaller areas, such as glaciers, the elevation estimates are less precise, because there are fewer data points.



Photo credit: NASA

Ice Sheet

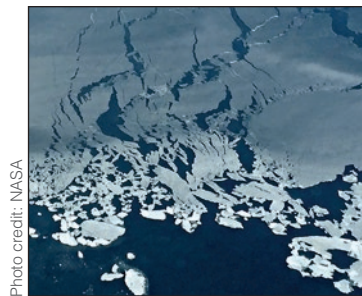


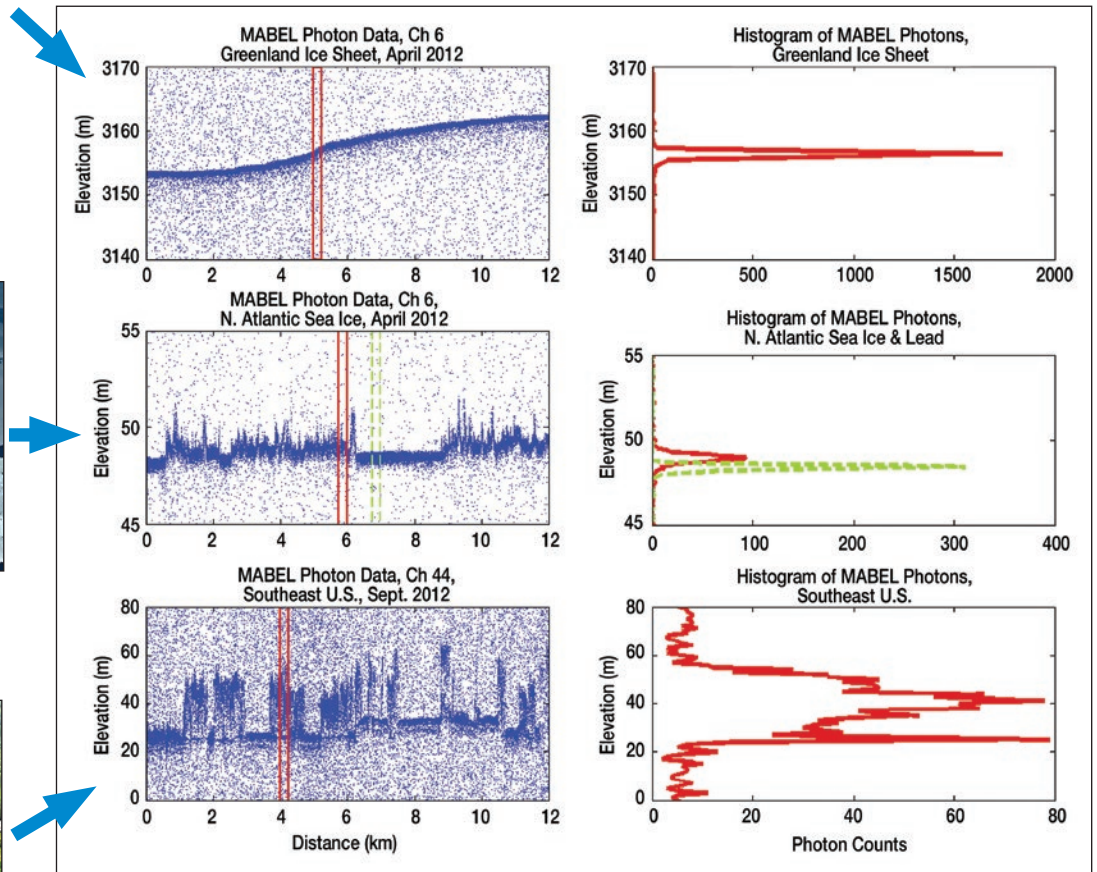
Photo credit: NASA

Sea Ice



Photo credit: Southeast Atmosphere Study

Forest



Credit: NASA

[Above] Scientists will analyze ICESat-2's data by plotting each photon that the satellite detects. Typical examples of these data plots, called *photon clouds*, are seen here for ice sheets [top], sea ice [middle], and vegetated areas [bottom]. For photon clouds over ice sheets, the surface can clearly be seen by the dense accumulation of photons. The "random" photons from all over the plot are indeed random and sporadic—these are photons from the sun that naturally bounce off Earth and make it to ICESat-2's telescope and past the filters. To extract the surface height of more varied terrain with great confidence, scientists use computer

programs to analyze the data. On the graphic's right-hand side are plots of the photon density (histograms) for the photons between the two red lines. Over sea ice, researchers will calculate the height of the ice itself (red lines) as well as for the adjacent open water (green lines), so that we can calculate the portion of the sea ice that is above sea level. The photon cloud is more diffuse when measuring vegetation, but from the histogram researchers can detect the crown of the tree as well as the ground surface, which is the narrow peak below the tree.

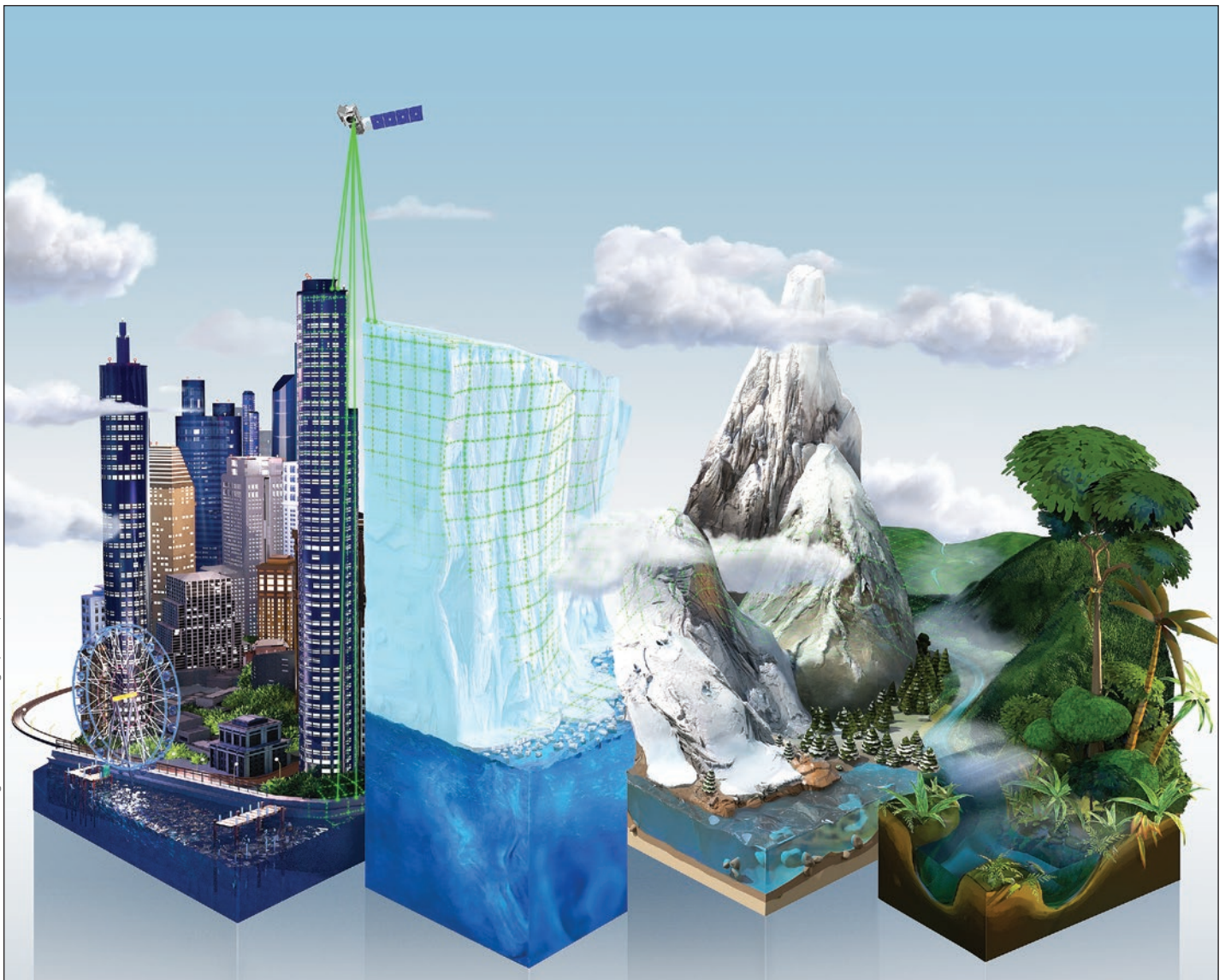
Receiver field of view diameter:
139 feet (42.5 meters)

Single photon time-of-flight precision:
800 picoseconds

While detecting a dozen or so returning photons for each laser pulse, ATLAS will also detect a significant number of background photons. These photons did not originate from ATLAS, but from reflected sunlight from Earth's surface. Some may have exactly the same wavelength as the laser and thereby are allowed to pass through the filters. To isolate

the laser photons from reflected photons, scientists will use computer programs to create photon cloud graphs, showing thousands of data points. By applying additional computer programs, which identify stronger signals within the photon cloud graphs, scientists can determine the elevation of Earth's ice, land, water, and vegetation.

ICESat-2's laser instrument will measure the elevation of ice sheets, glaciers, sea ice, vegetation, fresh water, the ocean, and land surfaces in unprecedented detail.



credit: ICESat-2/Savannah College of Art and Design (SCAD) collaboration

Algorithm and Data Product Development

Before ICESat-2 ever reaches orbit, scientists conduct airborne campaigns to learn how to interpret the satellite data of ice sheets, glaciers, and sea ice.



[Above] A laser instrument was flown aboard NASA's ER-2 plane in multiple campaigns to simulate the type of data collected by ICESat-2.

Once data start streaming down from ICESat-2, scientists want to be ready to analyze the information. Before launch, the mission developed the computer programs that will analyze and interpret the elevation data points from the satellite, with the help of airborne campaigns that fly similar instruments that gather similar types of data. In order to do so, they conducted multiple airborne campaigns with similar instruments to figure out how to interpret elevation data from the satellite.

The Multiple Altimeter Beam Experimental Lidar (MABEL) instrument has been flown on

three scientific campaigns to test the photon-counting system used by ATLAS on ICESat-2. Each MABEL campaign was designed to gather data that scientists could use to develop computer programs, called *algorithms*, that analyze ICESat-2 measurements over different surface types.

In 2012, the instrument was flown over Greenland to observe ice sheets and glaciers, as well as the adjacent sea ice. The flights over the Arctic Ocean on that campaign allowed researchers to demonstrate that they can measure the height difference between open water and sea ice.

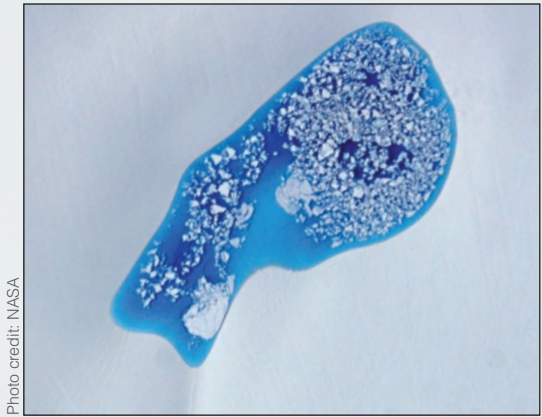


Photo credit: NASA

[Above] On its July 2014 campaign in Alaska, MABEL measured melt ponds to better understand how the ICESat-2 data would look over ice, water, and the shallow pools.

In 2013, MABEL flew over forests in the mid-Atlantic United States to gather height data from the tops of trees and the forest

floor. Forestry researchers can use this dataset to estimate the amount of plant matter. Flights also took MABEL over the Chesapeake Bay to take measurements over water, since the mission will provide data on ocean heights.

MABEL flew out of Fairbanks, Alaska in July 2014 to gather data over melting snow and sea ice. In the summers, *melt ponds*—regions of melted ice and snow pooled on glaciers or ice floes—are a key feature in many Arctic landscapes. Researchers wanted to understand how the photons would interact with the water bodies. The campaign also flew several routes over land flown by another laser instrument—Goddard’s Lidar, Hyperspectral and Thermal (G-LiHT) instrument—to compare the measurements.

On the Ice at the South Pole

It was an extremely cold road trip. For 15 days starting in late December 2017, two ICESat-2 scientists, a mechanic and a mountaineer drove tank-like snow machines called PistenBullys in an arc around the South Pole. Their goal—to take precise GPS elevation measurements at 88 degrees south, the latitude at which the ICESat-2 orbits converge. By comparing these elevation measurements with those collected by ICESat-2 in orbit, the mission scientists can assess the satellite’s accuracy. The Antarctic traverse is part of a larger ground validation and calibration campaign, in which scientists will use instruments on other spacecraft, on airplanes, and on the ground to check ICESat-2’s data.

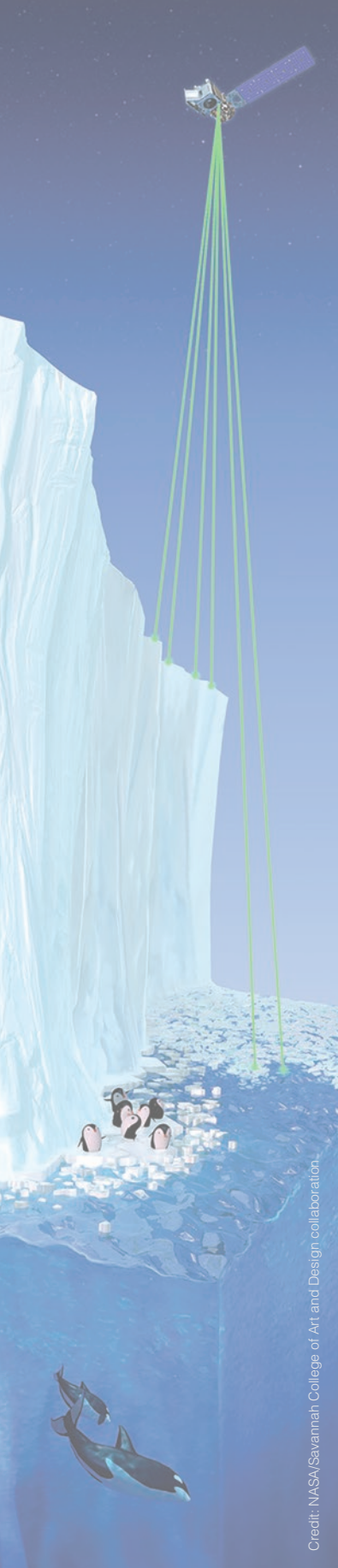


Photo credit: Chad Seay

[Above] Two tracked vehicles pulled the living quarters and equipment across 466 miles (750 kilometers) of Antarctic ice, as part of a campaign to assess the accuracy of ICESat-2.

Photo credit: Alec Petty/NASA

Spacecraft Design and Launch



Credit: NASA/Savannah College of Art and Design collaboration.



Photo credit: USAF 30th Space Wing/Vanessa Valentine

[Above] ICESat-2 is uncrated inside the airlock of the Astrotech processing facility on June 13, 2018, at Vandenberg Air Force Base in California. The satellite was shipped from the Northrop Grumman facility in Gilbert, Arizona, where the instrument was integrated with the spacecraft and tested.

ICESat-2's instrument, ATLAS, is the first of its kind flown in space—but the spacecraft that controls it and the rocket that launches it are tried and true machines. The spacecraft, which was built by Northrop Grumman, has a pedigree that includes the Landsat 4, 5 and 8 satellites, the planetary explorer Dawn spacecraft, and the Fermi Gamma-Ray Observatory. The rocket, United Launch Alliance's Delta II, has launched more than 150 payloads—and ICESat-2 will be its final launch.

The LEOStar-3 spacecraft bus provides power and orbit control for ATLAS, as well as propul-

sion, navigation, attitude control, thermal control, data storage and handling, ground communication and more.

Four solar panels will deploy after the launch to power the craft and the instrument, producing an average of 3,800 watts. The panels will charge the spacecraft's lithium ion battery.

The spacecraft has an onboard data recorder that will store more than the 580 gigabits of data per day that's collected by the instrument and sent back to Earth. An X-band downlink system can transmit 220 megabits per second.

Altitude
310 miles (~500 kilometers)

Inclination
92° (coverage up to 88° N & S)

Speed
15,660 miles/hour
(7 kilometers/second)

Orbit duration
90 minutes

The assembled and tested ICESat-2 satellite will launch from Vandenberg Air Force Base in California, aboard United Launch Alliance's Delta II rocket. It is the last Delta II rocket, which has launched more than 50 NASA science missions.

The launch of ICESat-2 will be followed by a 60-day check-out period, where the spacecraft and instrument will be tested to ensure everything is functioning as it should.

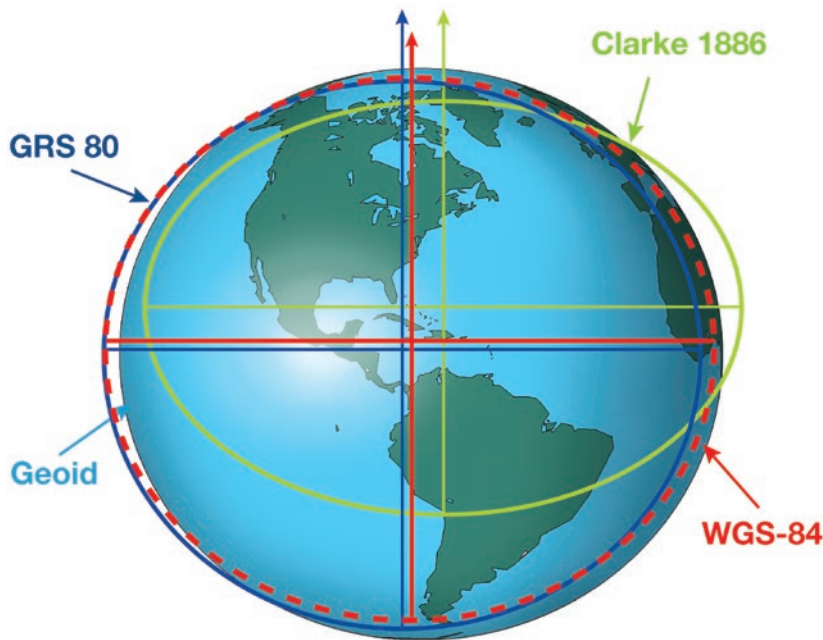
Where in Space is ICESat-2?

ICESat-2's spacecraft and its ground-based computer programs are designed with strict specifications so scientists can know

precisely where on the planet's surface the instrument is taking measurements.

It is also critical to know where in space the satellite is positioned.

To achieve this, the spacecraft has a global positioning system (GPS) on-board, a star tracker, and a very specific center-of-gravity knowledge. Scientists will conduct ground calibration studies and analysis to refine the positioning even further. Knowing the spacecraft's altitude is key, since the instrument measures the distance from itself to the ground; if the laser and receiver are higher or lower than expected, the Earth elevation measurements will be off.



Credit: NASA (source NOAA)

[Above] Unlike traditional elevation measurements that use global mean sea level as a reference point (which changes as sea level goes up and down), ICESat-2 will reference its elevation measurements to an idealized shape, called an *ellipsoid*, to represent Earth's surface. There are many different kinds of ellipsoids, but ICESat-2 will use the WGS-84—the same one that United States global positioning system (GPS) uses.



Photo credit: NASA

| | | | |
|------------------------------------|--|---|---|
| Orbit repeats every 91 days | Design life: 3 years Fuel life: 7 years | Size: 8.1 feet x 6.1 feet x 12.5 feet (2.5 meters x 1.9 meters x 3.8 meters) | Mass 3,338 pounds (1514 kilograms) with propellant |
|------------------------------------|--|---|---|

Ground System and Data Products

The ICESat-2 mission ground system includes all of the assets needed to operate the satellite in orbit, as well as manage and distribute the data collected by the ATLAS instrument.

The spacecraft and instrument, together called the observatory, are controlled from the Mission Operations Center at Northrop Grumman in Dulles, Virginia. The Mission Operations Center will send software commands to ICESat-2 through the ground stations in Svalbard, Norway, and Poker Flat, Alaska.

The ATLAS instrument is monitored by the Instrument Support Facility at NASA's Goddard Space Flight Center.

ICESat-2 will transmit its science data through an X-band downlink to a station in Svalbard, Poker Flat, or Wallops Island, Virginia. The raw data is sent to Goddard where the data products are generated. A terabyte a day of these products is sent to the National Snow and Ice Data Center in Boulder, Colorado. From the National Snow and Ice Data Center, the data products will be distributed, free of charge, to the public.

Data will be available for download from nsidc.org.

| ICESat-2 Data Products | | |
|------------------------|------------------------------------|--|
| ATL00 | Telemetry Data | Raw ATLAS telemetry in packet format. |
| ATL01 | Reformatted Telemetry | Parsed, partially reformatted into HDF5, generated daily, segmented into several minute granules. |
| ATL02 | Science Unit Converted Telemetry | Photon time of flight, corrected for instrument effects. Includes all photons, pointing data, spacecraft position, housekeeping data, engineering data, and raw atmospheric profiles, segmented into several minute granules. |
| ATL03 | Global Geolocated Photon Data | Precise latitude, longitude and elevation for every received photon, arranged by beam in the along-track direction. Photons classified by signal vs. background, as well as by surface type (land ice, sea ice, land, ocean), including all geophysical corrections (e.g. Earth tides, atmospheric delay, etc.), segmented into several minute granules. |
| ATL04 | Uncalibrated Backscatter Profiles | Along-track atmospheric backscatter data, 25 times per second. Includes calibration coefficients for polar regions, segmented into several minute granules. |
| ATL06 | Land Ice Elevation | Surface height for each beam with along- and across-track slopes calculated for each beam pair. Posted at 40 meter along-track, segmented into several minute granules. |
| ATL07 | Arctic/Antarctic Sea Ice Elevation | Height of sea ice and open water leads at varying length scale based on returned photon rate for each beam presented along-track. |

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| ICESat-2 Data Products | | |
|-------------------------------|---|---|
| ATL08 | Land and Vegetation Height | Height of ground including canopy surface posted at variable length scales relative to signal level, for each beam presented along-track. Where data permits include canopy height, canopy cover percentage, surface slope and roughness, and apparent reflectance. |
| ATL09 | Calibrated Backscatter and Cloud Characteristics | Along-track cloud and other significant atmosphere layer heights, blowing snow, integrated backscatter, and optical depth. |
| ATL10 | Arctic/Antarctic Sea Ice Freeboard | Estimate of sea ice freeboard over specific spatial scales using all available sea surface height measurements. Contains statistics of sea surface and sea ice heights. |
| ATL11 | Antarctica/Greenland Ice Sheet H(t) Series | Time series of height at points on the ice sheet, calculated based on repeat tracks and/or crossovers. |
| ATL12 | Ocean Elevation | Surface height at specific length scale. Where data permit, include estimates of height distribution, roughness, surface slope, and apparent reflectance. |
| ATL13 | Inland Water Height | Along-track inland and near shore water surface height distribution within water mask. Where data permit, include roughness, slope and aspect. |
| ATL14 | Antarctica/Greenland Ice Sheet H(t) Gridded | Height maps of each ice sheet for each year based on all available elevation data. |
| ATL15 | Antarctic/Greenland Ice Sheet dh/dt Gridded | Height change maps for each ice sheet, for each mission year, and for the whole mission. |
| ATL16 | ATLAS Atmosphere Weekly | Polar cloud fraction, blowing snow frequency, ground detection frequency. |
| ATL17 | ATLAS Atmosphere Monthly | Polar cloud fraction, blowing snow frequency, ground detection frequency. |
| ATL18 | Land/Canopy Gridded | Gridded ground surface height, canopy height, and canopy cover estimates. |
| ATL19 | Mean Sea Surface | Gridded ocean height product. |
| ATL20 | Arctic/Antarctic Gridded Sea Ice Freeboard | Gridded sea ice freeboard. |
| ATL21 | Arctic/Antarctic Gridded Sea Surface Height w/in Sea Ice | Gridded monthly sea surface height inside the sea ice cover. |

ICESat-2 Science Requirements

To meet ICESat-2's four science objectives, the mission has seven requirements that drive the technical design of its instrument:

1. An ice surface elevation product that enables determination of ice-sheet elevation change rates to an accuracy of less than or equal to 0.4 centimeters per year on an annual basis.
2. An ice surface elevation product that enables determination of annual surface elevation change rates on outlet glaciers to an accuracy of less than or equal to 0.25 meters per year over areas of 100 square kilometers for year-to-year averages.
3. An ice surface elevation product that enables determination of surface elevation change rates for dynamic ice features that are intersected by its set of repeated ground-tracks to an accuracy of less than or equal to 0.4 meters per year along 1-kilometer track segments.
4. An ice surface elevation product that enables resolution of winter (accumulation) and summer (ablation) ice-sheet elevation change to 10 centimeters at 25-kilometer x 25-kilometer spatial scales.
5. Monthly surface elevation products to enable, when sea surface height references (leads) are available and under clear sky conditions, the determination of sea-ice freeboard to an uncertainty of less than or equal to 3 centimeters along 25-kilometer segments for the Arctic and Southern Ocean; the track spacing should be less than or equal to 35 kilometers at 70 degrees latitude on a monthly basis.
6. Elevation measurements that enable independent determination of global vegetation height, with a ground track spacing of less than 2 kilometers over a 2-year period.
7. A calibration and validation campaign to verify that the data meet the above requirements.