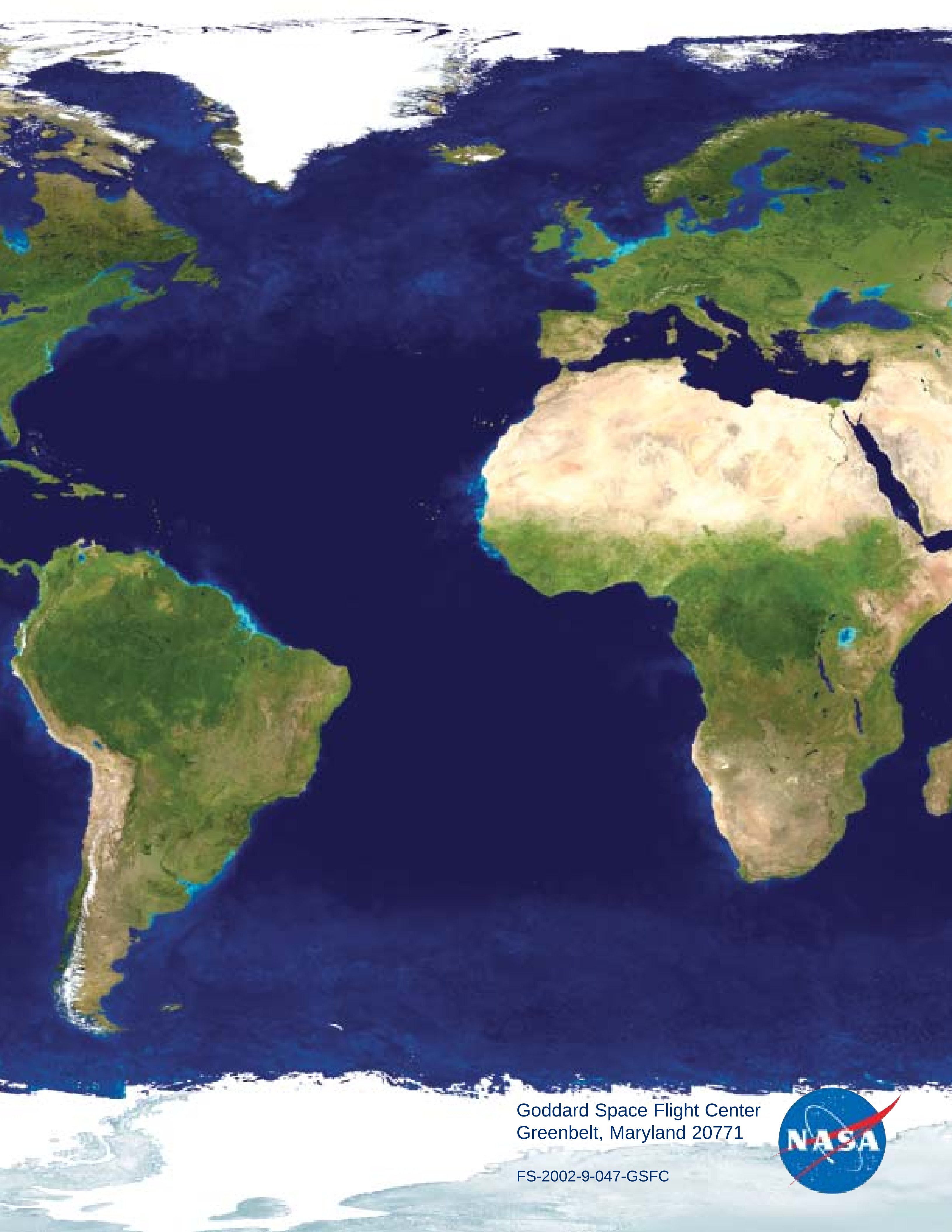

ICE, CLOUD, & LAND ELEVATION SATELLITE
ICESAT
CLIMATE ←→ POLAR ICE → SEA LEVEL
NASA
CLOUDS & AEROSOLS ←→ CLIMATE



Goddard Space Flight Center
Greenbelt, Maryland 20771

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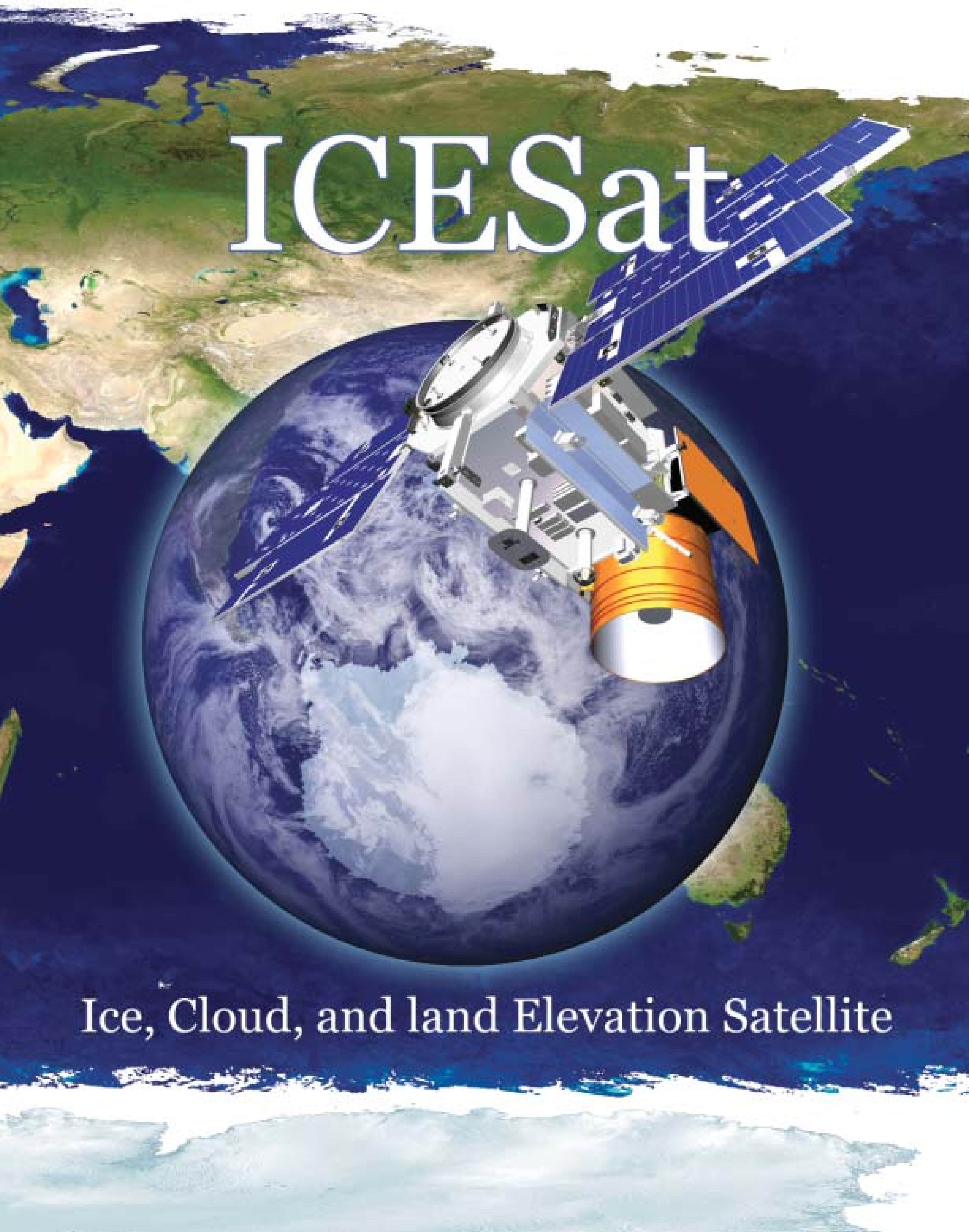


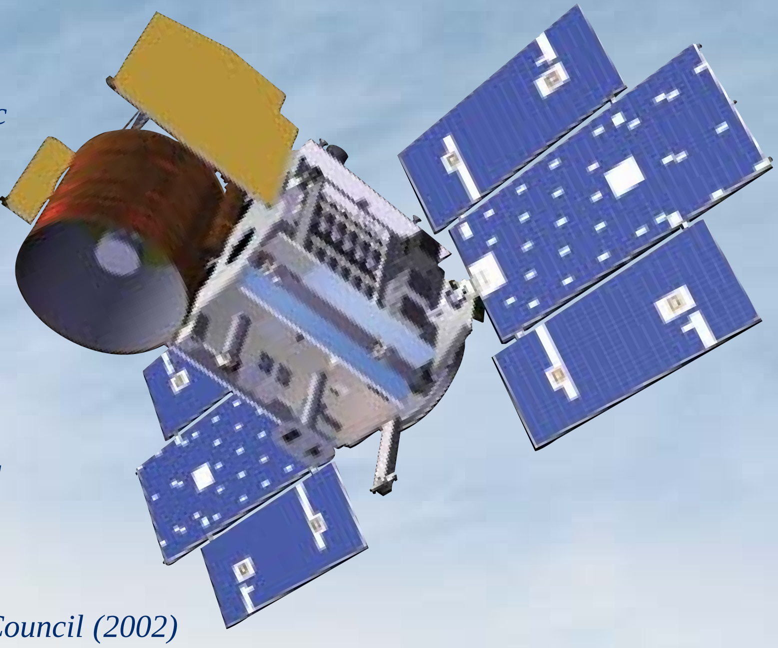
ICESat

Ice, Cloud, and land Elevation Satellite

The Geoscience Laser Altimeter System (GLAS) on the Ice, Cloud, and land Elevation Satellite (ICESat) spacecraft immediately following its initial mechanical integration on June 18th, 2002. Note that ICESat's solar arrays have not yet been attached. Left – Gordon Casto, NASA/GSFC. Right – John Bishop, Mantech. Courtesy of Ball Aerospace & Technologies Corp.

“Possible changes in the mass balance of the Antarctic and Greenland ice sheets are fundamental gaps in our understanding and are crucial to the quantification and refinement of sea-level forecasts.”

—Sea-Level Change report, National Research Council (1990)



“In light of…abrupt ice-sheet changes affecting global climate and sea level, enhanced emphasis on ice-sheet characterization over time is essential.”

—Abrupt Climate Change report, National Research Council (2002)

MISSION INTRODUCTION AND SCIENTIFIC RATIONALE

Ice, Cloud and land Elevation Satellite (ICESat)

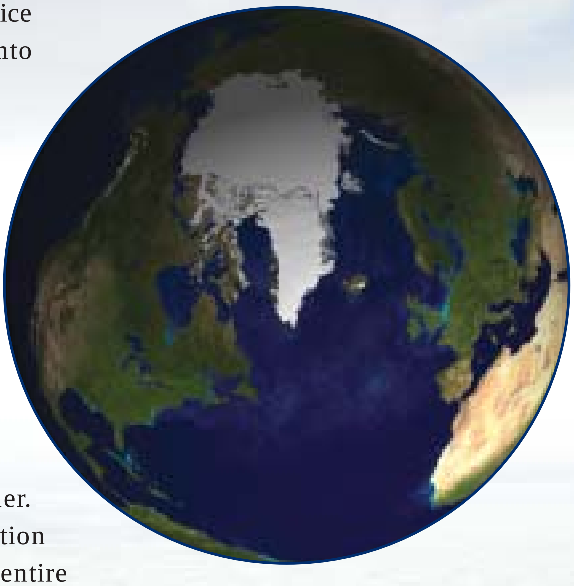
Are the ice sheets that still blanket the Earth’s poles growing or shrinking? Will global sea level rise or fall? NASA’s Earth Science Enterprise (ESE) has developed the ICESat mission to provide answers to these and other questions — to help fulfill NASA’s mission to understand and protect our home planet. The primary goal of ICESat is to quantify ice sheet mass balance and understand how changes in the Earth's atmosphere and climate affect the polar ice masses and global sea level. ICESat will also measure global distributions of clouds and aerosols for studies of their effects on atmospheric processes and global change, as well as land topography, sea ice, and vegetation cover.

Ice sheets are complex and dynamic elements of our climate system. Their evolution has strongly influenced sea level in the past and currently influences the global sea level rise that threatens our coasts. Ice streams that speed up, slow down, and change course illustrate their dynamic nature. Atmospheric factors cause snowfall to vary in space and time across their surfaces. In Antarctica, small ice shelves continue to retreat along the Antarctic Peninsula, and large icebergs are released from the largest ice shelves. In Greenland, the ice sheet margins are thinning and the inland parts of the ice sheet appear to be thickening. Surface meltwater seeps into the ice sheets and accelerates their flow. Some of the factors controlling the mass balance of the ice sheets, and their present and future influences on sea level, are just beginning to be understood.

The ICESat mission, part of NASA’s Earth Observing System (EOS), is scheduled to launch in December 2002. The Geoscience Laser Altimeter System (GLAS) on ICESat will measure ice sheet elevations, changes in elevation through time, height profiles of clouds and aerosols, land elevations and vegetation cover, and approximate sea ice thickness. Future ICESat missions will extend and improve assessments from the first mission, as well as monitor ongoing changes. Together with other aspects of NASA’s ESE and current and planned EOS satellites, ICESat will enable scientists to study the Earth’s climate and, ultimately, predict how ice sheets and sea level will respond to future climate change.

Are The Greenland And Antarctic Ice Sheets Growing Or Shrinking?

Courtesy of Robert Simmon



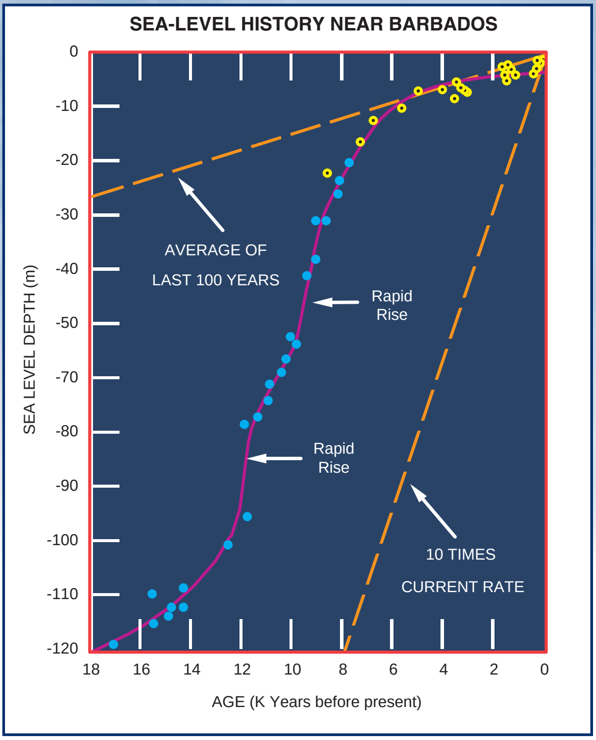
This question lies at the heart of NASA's rationale for the ICESat mission. The Greenland and Antarctic ice sheets are an average of 2.4 km (7900 ft) thick, cover 10 percent of the Earth's land area, and contain 77 percent of the Earth's fresh water (33 million km^3 or 8 million mi^3). The Antarctic ice sheet has 10 times more ice than Greenland because of its greater area and average ice thickness. If their collective stored water volume were released into the ocean, global sea level would rise by about 80 m (260 ft). A small change of only 0.1% (2.4 m or 7.9 ft) in the average thickness of the ice sheets would cause a change in global sea level of 8.3 cm (3.3 in). Their vast size and inhospitable environment make the ice sheets impossible to monitor completely except via satellite.

Presently, new ice accumulates on the ice sheets at about 17 cm (7 in) per year averaged over Antarctica and 28 cm (11 in) per year averaged over Greenland. Although most of the Antarctic ice sheet has net ice accumulation, about 9% of Greenland has a net ice loss of 1.4 m due to melting in the summer. Together, the volume of water required for this annual accumulation of ice is equal to the removal of 0.8 cm (0.3 in) of water from the entire surface of the Earth's oceans. Approximately the same amount of water is returned to the oceans by melting of ice and snow, by ice flow into the floating ice shelves, and the direct discharge of icebergs. However, the exact amounts being gained or lost vary significantly from region to region as well as through time. The difference between the total mass input and total mass output (called the mass balance) is important because it might be as much as ± 20% of the mass input, which is equivalent to a sea level rise or fall of 0.16 cm (0.06 in) per year.

ICESat is designed to detect changes in ice sheet surface elevation as small as 1.5 cm (0.6 in) per year over areas of 100 km by 100 km (62 mi by 62 mi). Changes in ice sheet thickness are calculated from elevation changes by correcting for small vertical motions of the underlying bedrock. Ice thickness changes will enable scientists to assess the ice behavior within individual ice drainage basins and major outlet glaciers, as well as the entire ice sheets. Detection of average thickness changes as small as 0.3 cm (0.12 in) per year over Greenland and Antarctica will reduce the uncertainty in their contribution to sea level change to ± 0.1 cm (0.04 in) every 10 years. Elevation time-series constructed from ICESat's continuous observations throughout its 3 to 5 year mission will detect seasonal and interannual changes in the mass balance, caused by short-term changes in ice accumulation and surface melting, as well as the long-term trends in the net balance between the surface processes and the ice flow.

How Fast Is Sea Level Rising?

Fifteen thousand years ago, vast ice sheets covered much of North America and parts of Eurasia. In Antarctica, the ice sheet reached to the edge of the continental shelf, as much as 200 km (125 mi) farther out to sea than today. As the climate warmed during the end of the last Ice Age, much of the Earth's ice cover melted. Global sea level rose rapidly by almost 100 m (330 ft) between 14,000 and 6,000 years ago. Although the average rise was about 1.25 cm per year (0.5 in), the total rise caused dramatic changes to coastlines around the world.



Published data on sea level rise with time (Fairbanks, 1989). Current sea level rise is about 2 cm per decade.

The Antarctic and Greenland ice sheets, which are the most significant remnants of that period, are currently reacting to present and past climate changes. Global sea level is believed to be rising about 2 cm (0.8 in) every 10 years, less rapidly than at the end of the ice age, but still significant. About 25% of the present rise is caused by thermal expansion as the oceans warm, and about 25% by the melting of small glaciers around the world. The remainder could be due to ice loss from Greenland and Antarctica, but our uncertainty of their actual contributions (plus or minus) is as large as the total rise in recent decades. Sea level rise is also affected by human activities such as pumping of ground water, filling of reservoirs, deforestation and biomass burning, and draining of wetlands. Although sea level changes are small in any given year, sea level increases over the last 50 to 100 years have seriously impacted low-lying coastal regions through shoreline retreat, storm erosion, and coastal flooding. Future changes associated with climate warming may cause an even greater threat to our populous coastal environments.

Of particular concern is the "marine" ice sheet in West Antarctica, much of which is grounded on bedrock and sediment 1500 m (4900 ft) below sea level. The three main components are: 1) interior ice that flows relatively slowly (10 m or 33 ft per year); 2) the fast-moving ice streams that flow a hundred times faster; and 3) the floating ice shelves through which most of the ice enters the ocean. Some researchers believe that if West Antarctica's ice shelves thinned significantly, they would no longer restrain the rate of ice discharge from the ice streams. ICESat's multi-year elevation-change data, combined with other remote sensing data, as well as atmospheric, oceanic, and ice flow models, should enable more accurate predictions of ice-sheet changes.

Examples of coastal erosion along the eastern seaboard of the United States following storms.

Will The Ice Sheets Thin Or Thicken In A Warmer Climate?

Increased warmth will melt more ice near the edges of the ice sheets. However, a warmer atmosphere holds more moisture, leading to more precipitation over the ice sheets and more ice accumulation. Changes in atmospheric circulation may also change the frequency of storms and the transport of moisture onto the ice sheets. A warmer climate should alter the area and thickness of sea ice surrounding the ice sheets, and thereby shorten or lengthen the moisture pathway for snowfall. Other important processes include redistribution of new snow by wind and sublimation from the ice sheet surface.

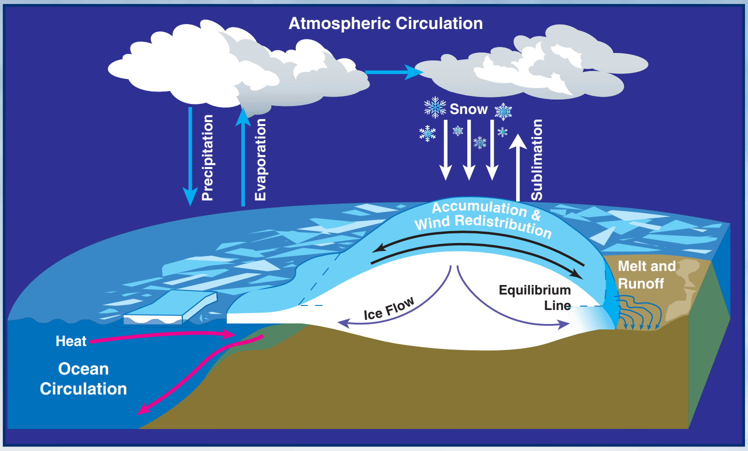


Illustration of key climate variables influencing ice sheet mass balance. Graphic by Deborah McLean.

Surface melt water ponds on the western flank of the Greenland ice sheet. Courtesy of Konrad Steffen.

Atmospheric interactions with the ice sheets have immediate effects on the ice sheet mass balance at the surface and therefore cause year-to-year effects on both the amount of water stored and global sea level. In contrast, the rate of ice flow tends to respond slowly to climate change, over centuries or longer, as temperature and other effects slowly propagate deep into the ice. However, the recent discovery of accelerations in ice flow during periods of increased summer melting in Greenland demonstrates a rapid dynamic response of the ice to climate change. Similarly in Antarctica, increases in surface and basal melting on ice shelves causes them to thin, which may lead to an acceleration of grounded ice discharge from the interior.

At present, we do not know which effect will have more impact on the overall ice sheet mass - increased melting and ice thinning at the edges or increased snowfall and ice accumulation over the entire ice sheet surface. The net change in mass input (snowfall) minus output (melting and icebergs) in the coming decades could be as much as -10 % to +10 % for each degree Celsius of climate warming, resulting in a change of -0.8 to +0.8 cm (-0.3 to +0.3 in) in global sea level per decade for each 1° C of temperature change. Over centuries, the interaction of climate with the ice flow could amplify the changes.

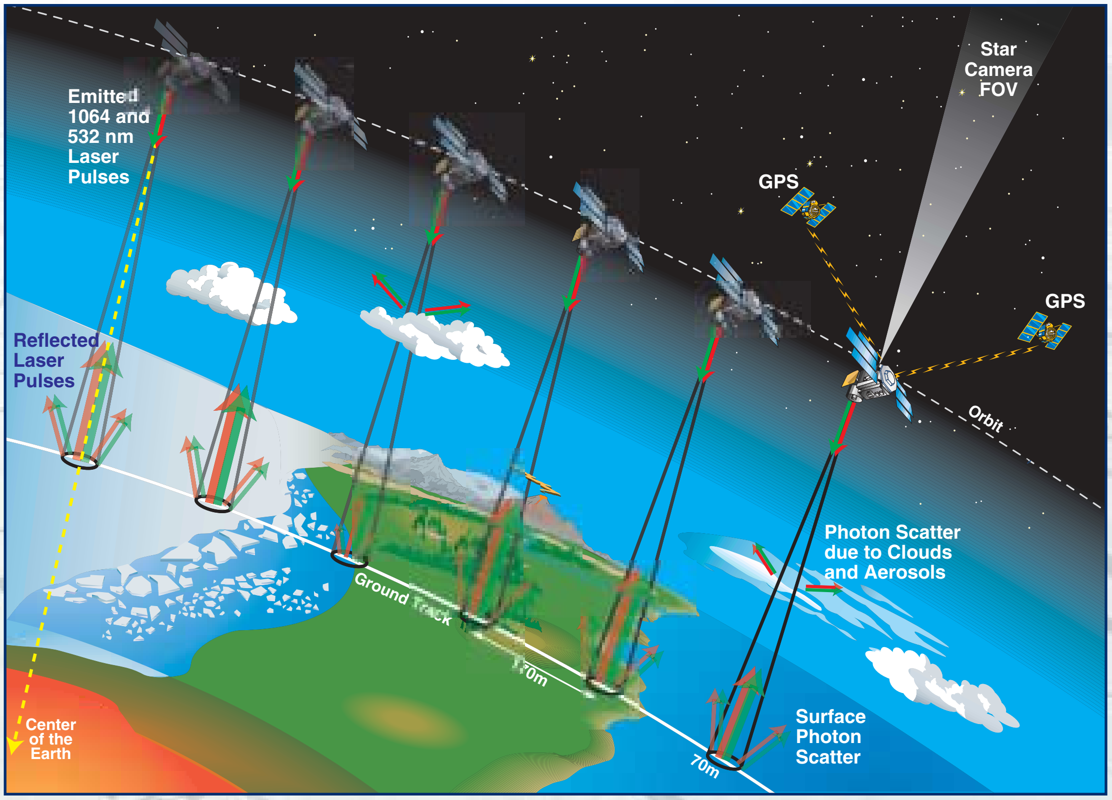
ICESat will measure seasonal and interannual variations in ice sheet elevations caused mainly by snowfall and surface melting, as well as enable estimates of the long-term trend in the overall mass balance. Scientists will use these data to answer questions such as which variables (e.g. temperature or precipitation) exert control on the ice sheet mass balance, and whether the observed ice changes are caused by recent or long-term changes in climate. These studies combined with ice models will be used to predict future changes in ice volume that would be linked to climate change.

OPERATIONAL OVERVIEW

How Will ICESat Measure Earth's Ice, Clouds, Oceans, Land, and Vegetation?

The GLAS instrument on ICESat will determine the distance from the satellite to the Earth's surface and to intervening clouds and aerosols. It will do this by precisely measuring the time it takes for a short pulse of laser light to travel to the reflecting object and return to the satellite. Although surveyors routinely use laser methods, the challenge for ICESat is to perform the measurement 40 times a second from a platform moving 26,000 km (16,000 mi) per hour. In addition, ICESat will be 600 km above the Earth and the precise locations of the satellite in space and the laser beam on the surface below must be determined at the same time.

The GLAS instrument on ICESat will measure precisely how long it takes for photons from a laser to pass through the atmosphere, reflect off the surface or clouds, return through the atmosphere, collect in the GLAS telescope, and trigger photon detectors. After halving the total travel time and applying corrections for the speed of light through the atmosphere, the distance from ICESat to the laser footprint on Earth's surface will be known. When each pulse is fired, ICESat will collect data for calculating exactly where it is in space using GPS (Global Positioning System) receivers. The angle at which the laser beam points relative to stars and the center of the Earth will be measured precisely with a star-tracking camera that is integral to GLAS. The data on the distance to the laser footprint on the surface, the position of the satellite in space, and the pointing of the laser are all combined to calculate the elevation and position of each point measurement on the Earth.



Schematic illustration of the GLAS instrument making measurement from ICESat while orbiting the Earth. Graphic by Deborah McLean.

GLAS measures continuously along ground tracks defined by the sequence of laser spots as ICESat orbits the Earth. The GLAS laser pulses are emitted at a rate of 40 per second from the Earth-facing (nadir) side of ICESat. This produces a series of approximately 70 m (230 ft) diameter spots on the surface that are separated by nearly 170 m (560 ft) along track. These tracks will be repeated every 8 days during the initial calibration-validation phase of the mission and every 183 days during the main portion of ICESat's multi-year mission. Points on the Earth where these ground tracks intersect are called crossovers. Crossovers increase in areal density near the North and South Poles. Over the ice sheets, the ICESat spacecraft will be controlled to point the laser beam precisely toward the same repeat ground tracks to within ± 35 m. Therefore, elevation changes can be analyzed along repeat ground tracks as well as at orbital crossover points. In addition, ICESat has the ability to point GLAS off-nadir to repeatedly measure areas of interest such as an erupting volcano or a collapsing ice shelf.

ICESat will also provide detailed information on the global distribution of clouds and aerosols. To do this, GLAS emits laser energy at both 1064 nm and 532 nm, as this allows co-located elevation and atmospheric data to be obtained simultaneously. This will aid precise determination of the distance between ICESat and the Earth, as it is important to know if the laser pulses have traveled through cloud and aerosol layers. If present, these phenomena will diffuse the laser energy and extend the distance the laser light photons travel by scattering.

Although ICESat's data on ice sheet surface elevations is of primary importance, land and ocean elevation data will be obtained around the globe along ICESat's ground tracks. Data on elevation changes of the world's oceans and ice-free landforms is expected to be of great interest to the broader scientific community. The recently launched GRACE satellite will enhance the ICESat mission by mapping the Earth's gravitational field in unprecedented detail. The GRACE data, in conjunction with ICESat results will enable a greater understanding of any changes in the distribution of snow, ice, and water mass around the globe.

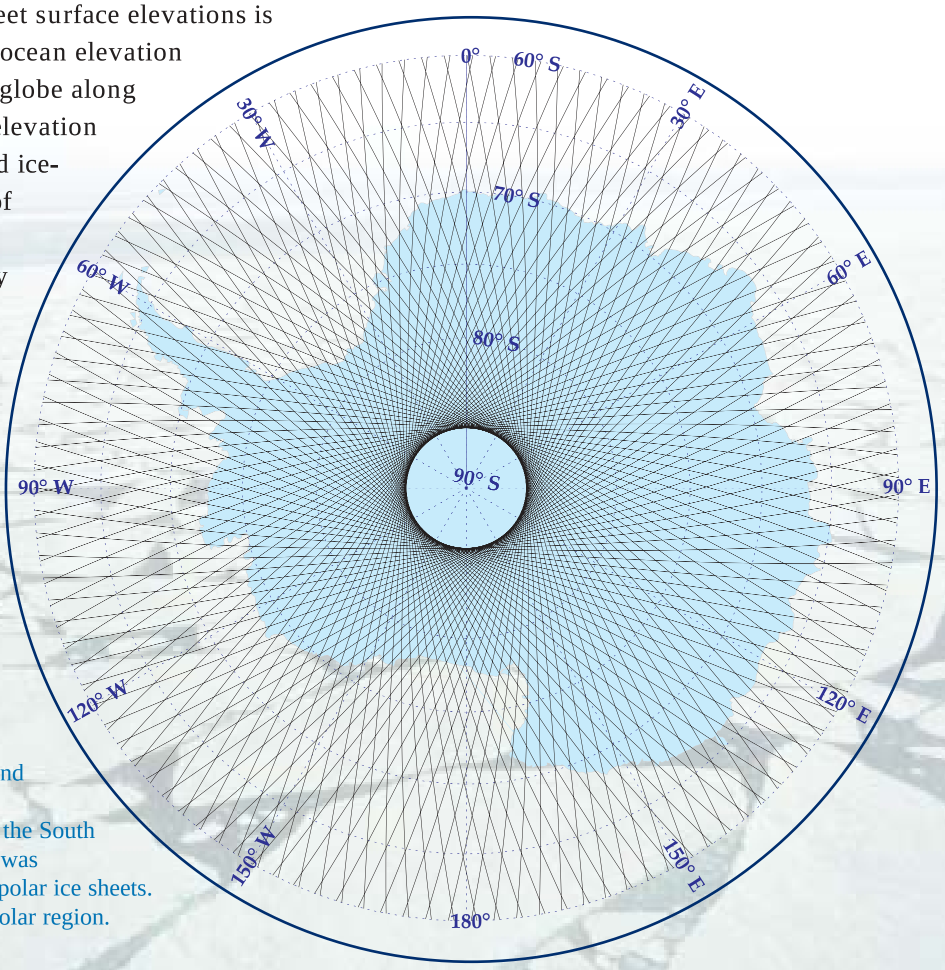


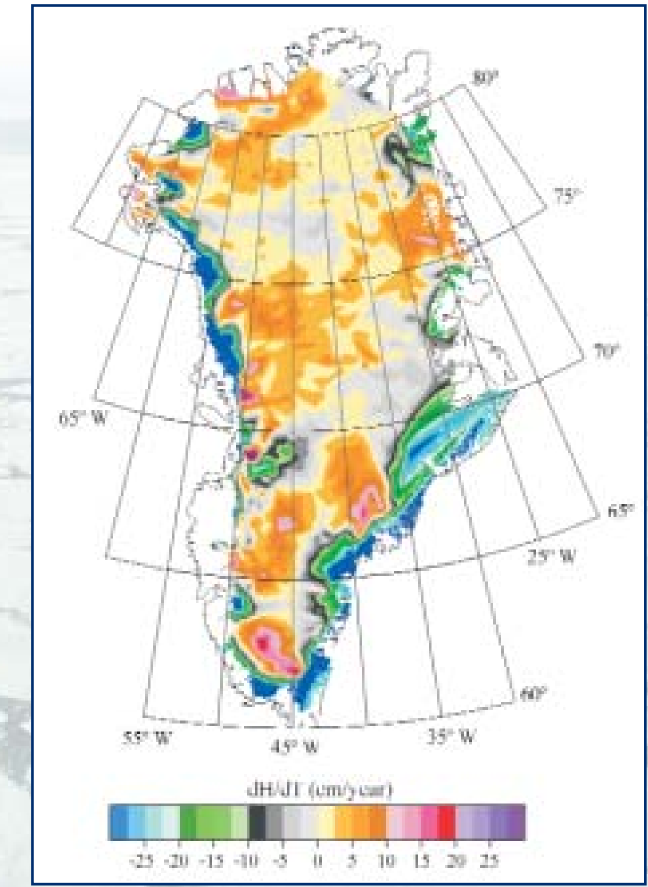
Illustration of ICESat's 8 day repeat ground track relative to the continental area of Antarctica. Note the convergence around the South Pole of the ground tracks. ICESat's orbit was designed to maximize coverage over the polar ice sheets. The pattern is similar over the northern polar region. Courtesy of Bob Schutz.

Rapid Thinning Of Greenland's Coastal Ice

After Antarctica, Greenland's ice sheet contains the second largest mass of frozen fresh water on Earth. The island of Greenland covers 2,175,000 square kilometers (840,000 square miles) and 85 percent is covered by ice up to 3370 m (11,050 ft) thick. With its southern tip protruding into temperate latitudes, it is more sensitive than Antarctica to climate changes experienced in the major population centers of Europe and North America. In contrast to the Antarctic ice sheet, for which most of the surface remains below the freezing point even in summer, 85% of the Greenland ice sheet has melting on the surface during summer. In the zone of net ablation below about 1200 m, all the winter snow plus several meters of ice melts each year. Therefore, the mass balance of the Greenland ice sheet is very sensitive to changes in temperature and melting, as well as to changes in accumulating snowfall.

A NASA study of Greenland's ice sheet during the 1990s revealed rapid thinning at its margins, but also some thickening across portions of the interior. A NASA aircraft flew a network of flight lines with a laser altimeter and global positioning satellite receivers in 1993 and 1994 and re-surveyed the lines in 1998 and 1999. From these data, scientists reported that the ice sheet has thinned by more than 1 m (3 ft) per year on many coastal outlet glaciers and by as much as 9 m (30 ft) per year in a few areas. Scientists estimated a net loss of approximately 50 cubic kilometers (12 cubic miles) of ice per year from the entire ice sheet during the 1990s. This volume is sufficient to raise global sea level by 0.13 mm (0.005 inches) per year, or about seven percent of the observed rate of rise in recent decades.

Explaining these observations and the ice and climate processes causing them is the subject of ongoing study by the Program for Arctic Regional Climate Assessment (PARCA). This joint effort by NASA and affiliated scientists consists of combined remote sensing, fieldwork, and modeling studies on the Greenland Ice Sheet. ICESat will contribute to PARCA by obtaining elevation data across Greenland throughout the year in a more consistent fashion than could ever be obtained by the pioneering airborne effort.

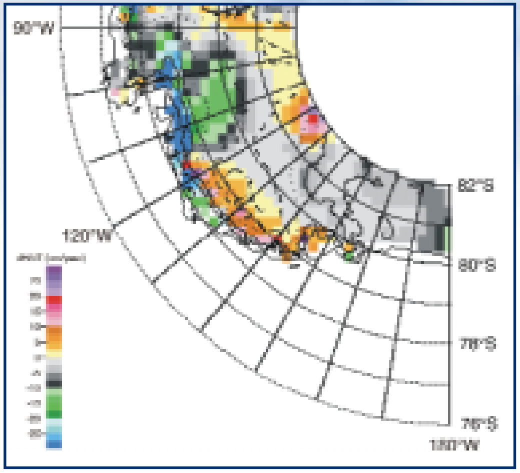


Results from a multi-year airborne laser altimetry study of the Greenland ice sheet. The map of observed elevation changes indicates significant variations in the changes from place to place and the complex behavior of the ice mass. Blue, green, and gray tones indicate areas of ice loss due to melting, reduced snowfall, or increased ice discharge. The pale-yellow, orange-brown, and red colors over much of the interior of the ice sheet indicate areas where the ice surface is rising. Courtesy of Bill Krabill.

Thinning of Part of the West Antarctic Ice Sheet

An additional illustration of ice sheet elevation changes is provided by analysis of 7 years of European Remote Sensing Satellite (ERS-1 and 2) satellite radar altimetry data (1992-1999) over part of the West Antarctic ice sheet (see pages 10-11). The large area of green and blue in the upper part of the figure covers much of the ice drainage basin that feeds into two major outlet glaciers (Pine Island Glacier and Thwaites Glacier). Elevation decreases there are as large as 30 cm (12 in) per year. The ice thinning is likely to be a continuing response to climate change over many centuries, and perhaps removal of an ice shelf in front of the glaciers in the past. Elevation increases up to 20 cm (8 in) per year are indicated (red and orange) on the ridge between the Pine Island / Thwaites drainage basin and the Ross Ice Shelf to the southwest (lower right).

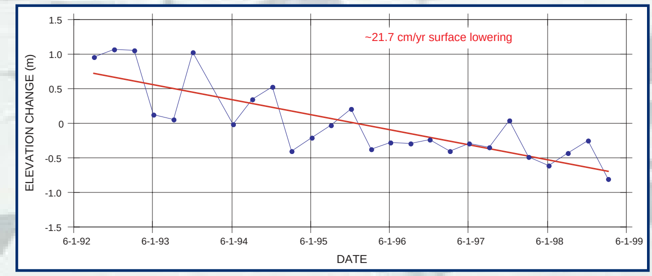
The average elevation change for the grounded ice (excluding the floating ice shelves) over this region is – 4.3 cm (1.7 in) per year, and the estimated average rate of bedrock uplift is 2.5 cm (1 in) per year. Therefore, the estimated rate of ice thinning is 6.8 cm (2.7 in) per year, which means a mass loss of 73 km^3 (17.5 mi^3) of ice per year. The resulting contribution to sea level rise is 0.2 mm (0.008 in) per year from this part of West Antarctica. ICESat will improve the resolution and accuracy of such measurements, especially near the coast where steeper slopes limit radar altimetry, and extend the measurement inland to 86° S.



Spatial illustration of surface elevation change across a part of West Antarctica from ERS-1 and -2 radar altimetry (Zwally et al., 2002).

Thinning of the Larsen Ice Shelf – Antarctic Peninsula

Analysis of the ERS-1 and 2 radar altimeter data on the northerly part of the Larsen Ice Shelf (“Larsen B”) for the period 1992 to 1999 (see pages 9 and 10) showed a lowering of the elevation of the ice shelf surface by 27 cm (11 in) per year. A 27-cm change in the height of the ice shelf surface above sea level means the total ice thickness changed by about 1.7 m (5.6 ft), because only 16% of the thickness of floating ice shelves is above the water line. Therefore over the 7 years, the shelf lost about 12 m (39 ft) of its total thickness of about 170 m (560 ft). The breakup the northern parts of the Larsen Ice Shelf and other ice shelves in this region has been associated with significant warming of the Peninsula region in recent decades. As shown in the figure, the surface elevation of the remaining part of the Larsen Ice Shelf (“C”) has also been lowering at a similar rate of 21.7 cm (8.5 in) per year, which implies ice thinning of 1.4 m (4 ft) / year. Although the Larsen C is about 100 m (330 ft) thicker than B was, it may face a similar breakup if warming continues.



Time series of surface elevation change of the Larsen C Ice Shelf, Antarctic Peninsula. Courtesy of Jay Zwally.

Larsen B Ice Shelf - Austral Summer 2002

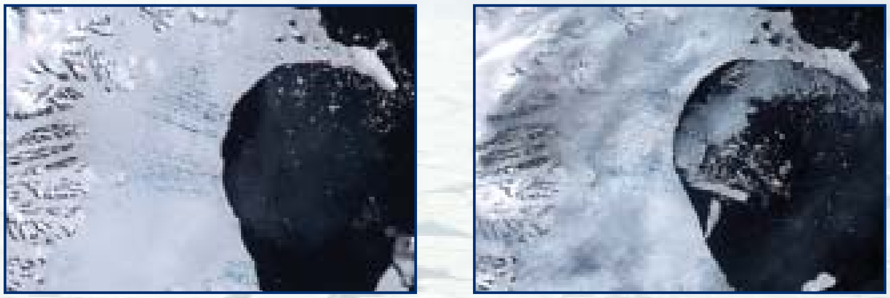
As predicted beforehand by scientists, the rapid thinning of the Larsen Ice Shelf led to a series of dramatic events captured by satellite images as well as witnessed by Argentine field researchers.

January 31, 2002 (top left image) — Melt ponds, with light blue tones, are observed across much of the ice shelf in surface depressions associated with crevasses and flow lines. At this time, the Larsen B ice shelf extended from Robertson Island (at the upper left) to the Jason Peninsula (along the lower margin), following a significant retreat between 1993 and 2001 from its "historical" observed extent earlier in the last century.

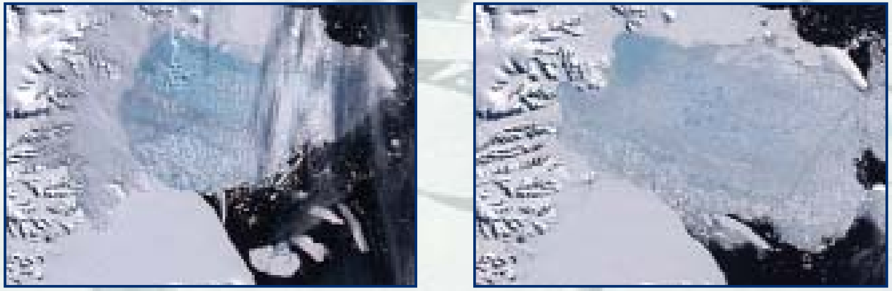
February 17, 2002 (top right image) — Small events resulted in a number of icebergs with a variety of sizes calving from the ice shelf front. Melt ponds were still evident but appear to be diminished in extent. The melt ponds became less obvious as the ice shelf began to break apart and water drained through the ice shelf to the ocean below.

March 5, 2002 (bottom left image) — Collapse of the majority of the Larsen B ice shelf. Due to wind and tidal forces, new icebergs now choke the embayment from the ice shelf front to the end of Robertson Island. The light blue color is the result of the exposure of glacial ice as the ice fragments rotate from a vertical to a horizontal position in the open water of the bay.

March 17, 2002 (bottom right image) — Disintegration of the ice shelf margins continues with dispersal of the ice shelf fragments due to wind and tidal forces. The area lost is about 3250 km^2 (1250 mi^2) or approximately the area of Rhode Island, with a weight estimated at 720,000,000,000 tons.



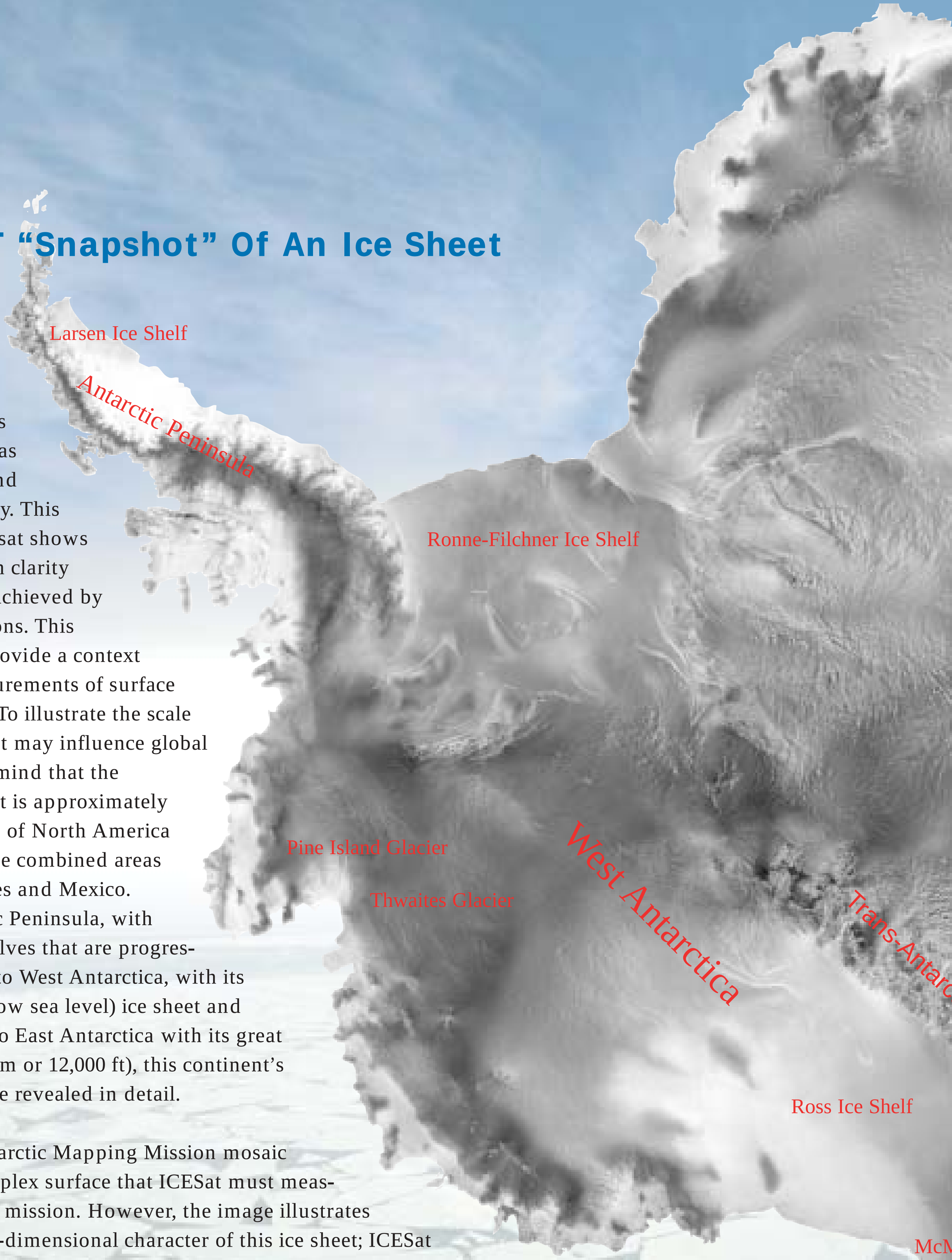
January 31, 2002 February 17, 2002



March 5, 2002 March 17, 2002

Collapse of the Larsen B ice shelf captured by a sequence of satellite imagery. See Scambos et al., J. Glaciology, 2000, for a history and mechanism of ice shelf collapses in Antarctica. The data were collected by the Moderate Resolution Imaging Spectrometer (MODIS) on NASA's Terra satellite. Courtesy of Ted Scambos.

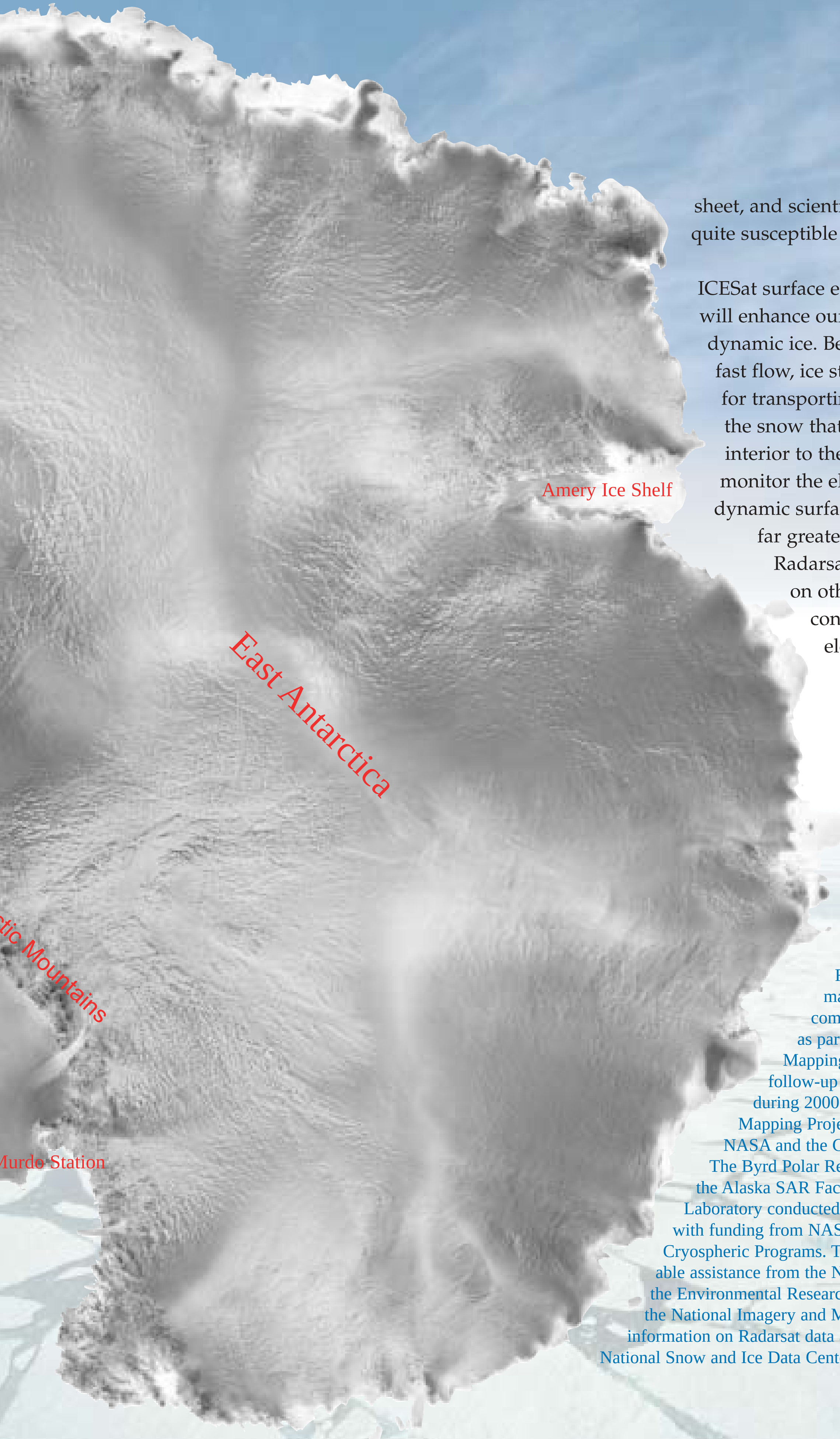
RADARSAT "Snapshot" Of An Ice Sheet



Antarctica, the frozen continent, is a landscape that has long challenged and intrigued humanity. This image from Radarsat shows spatial details with clarity never previously achieved by satellite observations. This image serves to provide a context for ICESat's measurements of surface elevation change. To illustrate the scale of the ice mass that may influence global sea level, keep in mind that the Antarctic continent is approximately two thirds the size of North America or equivalent to the combined areas of the United States and Mexico. From the Antarctic Peninsula, with its fringing ice shelves that are progressively collapsing, to West Antarctica, with its marine-based (below sea level) ice sheet and huge ice shelves, to East Antarctica with its great thickness (> 4,000 m or 12,000 ft), this continent's surface features are revealed in detail.

This Radarsat Antarctic Mapping Mission mosaic illustrates the complex surface that ICESat must measure throughout its mission. However, the image illustrates only the areal or 2-dimensional character of this ice sheet; ICESat will provide the needed 3rd dimension, surface elevation as well as its change through time. Note the huge Ronne-Filchner and Ross Ice Shelves that have produced huge icebergs since this mosaic was obtained. The twisted patterns of ice draining from the interior of the ice sheet out to the ice shelves are extraordinary. Although not distinct at this resolution, ice streams can be identified by the bright radar returns from their crevassed (fractured) margins that reflect radar energy more efficiently than surrounding unfractured interior ice. These ice streams are vast rivers of ice that flow up to 100 times faster than the ice they channel through, with speeds up to 1 km (3000 ft) per year. Some ice streams in East Antarctica extend almost 800 km (500 mi). They have changed their velocity and flow patterns in response to factors that are just now beginning to be understood through field research supported by intermittent satellite data. Ice streams form the most dynamic parts of the Antarctic ice sheet, and scientists believe that they are quite susceptible to rapid change.

ICESat surface elevation time series data will enhance our understanding of dynamic ice. Because of their relatively fast flow, ice streams are responsible for transporting a large percentage of the snow that falls on the continent's interior to the ocean. ICESat will monitor the elevation details of this dynamic surface for 3 to 5 years with far greater accuracy than Radarsat. Images from sensors on other satellites will provide context for this mission's elevation change data.



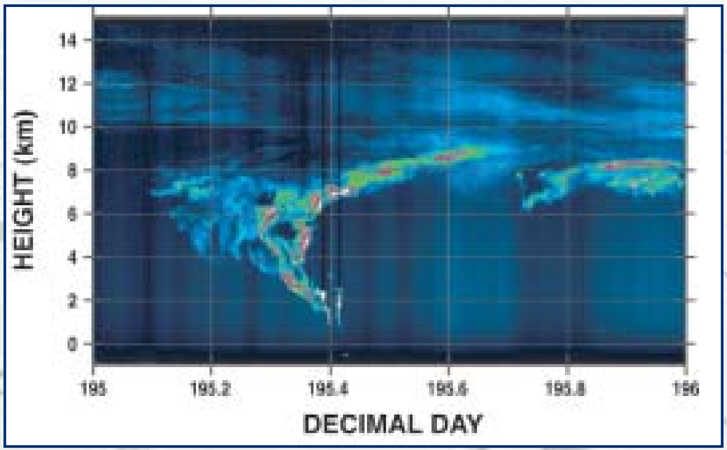
Radarsat can collect these spatial data day and night, through cloudy weather or clear. It was this capability that enabled Antarctica to be mapped in just 18 days, compared to the last satellite map that required images from five different satellites spanning a 13-year period from 1980 to 1994. Following a precise orbital maneuver, Radarsat acquired complete coverage of the continent as part of the first Antarctic Mapping Mission (AMM-1). A follow-up mission (MAM) took place during 2000. The Radarsat Antarctic Mapping Project (RAMP) is a joint effort of NASA and the Canadian Space Agency (CSA). The Byrd Polar Research Center, Vexcel Corp., the Alaska SAR Facility, and the Jet Propulsion Laboratory conducted the project collaboratively, with funding from NASA's Pathfinder and Cryospheric Programs. The project also received valuable assistance from the National Science Foundation, the Environmental Research Institute of Michigan, and the National Imagery and Mapping Agency. For more information on Radarsat data and this mosaic, contact the National Snow and Ice Data Center (NSIDC).

How Do Clouds and Aerosols Affect Climate?

The distribution of atmospheric clouds and aerosols is one of the most important factors in global climate. Clouds can cool the Earth's surface by reflecting solar radiation or warm the surface by trapping its radiated heat. Being typically more reflective than the Earth's surface, low clouds primarily reflect solar radiation and cause relative cooling. High, thin clouds are usually less effective at reflecting solar radiation but effectively trap outgoing infrared heat radiation. Accurate knowledge of the type and height of clouds is thus very important for climate studies. Like clouds, aerosols tend to cool the Earth's surface and heat the atmosphere by scattering and absorbing solar radiation. In general terms, aerosols are distinguished from clouds by existing at humidity levels below saturation and by a particle size which is typically 10 to 100 times smaller than cloud droplets.


Illustration of varying cloud optical thicknesses from the highest thinnest cloud (upper right) to the dense low-lying clouds (lower left). Courtesy of Art Rangno.

The laser profiling measurements from GLAS are a fundamentally new way to study the atmosphere from space. To better understand climate, scientists need to distinguish the multiple cloud and aerosol layers that typically exist in the atmosphere. Other satellite remote-sensing techniques currently in use are limited to passive observations, i.e. the sensor images the Earth at a given wavelength but views all atmospheric layers simultaneously. Another issue is that such passive instruments cannot measure the height of layers sufficiently to fully understand the role of clouds in global climate change. The GLAS instrument on ICESat will enable the accurate, multi-year height profiling of atmospheric cloud and aerosol layers directly from space for the first time.



Active profiling of the atmosphere by GLAS (model data shown here) allows individual cloud and aerosol layers to be seen separately, whereas traditional satellite imaging techniques combine the radiation from all layers into one measurement. Thicker clouds with higher optical densities (brighter colors) are contrasted with thin clouds, aerosols, and clear skies (progressively darker colors). Courtesy of Jim Spinhirne.

GLAS cloud and aerosol measurements will also improve studies of other atmospheric phenomena unique to the polar regions. Polar stratospheric clouds that form during periods of depleted atmospheric ozone can be easily detected from GLAS measurements. Polar "diamond dust", which refers to near-surface suspended ice crystals from an apparently non-precipitating sky, could also be detected by GLAS. Finally, GLAS will overcome an enduring limitation of high-latitude research, the inaccessible and uninhabitable nature of much of the polar regions, and make data available from regions that have previously not been well studied.


Image of clouds and sea ice around northern Greenland from NASA’s Aqua MODIS sensor. The 1 km resolution image was taken July 13, 2002. Courtesy of the Aqua MODIS Science Team.

Clouds play an especially critical role in the climate of the polar regions. The polar temperature balance is dependent on clouds preventing heat loss to space. Passive observations of clouds are can be inaccurate in these areas because the visible and infrared radiative signatures of clouds are hard to distinguish from that of the bright, cold snow and ice covered surfaces below them. Image techniques to distinguish between snow-covered surfaces and typical cirrus clouds in these regions are complex, and require considerable data analysis. The GLAS instrument will enable unambiguous detection of all but the thinnest atmospheric layers and this will permit the development of consistent climatologies of the Arctic and Antarctic. GLAS measurements will also improve studies of polar stratospheric clouds that facilitate depleted atmospheric ozone.

Understanding the role of haze aerosols is also an issue for climate change researchers. Atmospheric aerosols globally impact radiative transfer of energy and also influences cloud formation. In addition, the fertilization for biological activity of large parts of the ocean and parts of the tropical rain forest occur by aerosol transport. Significantly, aerosol distribution and characteristics are highly variable and complex. Aerosols are transported around the world by winds that can change dramatically with altitude, but no existing observation can reliably give the height of aerosol layers. The GLAS aerosol profiles will be a unique and critical contribution to earth science and global change research.


A true-color image acquired May 4, 2001, by the Sea-viewing Wide Field-of-view Sensor reveals a large plume of aerosols blowing eastward over the North Atlantic Ocean. Courtesy of the SeaWiFS Project.

Measuring Earth’s Land Surface And Vegetation

The topography and vegetation cover of the Earth’s land surface form a complex mosaic that is the product of a diverse set of solid Earth, glacial, hydrologic, ecological, atmospheric, anthropogenic, and other processes. The landscape we see today is the cumulative result of the interaction of those processes through time. Measurement of landscape properties, including elevation, slope, roughness, and vegetation height and density, is a necessary step toward understanding the interplay between formative processes and thus toward more accurate modeling of future changes. Knowledge of these properties and their changes with time is important for resource management, land use, infrastructure development, navigation, and forecasting the occurrence and impact of natural hazards such as volcanic eruptions, landslides, floods, and wild fires.

The ICESat profiles will provide a global sampling of the elevation of the Earth’s land surface with unprecedented accuracy. This globally-consistent grid of high-accuracy elevation data will be used as a reference framework to evaluate and improve the accuracy of topographic maps acquired by other air-borne and space-based methods such as conventional stereo-photogrammetry and radar interferometry. In particular, ICESat profiles will be combined with the near-global mapping accomplished by the Shuttle Radar Topography Mission to greatly improve our knowledge of the Earth’s topography. Also, using ICESat’s consistent global framework, topographic maps acquired through time using a variety of methods can be better co-registered, enabling long-term observations of topographic changes.

Dramatic topographic and vegetation cover change can be caused by natural hazards. This is illustrated here by two views of Mt. St. Helens, Washington, from Spirit Lake before (upper) and after (lower) the May 18, 1980 eruption. The upper picture is courtesy of Jim Nieland and the lower picture is courtesy of the USGS Cascades Volcano Observatory. The satellite view of Mt. St. Helens (right image) shows the ejected debris field outside the crater and is courtesy of the Landsat-7 Project.

ICESat profiles repeated through time across dynamic landforms will also enable direct observation of topographic change. By pointing the ICESat spacecraft off nadir, features can be targeted for profiling every 12 days on average near the equator, and even more frequently at higher latitudes. This targeting capability will be used to monitor selected phenomena such as volcanic eruptions, changes in river and lake levels, seasonal snow-pack dynamics, glacier surges and retreats, soil erosion, and migration of desert sand sheets. The global access of ICESat's elevation profiling will add the height dimension to images of the dynamic Earth acquired by other orbital remote sensing instruments.

In addition to acquiring elevation data, ICESat's measurement of the laser pulse return shape provides unique information about the height distribution of the surface features within each laser footprint. In areas lacking vegetation cover, this is a measure of relief (ground slope and roughness), an indication of the intensity of geomorphic processes. In vegetated areas of low relief, the elevation of the ground and the height and density of the vegetation cover can be inferred from the return pulse. The vegetation observations enable estimation of above-ground biomass and its loss due to deforestation, an important component of the carbon cycle.

Photograph of the Brazilian rain forest canopy. Courtesy of the Large Scale Biosphere-Atmosphere Experiment in Amazonia.

Photograph of Yosemite Valley, California, showing complex landscape elements. Courtesy of David Harding.

What Is The Geoscience Laser Altimeter System?

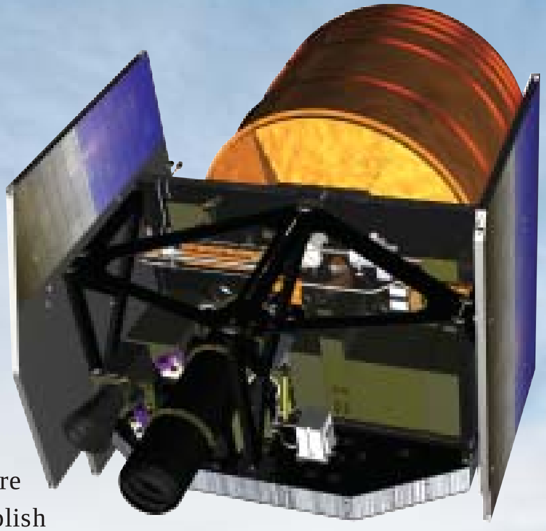
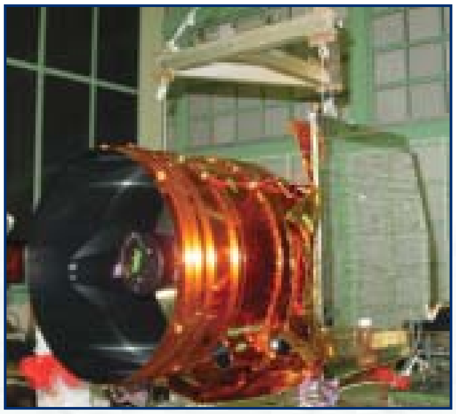


Illustration of the GLAS instrument from the zenith-facing side. Courtesy of the GLAS Instrument Team.

The Geoscience Laser Altimeter System (GLAS) is a next-generation space lidar. It is the sole science payload for NASA's ICESat Mission. The GLAS design combines a 15 cm (6 in) precision surface lidar with a sensitive dual wavelength cloud and aerosol lidar. GLAS operates with infrared and visible laser light pulses at 532 nm and 1064 nm wavelengths at eye-safe signal levels. These laser light pulses illuminate the Earth and will enable GLAS to measure the surface elevation of the polar ice sheets accurately, establish a network of height data on the Earth's land topography, and profile the vertical distribution of clouds and aerosols on a global scale. GLAS is integrated onto the ICESat spacecraft built by Ball Aerospace. ICESat will be launched into a near-polar orbit that is slightly inclined relative to the equator, so that it will cover the Earth from 86° N to 86° S.



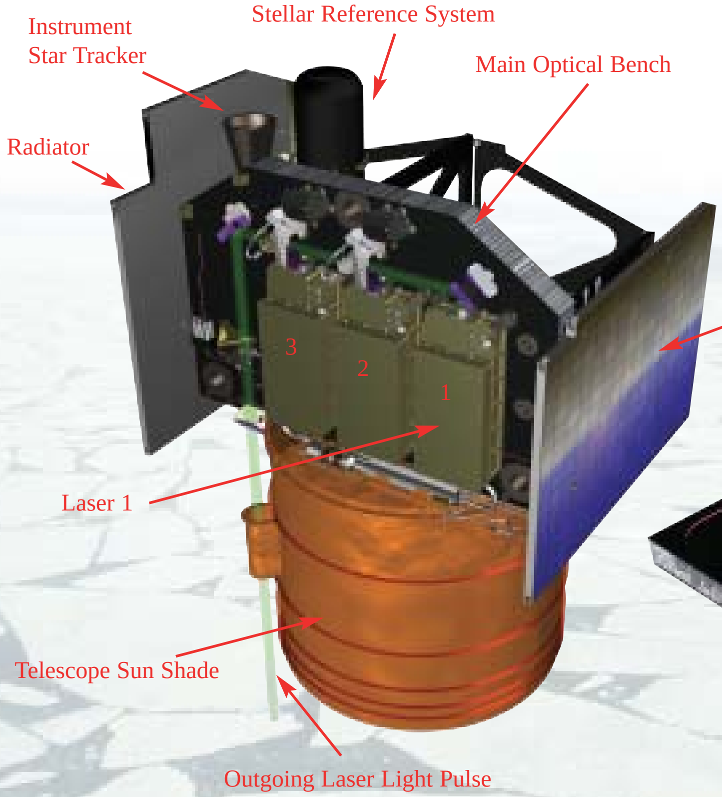
The GLAS instrument following final assembly and testing at NASA Goddard Space Flight Center. Courtesy of the GLAS Instrument Team.

GLAS will measure the vertical distance from orbit to the Earth's surface 40 times a second with pulses from a ND:YAG laser. Each GLAS laser pulse at 1064 nm can yield a single distance measurement as well as other information about the character of the Earth's surface. On Earth, the laser footprints have a diameter of approximately 70 m (230 ft) and 170 m (560 ft) center-to-center spacing. The GLAS receiver uses a 1 m (3 ft) diameter telescope to collect the reflected 1064 nm laser light and a detector that precisely times the outgoing and reflected laser pulses. A digitizer records each transmitted and reflected laser pulse with 1 nano-second (ns) resolution.

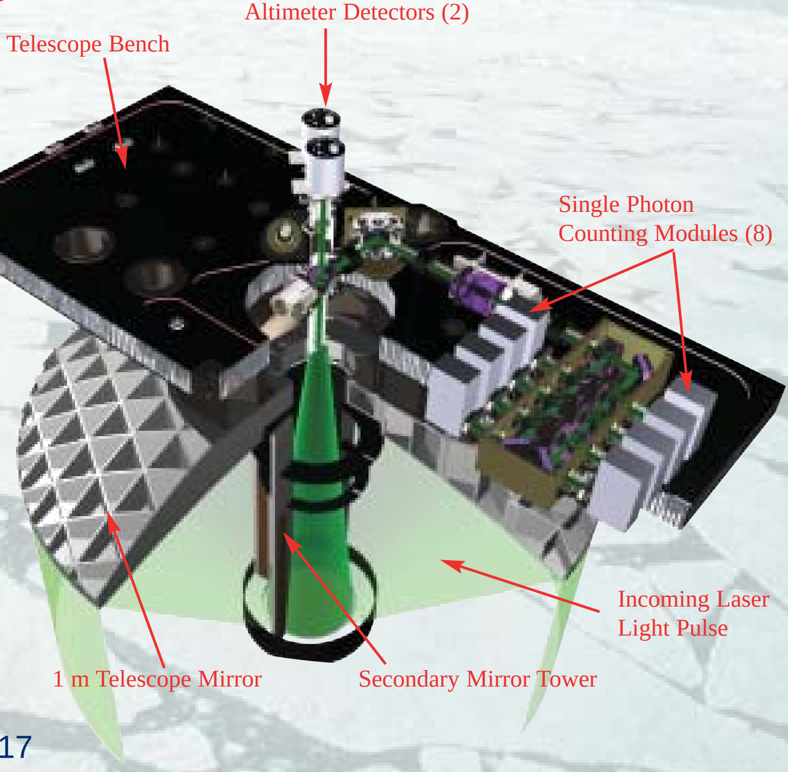
Three views of the GLAS instrument following integration with the ICESat satellite at Ball Aerospace & Technologies Corp. in Boulder, Colorado. Courtesy of Ball Aerospace.

GLAS will also measure the vertical distributions of clouds and aerosols by recording vertical profiles of laser backscatter at both 1064 nm and 532 nm. A 1064 nm detector will be used to measure the height and echo pulse shape from thicker clouds. The lidar receiver at 532 nm uses a narrow bandwidth etalon filter and highly sensitive photon counting detectors. The 532 nm backscatter profiles will be used to measure the vertical extent of thinner clouds and the height of the atmospheric boundary layer.

A precision "Blackjack" GPS receiver carried on the ICESat spacecraft will measure GLAS's location in orbit. Accurate knowledge of the laser's pointing angle relative to inertial space is needed to minimize uncertainty when measuring over sloping surfaces such as ice sheet margins. On its "zenith" or star-facing side, GLAS uses a stellar reference system (SRS) to measure the pointing angle of each laser pulse relative to selected bright stars that are effectively static reference points in space. GLAS uses redundant high precision star cameras and gyroscopes to determine the orientation of its measurement baseline on the instrument's optical bench. Each laser pulse is measured relative to the star camera with a laser reference system (LRS). Analysis of the reflected 1064 nm and 532 nm pulse data, along with the GPS and LRS data, enables final determination of the distance to the reflecting surface, the degree of pulse spreading due to atmospheric conditions, and vertical distribution of any surface vegetation.



Graphical illustration of the GLAS instrument showing Laser-1 firing a laser pulse (in green) toward Earth. Courtesy of the GLAS Instrument Team.



Graphical illustration of the GLAS instrument (with its telescope sun shade and main optical bench removed) showing the 1 m telescope mirror receiving a reflected laser pulse (in green) from Earth into its detectors. Courtesy of the GLAS Instrument Team.

The ICESat Mission — Overview

The overall mission is composed of the GLAS instrument, the ICESat spacecraft, the launch vehicle, mission operations, and the science team. Goddard Space Flight Center (GSFC) staff developed the GLAS instrument in partnership with university and aerospace industry personnel. The ICESat spacecraft was developed by Ball Aerospace & Technologies Corp. (Ball Aerospace) in Boulder, Colorado. Ball Aerospace will also support ICESat when it is on orbit. NASA Kennedy Space Center is providing the expendable Boeing Corporation Delta II launch vehicle. The science team is composed of researchers from universities, GSFC staff, and supporting industry personnel. The science team is developing the science algorithms and is responsible for all science data processing, as well as the generation of science data products.

A Delta II launch vehicle will carry ICESat, as well as a second payload called CHIPSat, into a near-polar low Earth orbit of approximately 600 kilometers altitude. The Delta II will be launched from Space Launch Complex-Two (SLC-2), Western Test Range, Vandenberg Air Force Base, California in mid-December, 2002. While on orbit, ICESat achieves ±10 arcsec pointing accuracy and ~2 arcsec pointing knowledge. To accomplish this, a three-axis stabilized attitude control system composed of two star trackers, four reaction wheels, a hemispherical resonator gyroscope on the GLAS instrument, 15 coarse sun sensors, three magnetometers, and three torque rods is used. Orbital position is derived from a redundant set of NASA JPL “Blackjack” GPS receivers and a global network of ground receivers, provided by the International GPS Service. Additional orbit position information is obtained from the International Laser Ranging Service, a network of ground laser stations that will use a laser retroreflector mounted on the nadir (earth-facing) side of ICESat. While on orbit, the spacecraft will communicate with the Earth Observing System (EOS) Polar Ground Stations (EPGS) four times a day over X-Band and S-Band radio frequency channels.

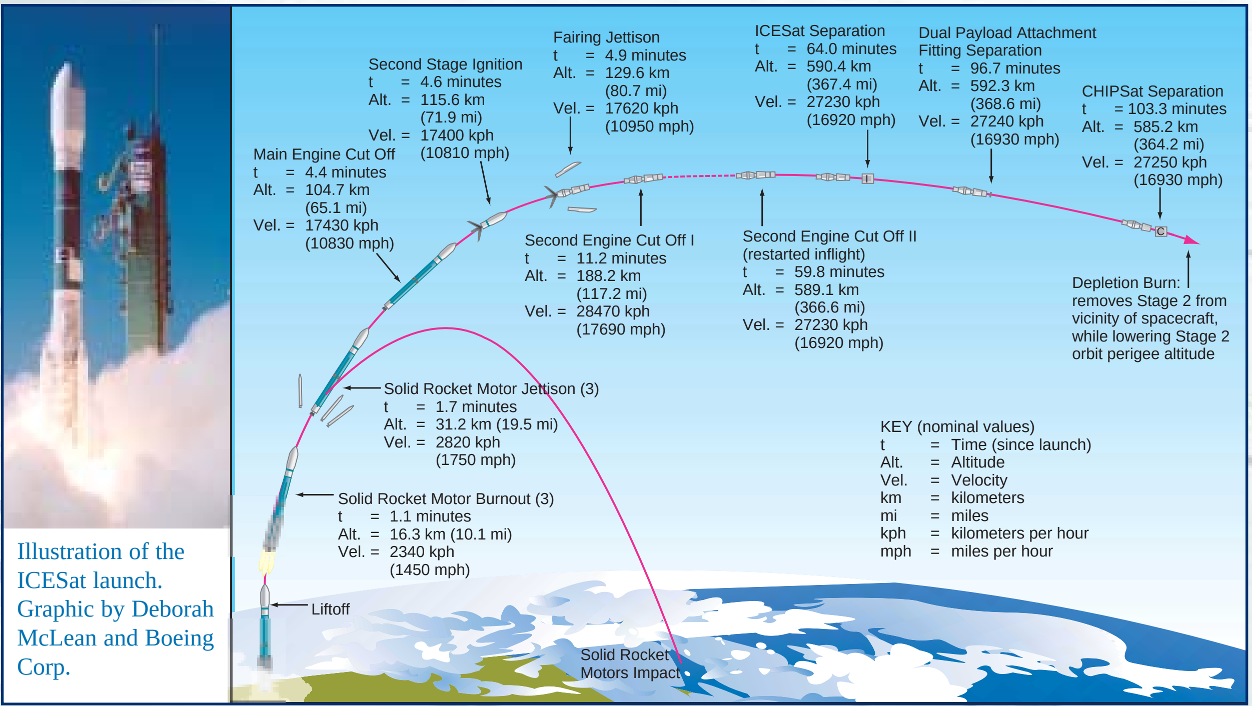
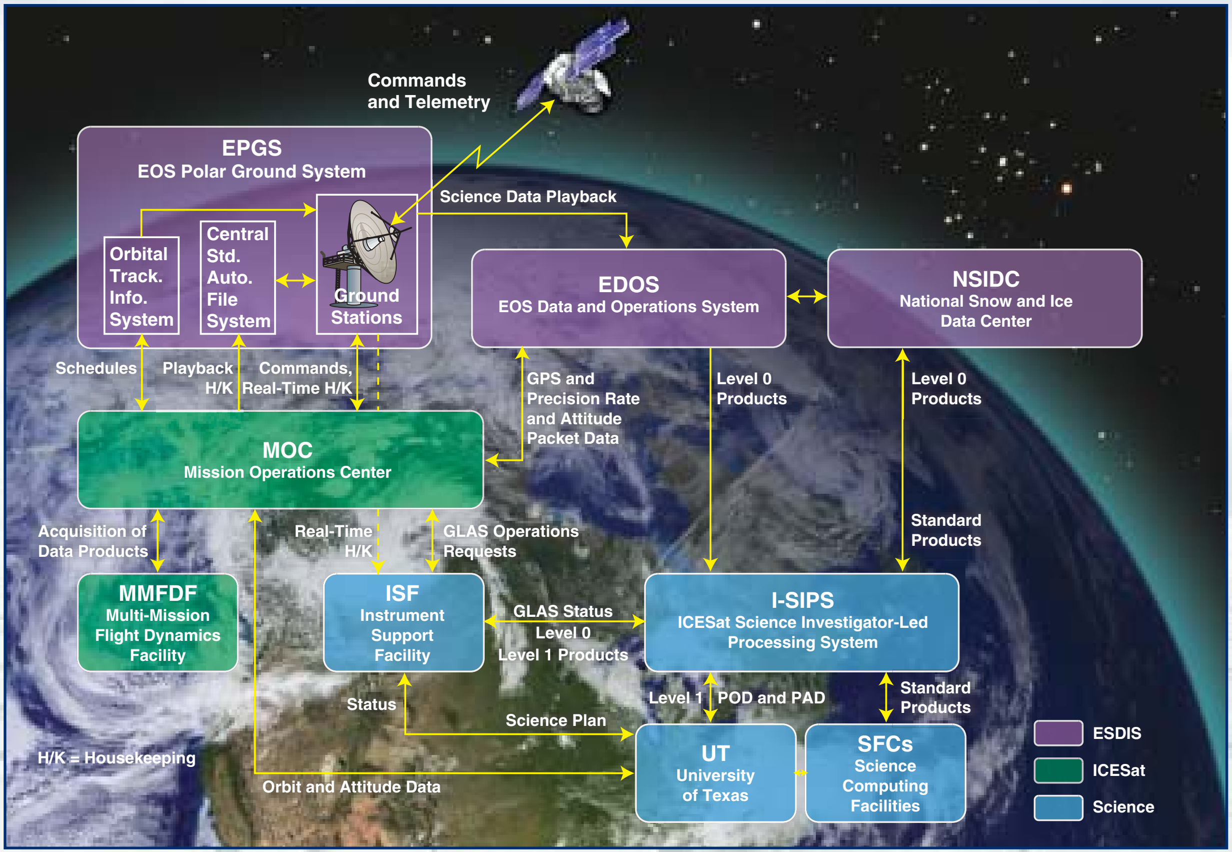


Illustration of the ICESat launch. Graphic by Deborah McLean and Boeing Corp.

Mission Operations And Calibration/Validation

Once ICESat is on orbit, mission operations will be conducted by two organizations. The Earth Science Data and Information System (ESDIS) Project at GSFC will provide space and ground network support. The University of Colorado's Laboratory for Atmospheric and Space Physics (LASP) teamed with Ball Aerospace will provide mission operations and flight dynamics support. The GLAS data are recorded by the on-board Solid State Recorder and are played back during scheduled contacts via X-band downlink communications. The ICESat Science Investigator Processing System (I-SIPS) at GSFC will conduct data processing and generation of products with support from the Center for Space Research (CSR) at the University of Texas, Austin. The National Snow and Ice Data Center (NSIDC), located at the University of Colorado in Boulder, will archive and distribute ICESat data products to the scientific community and other users. The interactions of these organizations are summarized in the chart below.



Schematic diagram of ICESat mission operations. Graphic by Deborah McLean.

In the 60 days following launch, ICESat will undergo a series of tests to establish that all systems are functioning within specifications in the orbital environment. This commissioning phase will be followed by a period of intense activity to verify the performance of GLAS and all related systems. The objective of this intense period (calibration / validation or cal / val), is to help insure that geophysical interpretations can be drawn from the data products. Cal / val includes evaluation of the GLAS measurements against ground truth observations. A variety of instrumented and precisely mapped ground-truth sites will be used, including dry lakebeds, landscapes with undulating surface topography, and the ocean, all of which will be periodically scanned.

Acronyms

ATBD	Algorithm Theoretical Basis Document
Ball	Ball Aerospace & Technologies Corp.
CHIPSat	Cosmic Hot Interstellar Plasma Spectrometer
CSR	Center for Space Research University of Texas, Austin
EOS	Earth Observing System
EOSDIS	EOS Data and Information System
EPGS	EOS Polar Ground System (Alaska and Svalbard)
ESDIS	Earth Science Data and Information System
FOV	Field Of View
GLAS	Geoscience Laser Altimeter System
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
GSFC	Goddard Space Flight Center
ICESat	Ice, Cloud, and land Elevation Satellite
I-SIPS	ICESat Science Investigator-led Processing System
IST	Instrument Star Tracker
JPL	Jet Propulsion Laboratory
KSC	Kennedy Space Center
LASP	Laboratory for Atmospheric and Space Physics University of Colorado, Boulder
LEO	Low Earth Orbit
lidar	LIght Detection And Ranging
LRS	Laser Reference System
LSM	Laser Select Mechanism
NASA	National Aeronautics and Space Administration
ND:YAG	Neodymium:Yttrium Aluminum Garnet
NSIDC	National Snow and Ice Data Center
PAD	Precision Attitude Determination
POD	Precision Orbit Determination
SAR	Synthetic Aperture Radar
SCF	Science Computing Facility
SLR	Satellite Laser Ranging
SPCM	Single Photon Counting Module

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More information on the ICESat mission can be found at: icesat.gsfc.nasa.gov as well as links to many other supporting sites related to this and other EOS satellite missions.

Acknowledgements

ICESat Scientists

Project Scientist:	Jay Zwally - NASA/GSFC
Deputy Project Scientist:	Christopher Shuman - NASA/GSFC
Program Scientist:	Waleed Abdalati - NASA Headquarters

GLAS Science Team

Team Leader:	Bob Schutz - University of Texas-Austin
Team Members:	Charles Bentley - University of Wisconsin-Madison Jack Bufton* - NASA/GSFC David Harding (ex officio) - NASA/GSFC Thomas Herring - Massachusetts Institute of Technology Jean-Bernard Minster - Scripps Institution of Oceanography James Spinhirne - NASA/GSFC Robert Thomas - EG&G Corporation Jay Zwally - NASA/GSFC

GLAS Instrument Team

Instrument Scientist:	Jim Abshire - NASA/GSFC
Instrument Manager:	Ron Follas - NASA/GSFC
Instrument System Engineer:	Eleanor Ketchum - NASA/GSFC

Lead Engineers:

Laser Lead:	Robert Afzal* - NASA/GSFC, Joe Dallas* - SSAI
SRS Lead:	Pamela Millar - NASA/GSFC, Marcos Sirota - Sigma
Optical Lead:	Marzouk Marzouk - Sigma, Luis Ramos-Izquierdo - OSC
Lidar Lead:	Michael Krainak - NASA/GSFC
Detector Lead:	Xiaoli Sun - NASA/GSFC
Electrical Lead:	Gregory Henegar, Steve Meyer - NASA/GSFC
Flight Software Lead:	Manuel Maldonado, Jan McGarry - NASA/GSFC
Mechanical Lead:	Cheryl Salerno, Gordon Casto - NASA/GSFC
Thermal Lead:	Eric Grob, Charles Baker, Walter Ancarrow* - NASA/GSFC
Integration and Test Lead:	Tom Feild - NASA/GSFC, Juli Landers - OSC
Bench Check Equip. Lead:	Haris Riris - Sigma

Project Managers	Joe Dezio, Jim Watzin, - NASA/GSFC
Deputy Project Manager	Linda Greenslade, Greg Smith - NASA/GSFC
Observatory Manager	Bill Anselm - NASA/GSFC
Mission Systems Engineer	Tim Trenkle - NASA/GSFC

Brochure Preparation

Brochure Writers:	Jay Zwally and Christopher Shuman - NASA/GSFC
Brochure Editors:	Jim Abshire, Bill Anselm, Bob Schutz, James Spinhirne, Michael King, Claire Parkinson, David Harding, Charlotte Griner, David Herring, Jack Saba, Anita Brenner
Brochure Design:	Winnie Humberson - SSAI
Cover Graphic	Robert Simmon - SSAI
ICESat and GLAS Graphics	Jason Budinoff - NASA/GSFC
ICESat Logo Design:	Hailey King - Knott Laboratory, Inc.

NASA/GSFC	*NASA Goddard Space Flight Center*
OSC	*Orbital Sciences Corporation*
SSAI	*Science Systems Applications, Inc.*
Sigma	*Sigma Research and Engineering Corporation*
*	*Changed affiliation*

GEOSCIENCE LASER ALTIMETER SYSTEM (GLAS)

Science Measurement Requirements:

- Measure ice sheet elevations to ≤1.5 cm/yr over 100x100 km areas
- Measure all radiatively significant clouds and aerosols globally
- Measure global land topography
- Three year operational life (5 year goal)

Specifications:

	Surface[1]	*Atmosphere*
Wavelengths	1064 nm	532 nm
Laser Pulse Energy	74 mJ	30 mJ
Laser Pulse Rate	40 Hz	40 Hz
Laser Pulse Width	5 nsec	5 nsec
Telescope Diameter	1.0 m	1.0 m
Receiver FOV	0.5 mrad	0.16 mrad
Receiver Optical Bandwidth	0.8 nm	0.03 nm
Detector Quantum Efficiency	30%	60%
Detection Scheme	Analog	Photon Counting
Vertical Sampling Resolution	0.15 m	75 m
Surface Ranging Accuracy (single pulse)	5 cm	
Laser Pulse Pointing Knowledge	< 2 arcsec	

[1] Also measures backscatter from optically thick clouds

Measurement Approach:

GLAS has 3 lasers, a single laser operates at any given time

Each Nd:YAG laser has 3 stages and emits pulses at 1064 and 532 nm continuously at 40 Hz

Precison orbital and pointing knowledge will be obtained via redundant GPS units, a gyro system, a laser reference sensor, and instrument-mounted star trackers, and ground-based laser ranging

Thermal control by heat pipes and radiators supplemented by heaters

Measurement Characteristics:

GLAS operates at 40 pulses per second (Hz); ground track is ~70 m "spots" separated along-track by ~170 m; cross-track resolution is a function of the 183-day ground-track repeat cycle (15-km spacing at equator and 2.5 km spacing at 80° latitude); orbit inclination is 94°

Altimetry measurements are determined from the round-trip travel time of the 1064 nm pulse

Cloud and aerosol data are extracted from the 532 nm pulse signal with optically thick cloud tops extracted from the 1064 nm pulse signal

Post-processed laser pointing knowledge (1σ) will be ~2 arcsec

Post-processed position requirements: radial orbit for ice sheet to < 5 cm and along-track/cross-track position to < 20 cm

The ICESat spacecraft can control GLAS to point within 30 arcsec roll, 30 arcsec pitch, and 1° yaw (3σ)

Physical Characteristics

Mass: 300 kg

Power: 330 W average

Data rate: ~450 kbps

Physical size: telescope diameter is 100 cm, instrument height is ~175 cm

Introduction To Ice

Ice exists in the natural environment in many forms. The figure below illustrates the Earth's dynamic ice features. At high elevations and/or high latitudes, snow that falls to the ground can gradually build up to form thick consolidated ice masses called glaciers. Glaciers flow downhill under the force of gravity and can extend into areas that are too warm to support year-round snow cover. The snow line, called the equilibrium line on a glacier or ice sheet, separates the ice areas that melt on the surface and become snow free in summer (net ablation zone) from the ice areas that remain snow covered during the entire year (net accumulation zone). Snow near the surface of a glacier that is gradually being compressed into solid ice is called firn.

Ice sheets, which are the largest forms of glaciers in the world, cover much of Greenland and Antarctica. Smaller ice caps are located in Iceland, Canada, Alaska, Patagonia, and mountainous regions of central Asia. These types of large ice mass have smaller outlet glaciers or ice streams near their margins. Mountain glaciers, smaller than ice sheets or ice caps, flow from high mountain areas and are present on all continents except Australia. In some places where the ice sheets reach the ocean, large floating ice shelves or floating glacier tongues are formed. Icebergs are floating ice masses that have broken away from ice shelves, glacier tongues, or directly from the grounded ice sheet in some locations. Sea ice, which is produced when saline ocean water is cooled below its freezing temperature of approximately -2°C or 29°F, extends on a seasonal basis over great areas of the ocean.

Sea ice and icebergs are both carried by winds and currents into warmer waters. Melt water from sea ice, ice shelves, ice tongues, and icebergs does not contribute to sea level rise, because these ice masses already displace an equivalent amount of sea water. However, sea level rise is caused by the flow of grounded glacial ice into the ocean and by surface or subsurface melt water discharged from the glacier, if the sum of those amounts exceeds the amount of ice accumulated from snowfall on the glacier or ice sheet.

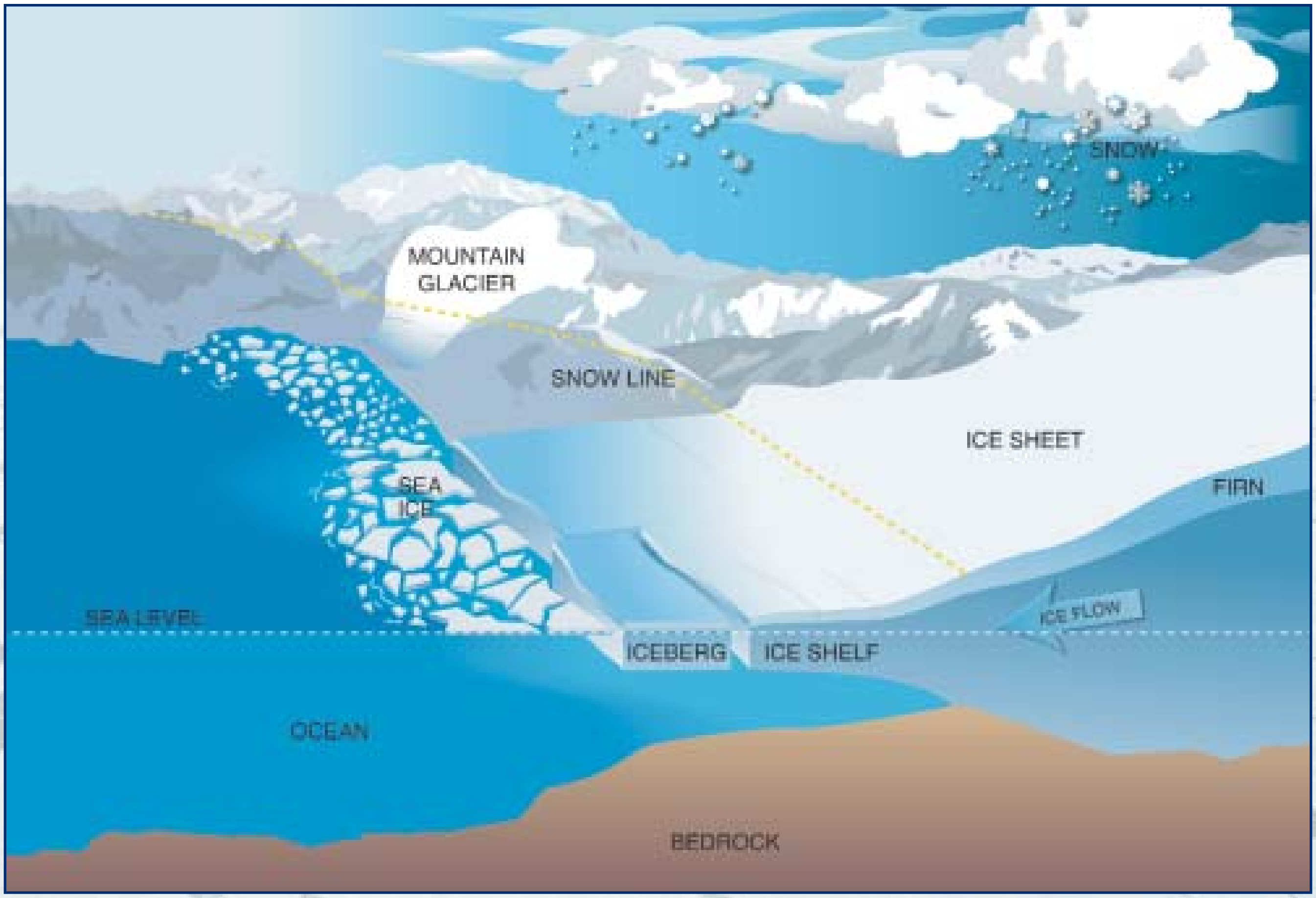

Illustration of ice in the natural environment. Graphic courtesy of Christopher Shuman, Claire Parkinson, Dorothy Hall, Robert Bindschadler, and Deborah McLean.