NASA Earth Observing System

Geoscience Laser Altimeter System
GLAS
Science Requirements

Prepared by
GLAS Science Team

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GLAS Mission Requirements
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Table of Contents

Figures

Tables

1.0 SUMMARY

This document provides the Science Requirements for the Geoscience Laser Altimeter System (GLAS), part of the Earth Observing System (EOS). The instrument contributes to the 24 EOS measurements across several disciplines: land ice, sea ice, cloud properties, radiative energy fluxes, aerosol properties, land cover and land-use change, and vegetation dynamics.

The Science Requirements for GLAS are summarized below. The cryosphere applications address scientific issues with unprecedented accuracy and, as such, the cryosphere requirements are among the most stringent for the GLAS instrument. Where conflicts with higher-level requirements between the disciplines occur, the cryosphere requirements have taken precedence.

The science goals for GLAS are:

SCIENCE GOALS

Cryosphere

• *The primary cryospheric science goals of GLAS are to measure long-term changes in the volumes (and mass) of the Greenland and Antarctic ice sheets to sufficient accuracy to assess their impact on global sea level, and to measure seasonal and interannual variability of the surface elevation in sufficient spatial and temporal detail to permit identification of long-term trends and to help explain those trends. A further goal is to provide a precise elevation topography of these ice sheets and describe the nature of surface characteristics (e.g., roughness), including sea ice.*

Land Processes

• *The primary land processes science goal of GLAS is to conduct topographic measurements of the Earth's land surface on a global basis in order to contribute to a global grid of ground control points for georeferencing of topographic maps and digital elevation models. The secondary land processes science goal is to detect topographic change at the meter per year level or better in selected regions of limited spatial extent.*

Atmospheric Science

• *The primary atmospheric science goal of the GLAS cloud and aerosol measurement is to determine the radiative forcing and vertically resolved atmospheric heating rate due to cloud and aerosol by directly observing the vertical structure and magnitude of cloud and aerosol parameters that are important for the radiative balance of the earth-atmosphere system, but which are ambiguous or impossible to obtain from existing or planned passive remote sensors. A further goal is to directly measure the height of atmospheric transition layers (inversions) which are important for dynamics and mixing, the planetary boundary layer and lifting condensation level.*

The Level 0 Requirements necessary to achieve the Science Goals are summarized below, followed by the Levels 1 and 2 Requirements.

LEVEL 0 REQUIREMENTS SUMMARY

Cryosphere

• The instrument shall provide data to enable determination of ice sheet elevation and its temporal changes over the instrument lifetime. For example, one of the most stringent requirements is in the vicinity of the Ross ice streams, where the determination requires that elevation change be determined with an accuracy of 15 mm/yr over 100 km x 100 km areas with regional surface slopes < 0.6° (0.1 *rad). (Table 2 contains a more complete set of requirements for elevation change determination).*

• The surface elevation shall be described in an internationally defined reference frame tied to the Earth's center of mass.

• The instrument shall provide data to enable characterization of the ice surface (e.g., roughness).

• A data set spanning 15 years over Greenland and Antarctica is required to assure separation of secular changes in surface elevation from annual, interannual, decadal and other temporal variations.

• Assuming three GLAS instruments to meet the 15-yr requirement, the first instrument shall have a three-year lifetime (minimum), but should be designed with a 5-year goal; subsequent instruments shall have five-year lifetime requirements.

• Data from individual instruments shall be verified and calibrated; each instrument shall be calibrated with respect to preceding instruments and instrumental changes with time shall be characterized.

• The data products leading to determination of elevation and elevation change shall be validated.

• The data collected by the instrument and the ancillary data shall be deposited in a long-term archive and be readily accessible to the scientific community.

Land Processes

• Determine land surface elevation to an accuracy of 10 m or better and a spatial accuracy of 100 m or better at point locations on a global basis.

• Detect topographic change at the meter per year level in selected regions of limited spatial extent.

Atmospheric Science

• The instrument will measure the vertical structure of radiatively significant cloud and aerosol structure with sufficient vertical and horizontal resolution to resolve large scale dynamically and energetically important variability. Sufficient accuracy is needed for the optical thickness and vertical profile of total cross section to be obtained up to a limit of approximately 2 in optical depth.

• The atmospheric vertical structure will be measured full time over the entire orbital cycle including sunlit and dark scenes.

• The accuracy of derived atmospheric parameters must be validated.

• The atmospheric measurements will be made over the decadal time period required for all EOS atmospheric observation.

LEVEL 1 & 2 REQUIREMENTS SUMMARY

Based on the Level 0 Requirements, the Level 1 Requirements are summarized below.

Level 1A:

• Determination of temporal changes in surface elevation requires measurement of ice sheet topography as a function of time; temporal changes in surface topography gives ice volume changes, which can be mapped to mass change.

• Measured topography shall represent the ice surface at the time of the measurement without significant penetration to subsurface levels, and the measurements shall be made over a variety of surface characteristics, e.g., fresh snow, packed ice, sastrugi, etc.

• Measurements shall be made over a variety of sloped surfaces, as noted in Table 2.

• Regular and repeated topographic measurements of the ice sheets are required at intervals that enable monthly average surface properties in areas as small as 100 km x 100 km to be determined.

• An initial verification phase during the first 120-days after launch shall be conducted to evaluate the instrument calibrations and provide an initial validation of the data products. A second verification phase shall take place approximately 3 yrs after the initial phase; a third verification phase should take place approximately 5 yrs after launch. Additional verification phases shall be used if deemed appropriate.

Level 1B:

• A near-nadir, narrow-beam laser altimeter operating in the near infrared is required to measure topographic profiles over the ice sheets with little surface penetration.

• The instrument position in space as well as the altimeter pointing direction shall be known to support generation of topographic profiles.

• Surface returns with the altimeter must be obtained in the polar regions under both day and night conditions through thin clouds.

• The laser shall produce a surface footprint that contains 86% of the arriving pulse energy within a diameter of 70 m ± 10 m and with approximately Gaussian characteristics. The return pulse should be digitized and time tagged and the transmitted pulse characteristics should be known, with appropriate time tagging.

• The time interval measurement between pulse transmit and pulse receive time shall exhibit no long term drifts, i.e., the equivalent drift shall be < 10 mm over five years.

• The time tags of the transmit and receive pulses shall have an accuracy of better than 10 microsec in a time system that is traceable to international standards, such as GPS-System Time.

• The time tags of the transmit and receive pulses shall be measured with respect to a specified physical point within the instrument.

Level 1C:

• The orbit shall be nearly polar.

• The minimum allowed orbit altitude shall be 575 km.

• The orbit shall produce a ground track that repeats in 0.5 year, with a subcycle that nearly repeats in about one month.

• The post-launch orbit shall have a repeat cycle of about one week to support repeated overflights of verification sites. This initial verification phase shall extend for a maximum of 120 days after launch. A second verification phase shall take place after about 3 yrs and additional verification phases shall be conducted as deemed appropriate.

• The initial verification phase shall overfly validation sites defined by the GLAS Calibration/Validation Plan.

Level 1D-1:

• The mean orbit inclination shall be between 94°and 94.5°.

• The orbit shall be frozen, i.e., the mean perigee location shall remain fixed near the North Pole. The derived mean eccentricity is 0.0013.

• The verification phases shall use an orbit that repeats in 8 days and 119 orbit revolutions. For i=94°, the derived mean semimajor axis is about 6971 km.

• The main mapping phase shall use an orbit that repeats in 0.5 yr and 2723 orbit revolutions. For i=94°, the derived mean semimajor axis is about 6970 km.

Level 1D-2:

• The laser pulse-repetition rate shall be 40 Hz.

• The measured altitude shall be characterized by zero-mean, Gaussian noise with a standard deviation of 100 mm or less.

• The instrument position in orbit shall be known at each laser pulse with an error, σ_r*, of better than 50 mm in the radial direction and 200 mm horizontal. This requirement shall be met with GPS and SLR.*

• The flight GPS receiver shall record carrier-phase and pseudo-range data, time tagged in GPS-System Time, on two frequencies (L1 and L2) from a minimum of 8 GPS satellites. Carrier-phase must be recorded at one second interval, pseudo-range may be recorded at 10 sec or less. Carrier-phase precision shall be better than 5 mm on each frequency and better than 300 mm for pseudo-range.

• The laser pointing direction shall be known at each laser pulse with an error, σ_p*, of 1.5 arc second or better. This requirement shall be met with modern star camera/gyroscope systems and a means of monitoring the laser direction with respect to spacecraft axes.*

• Corrections for troposphere delay, solid-Earth and ocean-loading deformation, and any other significant corrections shall be provided with the altimeter data.

• The altimeter measurement, orbit position and laser pointing direction shall be time-tagged in a common time system, GPS-System Time.

• The laser spot location shall be described in the ITRF, or an equivalent reference frame.

• The position of the altitude reference point, the spacecraft/instrument center of mass, the GPS antenna phase center and the SLR array shall be known to better than 5 mm with respect to a specified point on the instrument or spacecraft over the instrument lifetime.

• The surface spot track shall repeat to within 170 m at 79° latitude after the 0.5-year repeat cycle. For a nadir pointing direction, the orbit nadir track shall repeat within ± 1 *km at the equator; alternatively, pointing control with an accuracy of 60 arc sec can compensate for*

looser orbit control.

• Activation of thrusters for orbit control shall be avoided in the polar regions; however, thrusting in the vicinity of the North Pole is acceptable provided the instrument does not fly over Greenland within 30 min of thrusting. Thrusting over the Antarctic is allowed only in extenuating circumstances.

Level 2D-2:

• The flight GPS receiver shall record carrier-phase and pseudo-range data on two frequencies (L1 and L2) from a minimum of 8 GPS satellites, but preferably from 12 satellites.

• Carrier-phase shall be recorded at one second intervals, pseudo-range should be recorded at 10 sec or less. Carrier-phase precision shall be better than 5 mm on each frequency and better than 300 mm for pseudo-range.

• The carrier-phase and pseudo-range measurement time tags shall be traceable to GPS-System Time through the pseudo-ranges. The receiver reference oscillator may drift with time or be steered to GPS-System Time.

• The GPS antenna shall be zenith-oriented and positioned on the spacecraft to minimize multi-path effects. The reference phase center of the antenna, with its ground plane, shall be fully characterized as a function of azimuth and elevation with respect to a fixed point on the antenna system to better than 5 mm. The location of this fixed point with respect to a specified point on the spacecraft shall be known to better than 5 mm.

• The SLR array shall be compatible with the global ground-based network of SLR stations. The array shall support SLR tracking from ground-based elevations as low as 10°.

• The SLR array shall be characterized to enable range corrections as a function of viewing direction. The location of the array with respect to a specified point on the spacecraft shall be known to better than 5 mm.

Level 1D-3:

• The pointing shall be controlled with an accuracy of 20 arc seconds (one-sigma).

Level 1D-4:

• The presence of atmospheric cloud and aerosol scattering layers of optical thickness of 0.1 or greater shall be determined for all surface ranging signals over sampling intervals of no more than four contiguous pulses.

• Pulse signal returns from dense low altitude clouds or fog shall be identified on a single pulse basis.

Level 1E-1:

• *Operate the GLAS laser altimeter in a continuous data acquisition mode over the Earth's landforms.*

• *Measure land surface elevation to 10 m or better vertical accuracy on a single laser pulse basis for footprint-scale slopes of less than or equal to 30 degree, improving to 1 m or better vertical accuracy for slopes of less than or equal to 3 degree. Slope angle is defined as the angle of incidence between the laser pulse direction and the normal to the Earth's surface in the laser footprint.*

• *Record the time history of individual, landform pulse echoes with sufficient amplitude dynamic range, temporal resolution, and temporal duration to reveal the signature of the vegetation-removed land surface when the vegetation canopy closure within a single laser footprint is 90% or less.*

• *Obtain an average density of 100 ground control points per 100 km square area at the equator for each mission year.*

Level 1E-2:

• *The GLAS spacecraft shall have the capability to control pointing of the sensor ground track of the GLAS laser altimeter in order to focus coverage over the Earth's landforms into narrow strips of 1 km width at the equator.*

Level 1F:

• *Profile all cloud and aerosol structure of the atmosphere from -5 km to 40 km altitude at the resolution and accuracy requirements in Table 2 throughout all orbital conditions and times.*

• *Measure the background radiance signal at the lidar wavelengths to the precision and resolution given in Table 2. Measure the background infrared radiance at 11 μm at the location of the lidar footprint to 1 km resolution.*

• *In the initial 40 days of the mission the orbit shall be in a plane to optimize the co-incidence of measurements with the EOS AM and PM platforms for validation activities and additional validation activities will take place at two year cycles.*

Level 1G-1:

• *The instrument shall measure the observed atmospheric scattering cross section to the sampling and cross section dependent accuracy as specified in Table 3 over to full range of atmospheric scatters.*

• *The atmospheric signals shall be retrieved over the full dynamic range without saturation and with sufficient linearity to meet accuracy requirements. This requirement gives need for* *two channels - an analog channel for detection of strong cloud signals and a high accuracy photon counting channel.*

• The vertical sampling resolution of the atmospheric signal shall be 75m. Signals shall be obtained over a range of -5 to 40 km.

• The strong signal channel shall be recorded on a single pulse basis and over the altitude range where cloud signals are present.

• The high accuracy channel shall be recorded on a horizontal resolution greater than 1 km. Given a 40 pulse per second rate as stated in section 3.4 a four pulse average or greater would be acceptable. A caveat on this sampling requirement is that further study of the problem of surface ranging bias due to cloud scattering may indicate a need for greater resolution.

• The polarization bias of the retrieved atmospheric signal shall be no greater than 2%.

• The background signal for each laser pulse shall be measured to 2% accuracy for each atmospheric channel.

Level 1H:

• The GLAS spacecraft shall be capable of pointing 2° off-nadir, with a desired angle of 5° or more.

• The GLAS launch shall take place when a MODIS platform is appropriately aligned with the launch site to enable maximum periods of coincident observations during the Initial Verification Phase.

2.0 SCIENCE GOALS AND LEVEL 0 REQUIREMENTS

2.1 CRYOSPHERE

2.1.1 Introduction

The huge ice sheets[1] of Greenland and Antarctica hold enough fresh water to raise global sea level by 80 meters if they melted completely. Although this melting is not imminent, it is known that changes are taking place within these ice sheets in response to natural processes and, possibly, as a result of anthropogenically-induced processes as well. The West Antarctic Ice Sheet, which alone contains the equivalent of 6-7 meters of sea level rise, rests on a bed far below sea level; this may make it particularly susceptible to dynamic, even unstable, change. On the other hand, the vastness of the entire Antarctic ice sheet suggests that small changes could have profound effects.

Measurements of sea level from the TOPEX/POSEIDON radar altimeter show a current rise of +2.1 ± 1.3 mm/yr (Nerem et al., 1997). Although the uncertainty in this measurement is comparable to the measured change, the value is in line with the rise over the last century measured by tide gauges (Warrick et al., 1996). However, the specific contribution of the ice sheets to this change is unknown; furthermore, our knowledge of the ongoing changes in the ice sheets is too poor to allow prediction of the future state of the ice sheets.

We do know that the ice sheets are not static. They change their masses (or volumes, as measured by changes in surface elevation) by complex processes that exhibit large spatial and temporal variations. The mass change, known to glaciologists as the mass balance, is the difference between the mass of snow and ice that accumulates on the surface and the mass that is lost from melting and iceberg calving. An ice sheet, or a region within an ice sheet, is in steady state if its mass balance is zero. But the mass balance of the polar ice sheets, even whether it is positive or negative, is unknown.

We expect the mass balance to exhibit both a long-term linear change with time (i.e., a secular change in mass) and other temporal changes, including both annual and interannual variations. The most dynamic portions of the ice sheets, the fast moving (0.5 km/yr to 3 km/yr) ice streams, transport most of the ice mass from the interior of the ice sheet to its edges, where the ice either flows into an ice shelf or calves and melts directly into the ocean. The mass balance of the floating ice shelves has no direct effect on sea level, but changes in the ice shelves, which buttress most of the ice streams, could affect their dynamic behavior.

Although sea level changes also in response to input from ice caps and glaciers, as well as thermal expansion of the ocean itself, the ice sheets contain the potential for the most significant contribution to sea level rise simply because they contain so much ice. As noted in the 1992 IPCC Supplement on Scientific Assessment of Climate Change, the largest uncertainty about sea level is

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1. By convention, the term “ice sheet” refers only to ice bodies that are sub-continental or larger in size; i.e., at the present moment of geologic time, the term applies only to the ice covers of Antarctica and Greenland.

“rooted in our inadequate understanding of polar ice sheets (whose response to climate change also affects predictions of sea level rise).” The National Academy of Sciences (1990) stated that “possible changes in the mass balance of the Greenland and Antarctic ice sheets are fundamental gaps in our understanding and are crucial to the quantification and refinement of sea-level forecasts.” This uncertainty was further iterated by Watson et al. (1996), who further noted that “monitoring of key components of the cryosphere must continue. The mass balance of the ice sheets of the world is poorly known.”

The impact of even small rises in sea level has been widely studied. Aside from the threat of inundation faced by low-lying coastal areas, increased beach erosion that would occur before inundation, for example, is a serious economic concern (Titus, 1985; Bird, 1993).

Finally, sea-ice surface roughness determines atmospheric drag on the sea ice, which is required for accurate modelling of sea-ice motion. Changes in sea-ice are important for commercial shipping, but sea-ice is also important within the context of climate change.

2.1.2 Science Goals: Cryosphere

Based on the previous discussion, the cryosphere science goals for the Geoscience Laser Altimeter System (GLAS) within the Earth Observing System (EOS) are as follows:

- *The primary cryospheric science goals of GLAS are to measure long-term changes in the volumes (and mass) of the Greenland and Antarctic ice sheets to sufficient accuracy to assess their impact on global sea level, and to measure seasonal and interannual variability of the surface elevation in sufficient spatial and temporal detail to permit identification of long-term trends and to help explain those trends. A further goal is to provide a precise elevation topography of these ice sheets and describe the nature of surface characteristics (e.g., roughness), including sea ice.*

Ice sheets thicken by snow accumulation and thin by snow densification, ice creep and motion, and evaporation and melting. Annual snowfall averages about 0.3 m of water equivalent per year in Greenland and about half this in Antarctica (Figures 1 and 2). Rates of snowfall, evaporation, densification, and melting change significantly throughout the year and from one year to the next; ice creep and ice motion exhibit less change. Consequently, the ice surface rises and falls in response to the seasonal and interannual changes. The magnitude of this short-term elevation variability is poorly known, but is estimated to be on the order of one meter over most of Greenland over periods of a few years, and less over most of Antarctica. Near the coasts, where snow accumulation and melt rates are high, this variability may increase to a few meters.

These short-term changes must be monitored for two major reasons: to infer the interannual variability of snow-accumulation and melting rates, and to reveal the longer-term changes in ice-sheet volume that could seriously affect sea level. Such trends will undoubtedly be different for each major ice drainage basin. Consequently, long-term changes must be measured over all the major drainage basins, and in enough spatial detail to detect major redistributions of volume within each basin. This level of detail is needed to help explain why the changes are occurring, and should be collected over each of the three regions that a drainage basin comprises: the high-elevation, slow-moving accumulation region; the faster-moving ice streams that drain the basin; and the low-elevation region where ice is lost by melting and/or the calving of icebergs.

In Antarctica, drainage basins are large, on the order of 200,000 km^2, with the accumulation region comprising most of this area, and the other two components together occupying on the order of 20,000 km^2. In Greenland, the corresponding areas are approximately half of these values. Present understanding of the magnitude of long-term changes is very poor. For the most part, it is based on comparison of total snow accumulation with total ice loss to yield an ice mass imbalance, which can be expressed as an average rate of increase/decrease of surface elevation over the region; errors are large. Table 1 lists some examples. Although the estimates cover a large range, there is a clear tendency for estimated thickening/thinning to be small (less than 0.1 m/yr) over the accumulation regions, and considerably larger (several tenths to more than 1 meter/yr) over the ice streams and seaward margins.

Fig. 1 (Antarctica)

Fig. 2 (Greenland)

Table 1. Example Elevation Changes

Location	Elevation Change Rate (m/yr)	Characteristic Area (km^2)	Reference
Antarctica			
Ice stream B, ice plain	-1 to +2	10,000	Bindschadler, et al., 1993
Ice Stream B, trunk	-2 to +2	2500	Shabtaie, et al., 1988
Ice Stream B, catchment	-0.1	100,000	Shabtaie, et al., 1988
Ice Stream A	-0.1	70,000	Shabtaie, et al., 1988
Ice Stream C	+0.1	150,000	Shabtaie, et al., 1988 Whillans and Van der Veen, 1993
Ice Stream D Alt model	-0.07 -0.1	110,000 160,000	Shabtaie & Bentley, 1987
Ice Stream E	-0.3	140,000	Shabtaie & Bentley, 1987
Ice Stream D	-0.3 to +0.8	2500	Bindschadler, et al., in pr.
Ice Stream E	0 to +0.4	3000	Bindschadler, et al., in pr.
Shirase Glacier	-2.5 to +0.5	2000	Nishio, et al., 1989
Interior Lambert/ Amery basin	0 ± 0.3	1,160,000	Allison, 1996
Central Lambert/ Amery basin	+0.5	140,000	ibid
Greenland			
Southwest ice sheet	+0.1 to +0.15	50,000	Krabill, et al., 1995; Thomas, et al., in prep. Davis, 1996

2.1.3 Level 0 Science Requirements: Cryosphere

The retreat of mountain glaciers over various time scales has been well documented. Because of their spatial extent, however, far less is known about the changes taking place within the polar ice sheets. We know from examination of ice cores extracted in Greenland and Antarctica that natural variations have taken place on a variety of time scales: annual, interannual, decadal and longer.

Separation of secular changes in ice sheet elevation from periodic variations, especially decadal variations but also interannual variations, requires measurement of changes in ice sheet topography over long intervals of time. Clearly, decadal variations will be falsely identified as secular change if the observations are limited to a few years duration. With this in mind, the measurements required for GLAS should be conducted for a period longer than a decade, preferably 15 years to provide reasonable assurance that the observed variations have been separated into secular, decadal, interannual and other periods.

The drainage basins of an ice sheet define, in part, the characteristics of elevation change. The determination of detailed ice-sheet topography is required to better understand the role of the drainage basins. As with the elevation change, the elevation must be expressed with respect to a well-defined reference frame, tied to the Earth's center of mass, to facilitate the determination of ice-sheet elevation and elevation change over decadal time scales.

It is unreasonable to expect that measurements over 15 years can be acquired with a single instrument, so it is the expectation that a series of instruments, each with a lifetime of up to five years, will be operated to achieve the science requirements. Such an expectation imposes other requirements, namely the assurance that each successive instrument is properly calibrated and the data products adequately validated to eliminate the possibility of instrumental effects being misinterpreted as geophysical processes. The instrumental calibration should characterize temporal changes within the instrument to assure the proper separation of instrumental and geophysical effects.

Although a series of instruments are required to meet the Science Goals, the first instrument is especially important. The results from the first instrument will form the epoch data set against which all future measurements will be compared to detect ice-sheet mass balance. Secular changes of the ice sheets will be detected by the first instrument, but assurance that the identified variations have been properly separated from long-term changes will require a 15-year data set. Recognizing the importance of the first instrument within the context of developing the technology to make the measurements, the science requirement for the first instrument allows for a three-year lifetime with a five-year goal, but subsequent instruments should have a five-year lifetime requirement.

Stipulating a required accuracy for elevation-change measurements within the three-year lifetime/five-year goal is difficult. Different research applications have different requirements, and the required accuracy will also depend on the type of ice mass under investigation. In Appendix A, arguments are presented for GLAS science requirements based on our present knowledge of ice-sheet behavior, and the requirements for each of the major components of an ice drainage basin have been identified. The drainage systems of the polar ice sheets are the basic components of mass balance. The required accuracy is the minimum necessary to enable the data from one GLAS mission to make significant contributions to most research applications, and particularly to measuring long-term ice thickness changes over all areas of the Greenland and Antarctic ice sheets overflown by GLAS with the exception of small, localized regions where surface slopes are too steep or areas that are perennially cloud-covered. The mission length is assumed to be four years, midway between the three year requirement and five year goal.

The science requirements for elevation change are summarized in Table 2. They are expressed as the accuracy in measuring the change in surface elevation, averaged over a prescribed area, that occurs over time intervals of 12 months (for interannual variability) or 4 years (for secular changes). The accuracy requirement for the equivalent rate of change is provided also. The most stringent requirements are set by the interior of the Antarctic ice sheet and the “Ross” ice streams, which flow from West Antarctica into the Ross Ice Shelf. These regions are at high latitudes; at lower latitudes, the requirements are relaxed because accumulation and ablation rates and/or ice velocities increase.

In summary, the basic GLAS science requirements, referred to as the *Level 0 Cryospheric Science Requirements*, are as follows:

- *The instrument shall provide data to enable determination of ice sheet elevation and its temporal changes over the instrument lifetime. For example, one of the most stringent requirements is in the vicinity of the Ross ice streams, where the determination requires that elevation change be determined with an accuracy of 15 mm/yr over 100 km x 100 km areas with regional surface slopes < 0.6°* (0.1 *rad). (Table 2 contains a more complete set of requirements for elevation change determination).*

- *The surface elevation shall be described in an internationally defined reference frame tied to the Earth’s center of mass.*

- *The instrument shall provide data to enable characterization of the ice surface (e.g., roughness).*

- *A data set spanning 15 years over Greenland and Antarctica is required to assure separation of secular changes in surface elevation from annual, interannual, decadal and other temporal variations.*

- *Assuming three GLAS instruments to meet the 15-yr requirement, the first instrument shall have a three-year lifetime (minimum), but should be designed with a 5-year goal; subsequent instruments shall have five-year lifetime requirements.*

- *Data from individual instruments shall be verified and calibrated; each instrument shall be calibrated with respect to preceding instruments and instrumental changes with time shall be characterized.*

- *The data products leading to determination of elevation and elevation change shall be validated.*

• *The data collected by the instrument and the ancillary data shall be deposited in a long-term archive and be readily accessible to the scientific community.*

Table 2.
GLAS accuracy requirements for measurement of changes in surface elevation over ice sheets.

	Area (km^2)	Time Interval	Elevation Change	Rate Accuracy	Regional Surface Slope
West Antarctic "Ross" ice streams (79°- 86° South Latitude)					
Secular trends	10,000	4 yrs	60 mm	15 mm/yr	< 0.6°
Variability	50,000	1 yr	13 mm		
Central East Antarctica (80°- 90° South Latitude)					
Secular trends	200,000	4 yrs	18 mm	5 mm/yr	< 0.2°
Variability	200,000	1 yr	4 mm		
East Antarctic (70°–80° South) and northeast Greenland plateaus (75°-80° North)					
Secular trends	50,000	4 yrs	60 mm	15 mm/yr	0.06°-0.6°
Variability	50,000	1 yr	13 mm		
Coastal Antarctica (65°–75° South) and most of Greenland plateau (70°-80° North)					
Secular trends	10,000	4 yrs	180 mm	45 mm/yr	0.2°-0.6°
Variability	10,000	1 yr	40 mm		
Southern Greenland (61°-70° North) and coastal Greenland (61°-80° North)					
Secular trends	2500	4 yrs	250-600 mm	63-150 mm/yr	0.2°-1.7°
Variability	2500	1 yr	50-130 mm		

2.2 LAND PROCESSES

2.2.1 Introduction

Understanding the detailed shape (i.e. topography) of the Earth's land surface is fundamental to diverse Earth science applications from the hydrological, soil, and ecological sciences to the geological, geophysical, and atmospheric sciences. Examination of major science drivers of NASA's Mission to Planet Earth finds that: (1) seasonal-to-interannual climate prediction; (2) long-term climate variability; and (3) land cover change and global productivity; and (4) natural hazards, all require some form of high-resolution and/or high-accuracy knowledge of landform topography. Climate prediction with the recently developed set of global and regional climate models has a critical dependence on the surface-atmosphere interactions including the fluxes of momentum, water vapor, and sensible heat that are controlled by the height and height variability of the Earth's land surface. In long-term climate variability, the central issues are sensitive monitoring of the height of not only the ice sheets, but high latitude ice-free terrain, the retreat or advance of mountain glaciers, the magnitude of post-glacial rebound and other long-wavelength geophysical phenomena, and the joining of high-vertical accuracy data sets on ocean surface, land surface, and ice surface topography. Surface-height change detection at the centimeter per year level, as characteristic of large spatial areas, is the emphasis. On the other hand, the scientific studies of land use and land cover demand very high-resolution (30 meter) spatial information while relaxing the vertical accuracy to the meter level. Important drivers in this area are the height of the ground surface in the presence of vegetation and anthropogenic modification factors. Finally, natural hazards such as volcanic processes, coastal and riverine flooding, surging glaciers, and unstable sloping terrain all require some form of detailed topography for their understanding.

Despite the broadly based needs of the Earth science community for a detailed topographic knowledge and the specific needs for topographic data sets to support individual space flight remote sensing projects, existing topographic data sets are often inadequate. The existing patchwork quilt of global topographic data lacks a common reference frame for maps and digital elevation models, lacks coverage at 100 m or better spatial resolution, lacks vertical accuracy at the sub 10 meter level, lacks civilian access to military and foreign data sets, and faces the non-existence of data in remote areas. For example, the Earth Observing System (EOS) Project imaging sensors ASTER, Landsat, MISR, and MODIS share a requirement for a global data base of 100 m spatial resolution topography for interpretation of their data sets. They need to make topographic corrections based on the surface slope at the scale of their pixel resolution or below. At the present time, about three quarters of the Earth's land surface is known at the 100 meter spatial resolution level and the vertical accuracy of that knowledge (16 meter rms) is insufficient by a factor-of-two for the 9 meter rms knowledge required to make surface slope corrections to 5 degrees in remote sensing imagery at the 100 meter pixel level. The US. Department of Defense, refers to this level of topography knowledge as Digital Terrain Elevation Data (DTED) Level 1. It should be noted that the 16 meter rms vertical accuracy specification for existing data sets (DTED level 1) generally applies only to local or regional datasets. A tie of these sets to one, common Earth-center-of-mass reference is frequently lacking. Thus biases of tens of meters to ~ 100 m are found to exist among the various regional data sets. To compound the problem, only a small fraction of the global 100 meter spatial resolution terrain knowledge, that for the continental United States, is available for unrestricted use. Contributions to spatial coverage and vertical accuracy improvement for land surface topography are in great need as we enter the Earth Observing System (EOS) era with its long-term monitoring of the Earth surface with an array of imaging sensors. Documentation of EOS requirements and the current state of topography knowledge have recently been reported (EOS DEM Science Working Group, 1997).

2.2.2 Science Goals: Land Processes

Space-based remote sensing missions focused on improving land topography knowledge can provide the global access at high spatial resolution and can uniquely provide the common Earth-center-of-mass coordinate reference system that is required for uniting all current and future topography data and providing the foundation data set for interpretation of EOS-era imagery data. The Shuttle Radar Topography Mission (SRTM) now planned for the 1999-2000 time frame has a mission goal of producing a 30 m (DTED Level 2) spatial resolution global map between 60° N and 54° S in its 14-day mission. The SRTM employs interferometric synthetic aperture radar (SCANSAR) for rapid imaging of topography. What the SRTM lacks (i.e. vertical control) in its method of relative topographic measurement based on radar phase difference signatures, it makes up in near-global access, complete coverage (i.e. mapping), and the tie of all observations to a common Earth center-of-mass coordinate system. Lack of SRTM vertical accuracy is not a sensor precision problem, it results from the need for independently known control points and the rather limited availability and accuracy of data sources for these control points. Currently control points are derived from ground survey markers and other features such as road intersections that are identified in the SRTM phase imagery and are known from ground-based observations with GPS or conventional surveying. In addition, a limited number of radar reflectors will be used to provide bright pixels with known surface elevation in the SRTM backscatter amplitude data which can then be assigned to SRTM phase imagery pixels. The SRTM Mission requires in excess of one million points of topographic knowledge on the Earth's surface to control its phase unwrapping process and remove long-wavelength tilts in its interferometer measurement baseline in order to achieve the stated goal of 10 m rms vertical accuracy in its delivered data set. It is likely that the SRTM scientific data quality will ultimately be limited by the number and accuracy of its control points.

Topography data derived from a Geoscience Laser Altimeter System (GLAS) Mission can be quite useful for landform applications and make important contributions by increasing the accuracy of maps and digital elevation models. Since the GLAS Mission is relieved of the burden of mapping by the operation of SRTM and stereo-photogrammetric imaging sensors, the opportunity exists to ensure the scientific utility of existing and planned topography data sets by using GLAS data to provide a global grid of ground control points (GCPs). A grid of GCPs such that each 100 km area (approximate size of a topographic map or DEM) contains ~ 100 points of order 10 m vertical accuracy or better at each grid point would be used to determine the absolute phase of SCANSAR data and would provide a global set of constraints for mosaicing of SCANSAR data swaths. Furthermore, if the GCPs generated by the GLAS Mission could be used for vegetation height error estimation and correction in mapping data, a major error source for surface elevation determination at the 10 m level would be controlled.

To the extent that GLAS Mission data can improve on the 10 m rms vertical accuracy of topographic maps and/or digital elevation models, the GLAS Mission data can also provide direct land science benefits. If the data can achieve the 1 m level of vertical accuracy with 100 m level spatial resolution there is significant benefit in the following geoscience application areas: (1) volcanic morphology; (2) fault zone tectonics; (3) global water balance; (4) lumped catchment routing; (5) ecological modeling; and (6) plate boundaries. For landform regions where sub-meter vertical accuracy is possible, applications in the following areas: (1) structural geology; (2) volcanic swelling; (3) glacial moraines; and (4) wetland circulation are enabled. Documentation of science requirements for global topographic data sets is contained in topographic working group reports published by NASA in 1988 and 1993.

Surface elevation measured to an accuracy of meter or sub-meter levels also has a prime benefit in multitemporal coverage for change detection. This application category poses the additional requirement of sequential observations of the same pixel of topography. In space-based monitoring these opportunities for change detection present themselves at orbit-track crossing points that occur with the crossovers of the ascending and descending orbit nodes. Crossover density and their spatial distribution can also be selectively enhanced by off-nadir pointing of the topographic sensor. Change detection opportunities are particularly available where we find vegetated regions, in-land water bodies, glaciers, and ice caps as well as areas prone to the redistribution of land mass, such as desert sand sheets, steep slopes, and coastlines/barrier islands. Global access to data sets at this level of accuracy is not currently available.

The preceding discussion leads to the following land processes science goals:

- *The primary land processes science goal of GLAS is to conduct topographic measurements of the Earth's land surface on a global basis in order to contribute to a global grid of ground control points for georeferencing of topographic maps and digital elevation models. The secondary land processes science goal is to detect topographic change at the meter per year level or better in selected regions of limited spatial extent.*

2.3.3 Level 0 Science Requirements: Land Processes

The Level 0 Requirements for Land Processes are:

- *Determine land surface elevation to an accuracy of 10 m or better and a spatial accuracy of 100 m or better at point locations on a global basis.*

- *Detect topographic change at the meter per year level in selected regions of limited spatial extent.*

2.3 ATMOSPHERIC SCIENCE

2.3.1 Introduction

The Earth-Atmosphere system is complex, dynamic and ever changing. Our ability to forecast short term weather as well as long term climate change is currently hampered by our limited ability to make global observations of atmospheric state. Climate is especially influenced by the vertical structure and horizontal coverage of clouds which alter the radiative fluxes at the top and bottom of the atmosphere and determine the vertical distribution of atmospheric radiative heating rates. Knowledge of the height, coverage and thickness of cloud layers is essential in modeling the radiative fluxes at the surface and within the atmosphere. Clouds frequently occur in multi-layer systems on many spatial scales. Satellite based radiometers and imagers do an excellent job of viewing the cloud tops, but the presence of upper layer clouds limits their ability to distinguish multi-level cloud formations and to determine the vertical distribution of clouds. Passive remote sensors also tend to underestimate the fraction of optically thick clouds, while overestimating the percent of broken, optically thick clouds. Recent sensitivity studies using calculations based on ISCCP (International Satellite Cloud Climatology Project) data indicate that the largest uncertainty in long wave radiative flux at the surface is caused by the lack of knowledge of the amount of cloud overlap or multi-layering (Wielicki, et al., 1996). Additionally, it has been noted that the most important satellite remote sensing measurements for climate prediction include the profiles of atmospheric water vapor, cloud top height, cloud base height, thickness and fractional coverage. The forthcoming suite of passive remote sensing instruments proposed for the Earth Observing System (EOS), the first of which will be launched into orbit in 1998, will improve our ability to accurately retrieve cloud characteristics over present day sensors, but will still have difficulty in providing accurate retrievals in many instances. It is by combining passive remote sensing techniques with active profiling of the atmosphere, such as with lidar and radar, that we can obtain a more accurate and robust data set on cloud properties for use in climate change research.

The measured increase in CO_2 over the last 100 years is well known and demonstrates mankind's unrelenting impact on his atmospheric environment. Climate models suggest that increases in this greenhouse gas will result in warming of the earth's climate. However, occurring simultaneously is an increase in anthropogenic aerosols which are believed to have an opposite, cooling effect (IPCC, 1995). The exact magnitude of the aerosol forcing is unknown, but is thought to be a substantial fraction of the greenhouse forcing. A major reason for the uncertainty is our limited ability to make global observations of tropospheric aerosols. Aerosols affect the earth's energy budget and climate by scattering and absorbing radiation (direct effect) and altering cloud particle size and number density, which ultimately affects the cloud albedo, scattering and absorption properties (indirect effect). In theory, it is possible to measure the expected increase in aerosol concentrations from space and AVHRR data is currently used to estimate aerosol loading in the atmosphere in clear regions over the oceans (Husar, et al., 1997). AVHRR aerosol measurements are not very accurate and are plagued with sensor calibration difficulties. Next generation (EOS) imaging instruments such as MODIS will improve on these measurements but will still have significant limitations. Passive sensors retrieve aerosol from reflected sunlight and night observations are not possible. The problem of separating surface reflected light from aerosol scattering limits retrievals to non-land areas. Passive sensing also does not show how aerosol are vertically distributed which is important for transport and radiative forcing. Vertically elevated layers of anthropogenic aerosol as well as naturally occurring aerosols such as Saharan dust and volcanic emissions are transported over long ranges and have been linked to air quality degradation, ocean and soil nutrients and in the case of Saharan dust to the formation and intensification of tropical storms and hurricanes

(Karyampudi and Carlson, 1988). Figure 3 is an example of aircraft lidar observations during the Global Backscatter Experiment over the Pacific basin showing a well defined marine atmospheric boundary layer and an elevated aerosol plume blowing off South-east Asia. The production and transport of such large areas of anthropogenic aerosols over and away from high population areas is common worldwide. Saharan dust transport over the Atlantic ocean was imaged by the Lidar In-space Technology Experiment. When coupled with wind direction and speed information, knowledge of the vertical distribution of aerosol materials provides information on aerosol mass transport. Long range transport of trace gases and aerosols is a dominating factor in the global chemical balance. Monitoring the distribution of these aerosol plumes by present passive techniques is difficult and inaccurate.

The height of atmospheric transition layers for atmospheric mixing and cloud formation are important parameters for the transfer of energy from the surface to the free atmosphere and for the hydrological cycle of the atmosphere. Neither the Planetary Boundary Layer (PBL) height or the Lifting Condensation Level (LCL) can be obtained directly from passive sensing. Global detection of boundary layer aerosols and clouds, if vertically resolved, would provide researchers with a basic data set on global boundary layer height, lifting condensation level and near surface moisture and bulk boundary layer moisture over the oceans.

The interpretation of satellite-based cloud imaging and retrievals in polar regions is very difficult due to factors such as extreme cold, darkness, or very high background albedo. Satellite radiometers operate at or beyond their limit of response. Clouds and haze are an important component of the Arctic regions and influence the net radiation balance and strongly affect atmospheric dynamics. In the coldest half of the year, hazes of small ice crystals occur in the lower troposphere. The vertical distribution of ice crystals is considered an important factor governing radiative transfer which determines the vertical temperature and humidity structure in the Arctic winter atmosphere. As previously described a primary science goal of the GLAS instrument is the accurate topographical mapping of the ice sheets over Greenland and Antarctica to assess changes in ice sheet mass which may be related to climate change. The measurement accuracy requirement to fulfill this science goal is on the order of a few centimeters. It has been determined through model calculations that multiple scattering from atmospheric haze and optically thin clouds will markedly affect (spread) the ground return pulse which will in turn adversely affect ranging accuracy. Additionally, in some situations, low lying stratus and or ice crystal precipitation may obscure the surface and create false surface returns. An important requirement for the surface altimetry is an atmospheric observation to easily discriminate when surface signals are effected by high or low clouds, haze or blowing snow. Corrections for the effects of multiple scattering in some cases should be possible. It is not possible to obtain the necessary information for these effects from passive remote sensing instruments. It is thus essential to the ice sheet topography measurements to acquire the polar atmosphere scattering profile to insure accurate surface height retrievals.

Fig. 3 (Lidar measurements)

2.3.2 Science Goals: Atmosphere

The preceding discussion leads to the following atmospheric science goal of GLAS:

• *The primary atmospheric science goal of the GLAS cloud and aerosol measurement is to determine the radiative forcing and vertically resolved atmospheric heating rate due to cloud and aerosol by directly observing the vertical structure and magnitude of cloud and aerosol parameters that are important for the radiative balance of the earth-atmosphere system, but which are ambiguous or impossible to obtain from existing or planned passive remote sensors. A further goal is to directly measure the height of atmospheric transition layers (inversions) which are important for dynamics and mixing, the planetary boundary layer and lifting condensation level.*

In order to understand the effect and interaction of clouds, aerosol and other factors on long term climate and possible global warming, the goal of the EOS program is for a long term, 15 years or more, monitoring of a sufficient set of climate variables. For many requirements EOS passive measurements will provide the necessary data, but as discussed above there are significant observations that will not be obtained by passive sensing alone. Passive measurements have the fundamental limitation of a lack of a direct separation of surface and atmospheric signals and direct resolution of the vertical structure of the atmosphere. Atmospheric lidar remote sensing gives the vertical structure and separation of land and atmospheric signal as the fundamental result (Reagan et al., 1989). The GLAS atmospheric lidar profiling will provide, or in some cases improve, basic measurements needed to understand the role of cloud and aerosol in radiative forcing and dynamics for climate and weather. Acquisition of the atmospheric signal from GLAS are needed for applications relating to cloud, aerosols, radiative forcing and planetary boundary layer investigations. The GLAS atmospheric measurements should provide a unique data set which will aid climate change and related research. The time period over which the observations are required is the same as other EOS cloud and aerosol observations.

The GLAS atmospheric measurements are needed to provide global observations that are unique to active sounding and that are an important adjunct and validation to EOS passive sensors. The science goals for the GLAS atmospheric measurements are given for specific observations below:

1. Cloud vertical profiling

Active cloud profiling is needed to validate and to supplement the limitations of passive cloud retrievals. A main deficiency for parameterization of clouds is our lack of knowledge on the vertical distribution of clouds. Existing and planned passive measurements, while providing top of the atmosphere radiation information, do not adequately provide the essential vertical profiles of cloud and the resultant heating. The prospect of adding active measurements such as lidar will significantly add to progress on determining the 4-D distribution of cloud optical properties and the relationships between these properties and cloud liquid water, ice mass, and water vapor. The GLAS measurements will be applied to establishment of an independent data set of direct profile measurements.

2. Detection of optically thin cirrus

Optically thin, or sub-visual, cirrus is potentially a significant greenhouse component of the atmosphere (Jensen, et al., 1996). Current measurements indicate that typically over half of the west Pacific warm pool region is covered by a sub-visible layer of cirrus at the tropopause. The optical thickness of this persistent layer is small. However the net radiative impact over the entire region is estimated to be potentially significant. Such optically thin cirrus is not reliably detected by passive sensing other than solar occultation. Solar occultation has sampling limitations. Laser measurements are required provide a very sensitive measure of the presence, height and thickness of tenuous cirrus layers.

3. Polar clouds

GLAS cloud observations will have significant value for polar cloud studies. The interpretation of satellite-based cloud imaging and retrievals in polar regions have major problems due to factors such as darkness and extreme low temperatures. Current polar cloud retrievals are considered in large part unreliable. GLAS measurements would unambiguously define cloud type and fraction. Clouds and haze are very important for the processes of the Arctic atmospheres. Cloud cover defines the net radiation balance of the Arctic regions and strongly effects dynamics. In the cold half of the year in Arctic regions, hazes of small ice crystals occur in the lower troposphere which give rise to large reductions in visibility. The crystals are thought to be an important factor in the radiation transfer which determines the vertical temperature and humidity structure of the winter Arctic atmosphere. Cloudless ice-crystal precipitation is believed to be the dominant source of precipitation in large areas of Antarctica. Active laser sensing has the potential to reliably detect ice-crystal precipitation.

4. Multi-layer clouds

A major goal for observation is to define multiple layered and broken cloud cover. Observations of the structure multiply layered clouds is problematic for passive remote sensing techniques. The data set of laser measurements of cloud multiple layering will be important addition to cloud observations and would directly relate to all applications for cloud vertical profiling.

5. Cloud base height and LCL

For a large fraction of cloud cover, laser measurements will determine cloud base height. Although the laser measurements would not define cloud base height in all situations, the measurements are direct and unambiguous. Surface radiation budget is a critical factor for climate. Cloud effects on surface warming are largely related to the cloud component of the downward atmospheric flux. The determining factor of the cloud flux component is largely the distribution of cloud base height. For clouds forming in the PBL the cloud base indicates the LCL. The LCL is a significant variable for boundary layer dynamics. From the LCL the near surface moisture over the oceans can be accurately derived (Palm, et al., 1997)

6. Cloud morphology

The laser measurements image the vertical structure, or morphology of cloud systems. Such morphology information has applications for process studies of cloud and storm formation. As example recent studies indicate that many thick cirrus form primarily from precipitation from very thin generating layers. Such layers may be clearly identified from the structure revealed by the laser imaging and the height is precisely determined. The correlation of generating layer with temperature and humidity fields would aid the parameterization of cirrus formation. Other examples can be given.

7. Elevated aerosol layers and long range transport

Aerosol profiles provided by the GLAS instrument will provide information on episodic aerosol events such as volcanic emissions, ablated desert soils, continental particulates and arctic haze. Vertically elevated layers of particulates are transported over long ranges and have been linked to air quality degradation and ocean nutrients. The laser measurement uniquely defines the vertical aerosol structure throughout the troposphere. The active laser sounding is highly synergistic with and will support the interpretation of passive radiometric measurements and images when aerosol optical thickness becomes appreciable. Ground based laser radar measurements have long been a standard for monitoring volcanic aerosol layers in the stratosphere. The GLAS measurements would give global coverage of such events. Dense volcanic plumes have been known to be a hazard for aircraft transport. The laser observations would aid in the early detection and altitude definition of such layers, especially in conditions of darkness, and thus serve in a hazard avoidance function.

When coupled with wind direction and speed information, the vertical distribution of aerosol trace materials also provides information on aerosol mass transport. Long range transport of trace gases and aerosols is a dominating factor in the global chemical balance. Accurate aerosol vertical profile information is necessary.

8. PBL height

In many cases the GLAS observations will determine the height of the mixed layer from the aerosol scattering structure and in all cases, at high accuracy, the height for a cloud capped boundary layer. The planetary boundary layer height is a basic parameter linking the surface to atmosphere dynamics, especially over the world oceans. Measurement of the PBL height is unique to the active laser measurements.

9. Cloud filtering for GLAS surface altimetry

> The stated cryospheric science goal of the GLAS instrument is precise surface altimetry for polar ice sheets. Clouds and haze will obscure the surface for many laser returns. For conditions of partial transmission through clouds, multiple scattering will effect transmitted pulse shape and thus possibly range accuracy. Scattering for cirrus clouds in particular is highly forward peaked, and the effective transmission may involve a large fraction of scattered photons. Pulse spreading to a degree much larger than the desired surface altimetry accuracy is possible. The identification of cloud influenced surface returns will be provided by measurement of the GLAS atmospheric return.

The parameters which are needed from the GLAS observations are the direct height measurements of boundaries and variables which relate to the radiation and other influence of clouds and aerosols. The height of cloud boundaries are a direct measurement result from lidar profiling. The basic parameter which defines the integrated radiative influence of a layer is optical thickness. The resolution of the vertical resolved structure of radiative forcing, or the relation to physical parameters, requires that the total, or extinction, cross section be obtained. Both the cross section and optical thickness are derived parameters which involve the height resolved laser scattering data and appropriate retrieval algorithms. For boundary layer height levels, the heights are derived values from analysis of the aerosol and cloud scattering structure.

Requirements for the GLAS derived atmospheric measurements are summarized in Table 3. These specifications define the minimum required spatial resolution and accuracy to insure the science objectives outlined in Section 2.3.2 can be accomplished. The spatial resolution should be sufficient to resolve scales that are important to the physical processes being studied but not so fine as to introduce unwanted noise. The required spatial resolution varies with cloud type, aerosol density or atmospheric region as is defined in more detail below. For example, the spatial resolution required to study the radiative properties of cirrus clouds and multiple layered cloud systems is less than the spatial resolution required for the retrieval of LCL from the statistical analysis of PBL cumulus clouds. Thus, the spatial measurement requirement will vary according to which atmospheric parameter or process is retrieved. The measurement accuracy involves the inherent limitation of retrieval algorithms and the signal accuracy of the data.

2.3.3 Level 0 Science Requirements: Atmosphere

Based on the preceding discussion, the *Level 0 Science Requirements* to support atmospheric science are:

- *The instrument will measure the vertical structure of radiatively significant cloud and aerosol structure with sufficient vertical and horizontal resolution to resolve large scale dynamically and energetically important variability. Sufficient accuracy is needed for the optical thickness and vertical profile of total cross section to be obtained up to a limit of approximately 2 in optical depth.*

- *The atmospheric vertical structure will be measured full time over the entire orbital cycle including sunlit and dark scenes.*

- *The accuracy of derived atmospheric parameters must be validated.*

- *The atmospheric measurements will be made over the decadal time period required for all EOS atmospheric observation.*

The parameters which are needed from the GLAS observations are the height of boundaries and variables which relate to the radiation and other influence of clouds and aerosols. The height of cloud boundaries are a direct measurement result from lidar profiling. The basic parameter which defines the integrated radiative influence of a layer is optical thickness. The resolution of the vertical resolved structure of radiative forcing, and its relation to physical parameters, requires that the total, or extinction, cross section be obtained. Both the cross section and optical thickness are derived parameters which involve the height resolved laser scattering data and appropriate retrieval algorithms. For boundary layer and LCL height levels, the heights are derived values from analysis of the aerosol and cloud scattering structure.

The required GLAS atmospheric measurements are grouped into three categories: 1) Cloud, 2) Aerosol and 3) Planetary Boundary Layer measurements. The cloud measurements include multiple cloud layer heights, both top and bottom up to the limit of signal attenuation, percent cloud coverage, derived vertical profiles of scattering cross section and the derived optical thickness of thin clouds and polar stratospheric clouds. The aerosol measurements include aerosol optical thickness and profiles of extinction cross section for most aerosol including stratospheric dust (as from volcanic eruptions), ablated desert soils, continental particulates, anthropogenic sulfate aerosols and arctic haze. There are two basic measurements for aerosols that are not obtained from planned passive observations, the aerosol loading over land areas and the vertical distribution of aerosol loading. These measurements must be obtained from the laser sensing. The planetary boundary layer measurements include PBL height and entrainment zone thickness and, lifting condensation level (when applicable). and near surface moisture over the oceans.

<u>Clouds</u>

a. Cloud top, base and multiple layering heights

Typical cloud structure is multiply layered and broken. GLAS should obtain cloud top height with 150 meter accuracy and a horizontal resolution of 175 meters for clouds with cross sections greater than 10^{-3} (m-sr)$^{-1}$. For clouds with smaller cross sections (10^{-4}-10^{-6}), cloud top height accuracy of 300 meters and horizontal resolution of 2 km is needed. of all clouds existing in the atmosphere. When the upper cloud layer(s) is optically thin (τ=2 or less), the multiple layer structure of the clouds should be obtained. It has been estimated that a difference in average cloud heights of 300 m has a radiative impact comparable to impacts from doubling CO_2. The laser measurements need to give a precise baseline with absolute accuracy on the order of 50m for average regional values. Cloud tops and bottoms should be can be retrieved up to the limit of signal attenuation, typically an optical depth of about 2. Cloud base is an important parameter to be retrieved, both from transmission through thin upper layers and the statistical distribution of the heights of broken clouds. For convective boundary layer clouds, the lifting condensation level is indicated by the cloud base height.

b. Thin cirrus detection

The GLAS atmospheric channel will directly detect and measure the vertical structure of thin cirrus and discriminate between cloud layers when thicker, lower clouds have thin cirrus above them. Large areas of optically thin cirrus (τ<.01) have been detected over the Pacific warm pool region and it is thought that they play an important role in the radiative balance of that region with radiative impacts on the order of 5 w/m^2. The laser measurement needs to detect the presence of all thin tropopause clouds at resolution on the order of 100 km sampling.

c. Optical thickness

The optical thickness of cirrus and other thin clouds will be derived for an optical thickness of up to 2 for a 20 km horizontal resolution. The optical thickness can be obtained to an accuracy of about 30% by using an estimate of the extinction to backscatter ratio and correction for multiple scattering. If additional measurements of infrared radiance are available, the retrieval accuracy should be more than double.

d. Vertical profile of cross sections

The relative vertical profile of observed backscatter cross section is the basic measurement that provides information for resolution of the vertically resolved heating rates in the atmosphere due to clouds. A total scattering cross section and the backscatter cross section is needed. The profile of the total cross section will be obtained with a 20% or better relative accuracy to an optical thickness of 2 for 20 km horizontal resolution.

Aerosol scattering

a. Aerosol profile

The vertical distribution of aerosol is only obtainable from active laser profiling. Most total aerosol loading in the atmosphere is found in the PBL. The relative profile in the planetary boundary layer for aerosol scattering, defined by the observed backscatter cross section, must be acquired at 20 km or better horizontal resolution.

b. Elevated haze layers

The laser measurements will detect and profile elevated haze layers such as volcanic haze layers in the stratosphere and upper tropopause. Layers of optical thickness greater than 0.002 should be detected for a 200 km horizontal resolution. The vertical resolution should be 1000 m or better.

c. Optical thickness

The aerosol optical thickness is obtained from the lidar measurements most accurately with a procedure that employs the coincident surface signal and reflected solar background radiance. The basic technique to obtain the optical thickness from the lidar scattering alone is to employ a model of the relation of extinction to backscatter as a function of air mass. The measurement of the laser profile should be sufficient that the optical thickness is obtained with approximately 30% uncertainty.

d. Total cross section

The vertical resolved aerosol total scattering cross section is obtained in conjunction with retrieval procedures for optical thickness. Accuracy on the order of 30% for cross sections greater than 10^{-5} m^{-1} are sufficient to be useful.

PBL Measurements

The PBL and LCL height is a significant variable for atmospheric dynamics and energetics that can only be obtained by active laser sounding. In many cases, especially for marine atmospheres, the PBL height may be derived from the structure of the aerosol scattering profile. Analysis and field studies indicate that over large fractions of the ocean and many land areas the GLAS measurements should define the PBL height with 150 m vertical accuracy and a horizontal resolution of 20 km or better. Additionally, in areas of broken cumulus, the LCL should be defined at about 100 km horizontal resolution, enabling the retrieval of near surface moisture over the oceans (Palm, et al., 1997).

Requirements for the GLAS Level 0 atmospheric measurements are summarized in Table 3. These specifications define the minimum required spatial resolution and accuracy to insure the science objectives outlined in Section 2.3.2 can be accomplished. The spatial resolution is to be sufficient to resolve scales that are important to the physical processes being studied but not so fine as to introduce unwanted noise. The required spatial resolution varies with cloud type, aerosol density or atmospheric region as is defined in more detail in Section 3. For example, the spatial resolution required to study the radiative properties of cirrus clouds and multiple layered cloud systems is less than the spatial resolution required for the retrieval of LCL from the statistical analysis of PBL cumulus clouds. Thus, the spatial measurement requirement varies according to which atmospheric parameter or process is retrieved. The measurement accuracy involves the inherent limitation of retrieval algorithms and the signal accuracy of the data.

Table 3. GLAS Level 0 Requirements for Atmospheric Science

Measurement	Spatial Requirement Horizontal	Spatial Requirement Vertical	Accuracy Requirement
Cloud Top Heights for Layers (to τ<2)	0.2-5 km	75 m	100 m
Cloud Scattering Cross Section	5-20 km	150-300 m	20%
Thin Cloud Optical Depth	5-20 km	___	30%
Aerosol Scattering Cross Section	20-1000 km	300 m	20%
Aerosol Optical Depth	20-100 km	___	30%
PBL Height	20 km	150 m	150 m
LCL	100 km	200 m	200 m

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CRYOSPHERE

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3.0 LEVELS 1 AND 2 SCIENCE REQUIREMENTS

3.1 Level 1A Requirements: Cryosphere

The highest priority requirements are those that flow down from the Cryosphere Level 0 Requirements. As a consequence, the following Level 1 discussions are primarily in response to the Cryosphere requirements, except as noted. The Level 2 requirements address implementation issues necessary to meet the Level 1 requirements.

A set of Level 1 Science Requirements can be readily derived from the Level 0 Requirements for the Cryosphere stated in Chapter 2. It is apparent that temporal changes and mass balance of the Greenland and Antarctic ice sheets cannot be *directly* measured, but change must be inferred from measurements of topography, or surface elevation, collected over time. Furthermore, temporal changes in topography give volume change and, with appropriate mapping of volume into mass, the mass balance or mass change will be obtained.

A dedicated post-launch verification period is essential to assure proper calibration of the instrument and to assess, or validate, the data products. Since some instrumental changes can be expected over time, a second verification period should take place approximately 3 yrs after the first period to assess the mid-life performance. A third verification period should be conducted after approximately 5 yrs to assess the near end-of-life performance of the instrument.

With these observations, and considering the Level 0 Requirements, the *Level 1A Science Requirements* are:

- *Determination of temporal changes in surface elevation requires measurement of ice sheet topography as a function of time; temporal changes in surface topography gives ice volume changes, which can be mapped to mass change.*

- *Measured topography shall represent the ice surface at the time of the measurement without significant penetration to subsurface levels, and the measurements shall be made over a variety of surface characteristics, e.g., fresh snow, packed ice, sastrugi, etc.*

- *Measurements shall be made over a variety of sloped surfaces, as noted in Table 2.*

- *Regular and repeated topographic measurements of the ice sheets are required at intervals that enable monthly average surface properties in areas as small as 100 km x 100 km to be determined.*

- *An initial verification phase during the first 120-days after launch shall be conducted to evaluate the instrument calibrations and provide an initial validation of the data products. A second verification phase shall take place approximately 3 yrs after the initial phase; a third verification phase should take place approximately 5 yrs after launch. Additional verification phases shall be used if deemed appropriate.*

3.2. Level 1B Requirements: Narrow-Beam Altimetry

Based on current technology, a satellite-borne altimeter with a small footprint is the optimum approach to meet the Level 1A Science Requirements. Only satellite-based sensors can provide regular and repeated measurements over the vast Antarctic continent as well as Greenland. An altimeter will profile the surface and, through appropriate analysis, temporal changes in the surface will be extracted. Altimeter technology has been proven and accepted for ocean applications, but cryospheric applications require an instrument that is optimized for the ice-sheet characteristics. The disadvantages of radar altimetry over the ice sheets are described by Koblinsky et al. (1992). A laser operating in the vicinity of 1064 nanometers can provide the necessary small footprint and limited surface penetration.

Determination of temporal changes of surface elevation requires that measurements be made throughout the year. Since long periods of daylight exist in the polar regions, the instrument must be capable of making measurements in day and night conditions, through thin clouds.

A nadir-pointing altimeter measures the time required for a laser pulse to traverse the distance between a reference point within the satellite-borne instrument to the surface (ice, land, water, or clouds) and back to the satellite. The roundtrip time measurement can be converted into a distance, the “altitude” measurement. The altitude represents the distance between the satellite and the spot illuminated on the surface by the altimeter pulse, referred to as the altimeter “footprint.” This measurement can be converted into a profile of the surface, or elevations, with respect to the Earth center of mass by subtracting the height from the satellite orbital position, which is determined by an independent means, such as the Global Positioning System (GPS). Analysis of the elevations over time provides a determination of changes in the surface, but this analysis requires knowledge of the footprint location expressed in a well-defined and stable geodetic reference frame. This simplified description readily applies to a narrow-beam altimeter.

The rationale for requiring a narrow-beam altimeter is discussed by Curran et al. (1987). In summary, the pulse of a wide-beam altimeter will reflect from a sloped surface at the closest point, thereby complicating the analysis of the return pulse. Over an undulating surface, the narrow beam will either track the undulations or average them, depending on the footprint diameter and the wavelength of the surface undulations. In principle, the footprint diameter should be greater than the surface wavelength to average surface undulations, or the diameter should be significantly less than the wavelength to map the undulations.

Analysis of surface characteristics performed by Zwally et al. [1981] suggest that the optimal footprint diameter should be about 70 m, which can be achieved with an appropriate beam divergence of the laser. Under a fixed beam divergence, the spot diameter will change by a few meters with normal orbital altitude variations. Variations of ± 10 m are acceptable, but the beam divergence should be fixed.

The return pulse should be digitized and appropriately time tagged. To facilitate the analysis, the return pulse should be Gaussian after reflection from a smooth, flat surface. The analysis of the return pulse will provide the measured altitude as well as information about the surface characteristics, including roughness. The transmitted pulse characteristics should be known and appropriately time tagged. Both the transmit and receive pulses must be time tagged with respect to a specified physical point in the instrument to enable calibration of ranges between instruments. The time tags must have an accuracy of better than 10 microsec in a time system that is traceable to international standards, such as GPS-System Time. From the satellite orbital motion of 7 km/sec, an error of 10 microsec produces an along-track position error of 70 mm, but a smaller contribution in the radial direction will result.

Since the altimeter measurements will be used to determine surface-elevation change, it is essential that long-term instrument drifts be either nonexistent or well understood and modeled. Over the lifetime of the instrument (5-yr goal), the long-term systematic error should be less than 10 mm. In part, this error results from the interval measurement between the transmit time and the receive time.

The *Level 1B Science Requirements* that follow from this discussion are:

- *A near-nadir, narrow-beam laser altimeter operating in the near infrared is required to measure topographic profiles over the ice sheets with little surface penetration.*

- *The instrument position in space as well as the altimeter pointing direction shall be known to support generation of topographic profiles.*

- *Surface returns with the altimeter must be obtained in the polar regions under both day and night conditions through thin clouds.*

- *The laser shall produce a surface footprint that contains 86% of the arriving pulse energy within a diameter of 70 m ± 10 m and with approximately Gaussian characteristics. The return pulse should be digitized and time tagged and the transmitted pulse characteristics should be known, with appropriate time tagging.*

- *The time interval measurement between pulse transmit and pulse receive time shall exhibit no long term drifts, i.e., the equivalent drift shall be < 10 mm over five years.*

- *The time tags of the transmit and receive pulses shall have an accuracy of better than 10 microsec in a time system that is traceable to international standards, such as GPS-System Time.*

- *The time tags of the transmit and receive pulses shall be measured with respect to a specified physical point within the instrument.*

3.3 Level 1C Requirements: Orbit

Regular and repeated measurements over the entire ice sheets with a laser altimeter for period spanning several years require that the measurements be made from a satellite. The satellite orbit can be designed to provide uniform coverage of the ice sheets, as required to provide appropriate statistical sampling of the surface.

Two aspects must be considered for the orbit requirements: 1) the general orbit requirements (altitude, inclination, etc.) and 2) the orbit position knowledge required for the conversion of altitude into topographic profiles. Both aspects of the orbit requirements are necessary to satisfy the Level 0 Science Requirements.

The orbit must be near polar to provide coverage of the Antarctic ice sheet. The specific inclination, however, is the result of considerations associated with the data analysis approaches, described in Section 3.4. The orbit should be nearly circular to provide a uniform altitude variation.

The orbit altitude should be as low as possible to minimize instrument transmit power. However, low altitudes complicate the ability to determine the orbit position accurately, which is required to obtain surface topography profiles from altitude measurements. These complications result from accentuated errors in the models of Earth gravity and atmospheric density, both of which influence the accurate determination of position, known as the "Precision Orbit Determination" (POD) process. Furthermore, low altitudes introduce operational considerations, including propulsion requirements for orbit maintenance, required to compensate for drag-induced orbit decay. Based on simulations (Davis and Schutz, 1996) and the frequency of expected orbit maneuvers during solar maximum (~ 5 days), the minimum acceptable altitude is about 600 km, perhaps as low as 575 km.

If the spacecraft/instrument has no method of drag compensation, the altitude decay will result in clustering of the ground tracks (or nadir tracks). The result would be nonuniform sampling of the surface, which contradicts the Level 1A requirements for regular and uniform sampling. As a consequence, the orbit must be controlled to produce a repeating, or near-repeating ground track. For longer repeat intervals (or repeat cycles), the density of surface sampling will increase, but fewer repeat tracks will be made over the same location (a consideration for the data analysis). A long repeat cycle of 0.5-yrs produces a track separation of about 2 km at 80° latitude and it is compatible with the analysis for semiannual and longer variations. Furthermore, if the ground track nearly repeats in about one month (the subcycle), statistical averages over the subcycle can be formed as well. The dense spacing of tracks in the polar region is required for detailed mapping of the major Antarctic drainage basins.

An additional requirement results from the profound importance of instrument verification/calibration and data-product validation considerations. These activities, identified in the Level 0 Requirements, can be supported by a post-launch verification/validation period during which the ground track regularly overflies verification sites. Thus, the verification/validation requires that a repeat track with a repeat-cycle of about one week be used in an early post-launch phase and for a second time after about 3-yrs, the minimum instrument lifetime.

In summary, the following orbit requirements are represented in the *Level 1C Science Requirements*:

- *The orbit shall be nearly polar.*

- *The minimum allowed orbit altitude shall be 575 km.*

- *The orbit shall produce a ground track that repeats in 0.5 year, with a subcycle that nearly repeats in about one month.*

- *The post-launch orbit shall have a repeat cycle of about one week to support repeated overflights of verification sites. This initial verification phase shall extend for a maximum of 120 days after launch. A second verification phase shall take place after about 3 yrs and additional verification phases shall be conducted as deemed appropriate.*

- *The initial verification phase shall overfly validation sites defined by the GLAS Calibration/ Validation Plan.*

These general requirements will be refined in the next section to produce additional Level 1 Science Requirements.

3.4 Level 1D Requirements: Data Analysis

The mass balance of the major ice sheets cannot be directly measured, but must be derived from the analysis of a time series of data that is dependent on the temporal variations. As previously described, a satellite-borne, narrow-beam altimeter provides a profile of the ice sheet after account is taken of the orbit position component and the altimeter pointing direction. Simply stated, the time series of altimeter surface spot coordinates, expressed in a geodetic reference frame (surface profiles), contain information about temporal changes.

Detection of elevation change can be accomplished from two approaches: 1) differenced measurements at track intersection points, or crossovers (see Fig. 4), and 2) direct comparison of surface profiles taken along the same lines. The direct comparison is accomplished by comparing the surface elevation from two or more repeat tracks, i.e., tracks that repeat in the same direction. The crossover analysis uses differenced surface elevations at the intersection point.

Both analysis approaches will be used with GLAS to exploit the advantages associated with each approach. Crossovers are formed by differencing the surface elevations obtained at two different times from the same location. Common effects will cancel in the crossover formation, but temporal effects will remain, a distinct advantage. However, the crossover density is dependent on latitude, a disadvantage. On the other hand, repeat track comparisons will be influenced by crosstrack surface slopes. If the crosstrack slope effect can be mitigated, direct comparisons will enable assessment of surface change with data points that greatly exceed the number of crossover points. On balance, the crossover approach will be the primary mode of analysis to detect elevation change, but the ability to use the direct approach is, nevertheless, an important element of analysis tools.

3.4.1 Orbit Considerations

An exactly polar orbit ($i=90°$) has no useful crossovers. The orbit considerations are described by Schutz (1996) who concluded that the inclination should be 94°. This conclusion was based on a)

Fig. 4 (crossover geometry)

coverage of the West Antarctic Ice Sheet drainage basins, especially the ice streams that flow into the Ross Ice Shelf, and b) better geometry afforded by a retrograde orbit. Examination of the Ross Ice Streams (Fig. 5) suggests that the acceptable inclination range is 94° to 94.5°, which provides nadir coverage to a maximum latitude of 86° or 85.5°, respectively. A region of about 4° latitude, centered on the pole, will exist where a nadir-looking altimeter can acquire no data. Data from this excluded zone are still required, and methods are available to acquire data within the zone, as described in Section 3.5.

The altitude variation around the orbit is an important analysis consideration. An inherent variation will take place since the Earth is, to a good approximation, an oblate spheroid. However, the non-critical inclination of the orbit will generally result in a rotation of the semimajor axis, thereby producing an additional variation in altitude. A special orbit case exists, however, that has been used by most altimeter satellites to keep the perigee fixed, in an average sense, over the North pole. This orbit, referred to as the frozen orbit, will produce approximately the same altitude at each crossing of a specific latitude. As a consequence, crossovers will be bounded to a few hundred meters, rather than thousands of meters if perigee is allowed to rotate. The orbit eccentricity of about 0.0013 will produce a frozen orbit. Additional discussion is given by Lim and Schutz (1996).

With the inclination and the eccentricity fixed, other orbit characteristics can now be defined. The Level 1C Science Requirement calls for a repeat orbit with a period of 0.5-yr and a near-repeat subcycle of about one month, with a minimum altitude of 575 km. Furthermore, the verification period requires a one-week repeat for a period up to 120-days after launch. To minimize the impact on scientific analysis, the altitude of the verification phase orbit and the 0.5-yr main mapping phase orbit should be close. Candidate orbits in the vicinity of 600 km, with i=94°, are:

Verification Phases:
8-day repeat cycle in 119 orbit revolutions
Semimajor axis = 6971 km
Eccentricity = 0.0013 (frozen)

Main Mapping Phase:
183-day repeat cycle, with 25-day subcycle, in 2723 orbit revolutions
Semimajor axis = 6970 km
(equatorial altitude=592 km, S. Pole altitude=622 km, N. Pole altitude=603 km)
Eccentricity = 0.0013 (frozen)

A similar set of orbits exists at an equatorial altitude of 518 km, but this altitude is regarded as too low (Level 1C Requirements). If the inclination is i=94.5°, the same main mapping characteristics can be achieved, but the altitude (or semimajor axis) will be slightly higher by about 0.5 km.

With these considerations, part of the *Level 1D Requirements (Level 1D-1)* are:

- *The mean orbit inclination shall be between 94°and 94.5°.*

Fig. 5 (Antarctic Ice Streams)

• *The orbit shall be frozen, i.e., the mean perigee location shall remain fixed near the North Pole. The derived mean eccentricity is 0.0013.*

• *The verification phases shall use an orbit that repeats in 8 days and 119 orbit revolutions. For i=94°, the derived mean semimajor axis is about 6971 km.*

• *The main mapping phase shall use an orbit that repeats in 0.5 yr and 2723 orbit revolutions. For i=94°, the derived mean semimajor axis is about 6970 km.*

3.4.2 General Error Budget

A detailed discussion of the error sources that contribute to a single-shot laser-altimeter measurement is given by Schutz (1996). In symbolic notation, the dominant error sources are summarized in Table 3. As described in Section 3.2, conversion of the measured altitude into surface profile requires knowledge of both the instrument position in orbit and the laser pointing direction. The pointing error contribution, σ_p, for a 600-km-altitude orbit is 50 mm per arc second pointing error per degree surface slope. The error in orbit position, primarily the radial component, is represented by σ_r and the error in the measured altitude is σ_m. Other contributors to the error budget include parameter errors in the modeling of the signal delay from the troposphere, errors in the position of the instrument reference point with respect to the spacecraft center of mass, etc. The aggregated effect of these other errors is σ_o. Assuming all errors are random, the single-shot error, σ_{ss}, is formed by the square root of the sum of each individual error source squared. These error components form the set of parameters necessary to meet the Level 0 Requirements.

3.4.2.1 Crossover Analysis

The error components will contribute to both analysis approaches. However, the crossover has an additional consideration. As illustrated in Fig. 4, it is unlikely that the laser spots will exactly coincide at the intersection point of the spot tracks. The spot proximity will be determined by the laser pulse-repetition rate (PRR). As a consequence, a “crossover measurement” can be formed by interpolating the spots on each respective track to the intersection point. The interpolation error will be dependent on the PRR and the surface characteristics. Based on studies by Zwally and Saba (1996) using an aircraft-based emulation of GLAS over Greenland, the PRR should be 40 Hz, which will result in an interpolation error of about two centimeters. With this PRR and the previously specified altitude, the spot separation will be about 170 m. The crossover error budget is then dependent on the single shot errors and the interpolation error, which may be further reduced by smoothing several individual measurements before performing the interpolation. The aggregated effect of these errors in the crossover measurement is σ_{xo}, which is approximately $\sqrt{2}\,\sigma_{ss}$.

Error analyses have been performed by Schutz (1996) and Thomas (1996) and a high fidelity simulation has been conducted by Choe and Schutz (1997). These analyses consider the influence of various parameters, particularly the affect of σ_m, σ_r, σ_p, and σ_o on the ability to meet the Level 0 Requirements.The latter simulation has modeled the measurement error with zero-mean, Gaussian noise, the orbit error was modeled with a high-fidelity simulation with appropriate gravitational and nongravitational error sources and the pointing error was modeled as a Gauss-Markov stochastic process. It is important to note that the level of orbit error used in the simulation has assumed that the current gravity fields have been improved, since the covariance matrices of current gravity fields predict errors that exceed an acceptable level of error. These improvements are expected to occur from the following considerations:

- Ongoing analysis and inclusion of new data
- Operation of the ESSP gravity mission, GRACE
- Tuning of the gravity field in the verification phase

The latter technique was used on TOPEX/POSEIDON and it has been shown by simulations to be a viable approach for GLAS (Rim and Schutz, 1996).

These studies show that the following characteristics are required to meet the Level 0 Science Requirements:

- Measurement: the measurement of altitude should be characterized by zero-mean, Gaussian noise. The value of σ_m should be 100 mm or less;
- Orbit error: the radial orbit error, represented by σ_r should be less than 50 mm and the horizontal position error should be less than 200 mm.
- Pointing error: the laser pointing error, represented by σ_p, should be 1 arc second or less.

It can be concluded from these studies that orbit error is the dominating systematic error on flat surfaces and pointing error dominates on sloped surfaces. Furthermore, even though the systematic errors contained in the orbit and pointing contributions do not always average as well as the measurement error, the studies show that the general characteristics summarized above enable the variety of requirements given in Table 2 to be achieved.

Based on the conversion of the different components into determination of the surface footprint location and with consideration given to the Level 0 Requirements, a common time scale and terrestrial reference frame must be used. The altimeter measurements and the determination of an instrument reference point in space, as well as the laser pointing direction, must be time-tagged in a consistent system. The laser surface spot location should be described in the IERS Terrestrial Reference Frame (ITRF), or the equivalent. The ITRF is carefully scrutinized by the international community, which assists the validation of the stability and consistency with other related factors.

The comprehensive experience with TOPEX/POSEIDON (T/P), which has high accuracy positioning requirements that are similar to GLAS, showed that the orbit-position requirements can be met with the Global Positioning System (GPS). However, use of GPS also requires an appropriate ground-based network of GPS stations. Fortunately, the international community (including NASA) has a strong commitment to support such a ground network, the IGS (International GPS Service for Geodynamics), that is described by Beutler et al. (19xy). In concept, the GPS measurements from the GLAS spacecraft will be differenced with those collected by the ground network to remove undesirable features. In T/P, GPS has been demonstrated to produce orbit position accuracies of better than 30 mm (radial), as described by Yunck et al. (1994) and Schutz et al. (1994). To support validation of the orbit accuracy, the orbit position must be determined by an independent technique. Again, the T/P experience showed that satellite laser ranging (SLR) is one means of meeting that requirement. Hence, an SLR reflector must be carried on the GLAS spacecraft. This reflector must be designed to work with the global network of SLR stations.

The GPS receiver carried on the GLAS spacecraft must provide two-frequency (L1 and L2) pseudo-range and carrier-phase measurements. The two frequencies enable an ionosphere correction to be made, which is essential to achieving the orbit accuracy requirement. A single frequency receiver would require correction for the ionosphere using less reliable modeling approaches. Two methods will be used in the GPS analysis: dynamic orbit determination and kinematic positioning. To support the kinematic positioning, the carrier-phase should be recorded at an interval of one sec with a better than 5 mm precision on each frequency. Pseudo-range may be recorded at an interval of 10 sec or less with a precision of better than 300 mm. The pseudo-range and carrier-phase must be time-tagged in GPS-System Time, or the correction must be derivable. The receiver shall be capable of collecting simultaneous data from a minimum of 8 GPS satellites, preferably up to 12 satellites, to assure common visibility of at least 6-8 GPS satellites with the ground stations.

Knowledge of pointing direction for each laser pulse is required to determine the coordinates of the laser footprint on the Earth's surface. Since the laser pulse-repetition rate is 40 Hz (Level 1x Requirement), the techniques used to determine the pointing direction must be compatible with this rate. The pointing direction is determined by two factors: the laser orientation with respect to spacecraft (or optical bench) axes and the orientation of those axes in space. The determination of the orientation parameters associated with each factor may use separate sensors, but in-flight, intra-sensor procedures should be available for verification.

The determination of instrument orientation in space, or attitude, to 1 arc second can be accomplished with a star camera and gyroscope. Since the pointing direction is required for each laser pulse (40 Hz), the techniques used to determine pointing direction must be compatible with the pulse-repetition rate. This instrumentation may be modified or separate instrumentation may be used to determine the laser pointing direction with respect to the spacecraft.

Simulations and experience with existing satellites have shown that attitude determinations at the 1 arc second level can be accomplished using modern star cameras/gyro systems. Since current star cameras capture several stars in a single image with an imaging rate in the vicinity of 10 Hz, application of appropriate estimation methods aid the precision attitude determination at the level required for GLAS.

The laser pulse is delayed through the troposphere. A correction can be applied, provided the surface pressure is known. An error of 10 millibars in surface pressure will contribute 20 mm to the error budget. Other parameters, such as temperature and relative humidity also contribute at a lower level (see Appendix B). Other corrections for surface deformation include solid Earth and ocean loading should be applied as well. In addition, any other correction deemed to be important should be available with the data products.

To meet the Level 0 requirements, the following locations must be known throughout the instrument lifetime:

- the altitude measurement reference point location with respect to an identifiable point on the instrument or spacecraft (fundamental reference point).

• the center of mass location of the entire spacecraft (including the instrument) with respect to the fundamental reference point.
• the GPS antenna phase center with respect to the fundamental reference point.
• the SLR array with respect to the fundamental reference point.

All position vectors should be known to better than 5 mm.

As described in the Level 1C Requirements, the orbit ground track should repeat with an interval of 0.5-yrs. For the crossover approach, this requirement assures that a set of uniformly distributed crossovers will result, aside from losses associated with inability to penetrate thick clouds. Since the semimajor axis will decay as the result of atmospheric drag, a repeat ground track requires periodic thrusts to compensate for drag. The level of the drag compensation will be determined by the allowable deviations from an exact ground track repeat. More specifically, the repeatability of the laser spot track on the Earth's surface is the important characteristic. With a spot separation of about 170 m that results from the 40 Hz pulse-repetition rate, a comparable cross-track separation is required with the repeat orbit.

Thrusting by the spacecraft will complicate the determination of orbit position during maneuver periods using traditional techniques. As a consequence, thrusting should be avoided, if possible, in the polar regions. However, if necessary, thrusting can occur in the vicinity of the North Pole) (perigee of the frozen orbit) when the spacecraft will not fly over Greenland immediately after thrust completion. Thrusting over the Antarctic should be avoided, except in extenuating cases.

As shown in Table 2, the Ross Ice Streams represent the most stringent requirements. The minimum latitude is 79°, thus the nadir track separation at the equator should be 1 km to produce 170 m spot track separation at 79° latitude. Thus, if the spacecraft/instrument attitude is controlled perfectly to nadir, then the orbit nadir track must repeat to ± 1 km at the equator (1 km East or West) to produce a nadir track separation of 170 m at 79° latitude. There are two contributing factors that determine the spot track repeatability: the orbit repeatability of the nadir point and the spacecraft pointing control. Thus, the orbit repeatability can be compensated by pointing control.

The following *Level 1D-2 Requirements* result from the foregoing considerations:

• *The laser pulse-repetition rate shall be 40 Hz.*

• *The measured altitude shall be characterized by zero-mean, Gaussian noise with a standard deviation of 100 mm or less.*

• *The instrument position in orbit shall be known at each laser pulse with an error,* σ_r, *of better than 50 mm in the radial direction and 200 mm horizontal. This requirement shall be met with GPS and SLR.*

• *The flight GPS receiver shall record carrier-phase and pseudo-range data, time tagged in GPS-System Time, on two frequencies (L1 and L2) from a minimum of 8 GPS satellites. Carrier-phase must be recorded at one second interval, pseudo-range may be recorded at 10 sec or less. Carrier-phase precision shall be better than 5 mm on each frequency and better than 300 mm for pseudo-range.*

• The laser pointing direction shall be known at each laser pulse with an error, σ_p, of 1 arc second or better. This requirement shall be met with modern star camera/gyroscope systems and a means of monitoring the laser direction with respect to spacecraft axes.

• Corrections for troposphere delay, solid-Earth and ocean-loading deformation, and any other significant corrections shall be provided with the altimeter data.

• The altimeter measurement, orbit position and laser pointing direction shall be time-tagged in a common time system, GPS-System Time.

• The laser spot location shall be described in the ITRF, or an equivalent reference frame.

• The position of the altitude reference point, the spacecraft/instrument center of mass, the GPS antenna phase center and the SLR array shall be known to better than 5 mm with respect to a specified point on the instrument or spacecraft over the instrument lifetime.

• The surface spot track shall repeat to within 170 m at 79° latitude after the 0.5-year repeat cycle. For a nadir pointing direction, the orbit nadir track shall repeat within ± 1 km at the equator; alternatively, pointing control with an accuracy of 60 arc sec can compensate for looser orbit control.

• Activation of thrusters for orbit control shall be avoided in the polar regions; however, thrusting in the vicinity of the North Pole is acceptable provided the instrument does not fly over Greenland within 30 min of thrusting. Thrusting over the Antarctic is allowed only in extenuating circumstances.

The following Level 2D-2 Requirements follow from the preceding discussions:

• The flight GPS receiver shall record carrier-phase and pseudo-range data on two frequencies (L1 and L2) from a minimum of 8 GPS satellites, but preferably from 12 satellites.

• Carrier-phase shall be recorded at one second intervals, pseudo-range should be recorded at 10 sec or less. Carrier-phase precision shall be better than 5 mm on each frequency and better than 300 mm for pseudo-range.

• The carrier-phase and pseudo-range measurement time tags shall be traceable to GPS-System Time through the pseudo-ranges. The receiver reference oscillator may drift with time or be steered to GPS-System Time.

• The GPS antenna shall be zenith-oriented and positioned on the spacecraft to minimize multi-path effects. The reference phase center of the antenna, with its ground plane, shall be fully characterized as a function of azimuth and elevation with respect to a fixed point on the antenna system to better than 5 mm. The location of this fixed point with respect to a specified point on the spacecraft shall be known to better than 5 mm.

• *The SLR array shall be compatible with the global ground-based network of SLR stations. The array shall support SLR tracking from ground-based elevations as low as 10°.*

• *The SLR array shall be characterized to enable range corrections as a function of viewing direction. The location of the array with respect to a specified point on the spacecraft shall be known to better than 5 mm.*

3.4.2.2 Direct Comparisons

The analysis approach based on direct comparisons of profiles collected along two or more repeat tracks has been widely used with ocean radar altimetry. The error budget associated with direct comparisons is based on the single shot budget, described in the preceding section. With the requirements derived from the crossover analysis, the detailed error budget is shown in Appendix B.

As described in the preceding section, the repeat track was defined to be one that follows essentially the same path, to within ± 1 km at the equator. At 79° latitude, the tracks will be separated by 170 m. But if the surface is sloped by 1° in the crosstrack direction, then the slope will offset the repeat tracks by 3 m in the vertical direction and local variations on the respective tracks will complicate the analysis. If, however, through analysis of data collected in both directions, the crosstrack slope can be determined with a 10% error, then the vertical offset can be reduced to 100 mm if the tracks are separated by 57 m. This track separation can be achieved by pointing control with an accuracy of 20 arc seconds (20 arc seconds times 600 km altitude equals 58 m).

The Level 1D-3 Requirement is:

• *The pointing shall be controlled with an accuracy of 20 arc seconds (one-sigma).*

3.4.2.3 Atmospheric Pulse Spreading and Cloud Blocking

The surface laser altimetry requires an analysis of the pulse shape of the signal return pulse in order to determine an altitude. A short pulse Nd:YAG laser will have a pulse length on the order of 5 ns or 75 cm in ranging distance. The ranging distance is determined by a centroid analysis of return signal pulse shape. The centroid range is that for which the pulse integral proceeding and following is equal. When the pulse is lengthened by surface slope or irregularity the centroid analysis has the advantage that the centroid indicates the average altitude within the pulse foot print. A pulse rise threshold analysis or pulse peak analysis would not indicate average altitude correctly and would be more effected by signal noise.

Scattering in the atmosphere as a laser pulse propagates through cloud and aerosol layers has the effect of spreading the laser pulse. Photons which scatter at sufficiently small angles that they remain within the field-of-view (FOV) of the receiver arrive at a time delay due to the longer path length. For scattering by large cloud particles especially, there is a strong bias toward forward scattering, know as the diffraction peak of the scattering. Because of the diffraction peak in the forward direction, forward scattered photons can be a significant fraction of the laser pulse even after propagation through layers of low optical thickness, and pulse spreading from the forward scattering is a significant factor. Pulse spreading gives rise to a ranging error. The centroid of a reflected laser pulse is shifted in time by the pulse spreading.

Calculations based on Monte Carlo radiative transfer indicate the bias in centroid analysis ranges will be significant for GLAS. Return pulse magnitude is decreased by the attenuating effect of cloud and aerosol layers. A large fraction of surface pulses, likely exceeding 50%, will be received through thin cloud and aerosol scattering where the surface pulse strength is still sufficient for ranging. Models of the ranging error were calculated for a receiver at 600 km, a 5 ns Gaussian laser pulse, a 325 (radian FOV and a 75 cm surface irregularity. The forward scattering effect will be a function of the optical thickness of the scattering layer, the scattering phase function of the particle type and the altitude distribution of the layer. Representative error results are given in the table below:

Scattering Type	Altitude	Optical Thickness	Altitude Bias
Cirrus Cloud	7-8 km	0.5	60 mm
Stratus Cloud	1-1.5 km	0.5	173 mm
Ice Crystals	0-2 km	0.5	103 mm
Haze	0-1 km	0.3	36 mm

Since cloud cover and aerosol loading varies significantly from season-to-season and year-to-year, the range bias introduced from the effect of cloud and aerosol layers will not be random errors that average out but will reflect errors in change in surface height that will vary with time and location. The effect can be ameliorated if surface signals where pulse spreading is a possible effect are eliminated. The presence of scattering layers in the atmosphere should thus be detected by acquiring the atmospheric scattering signal. A more sophisticated procedure would be employ a ranging correction based on a measured atmospheric scattering profile.

Another effect from cloud scattering on surface ranging is the possible mis-identification of the pulse signals from dense low altitude clouds, blowing snow or fog. A measurement and data analysis technique to avoid such mis-identified signals must be employed.

From the discussion above the Level 1D-3 Requirements follow:

• *The presence of atmospheric cloud and aerosol scattering layers of optical thickness of 0.1 or greater must be determined for all surface ranging signals over sampling intervals of no more than four contiguous pulses.*

• *Pulse signal returns from dense low altitude clouds or fog must be identified on a single pulse basis.*

3.5 Levels 1E Requirements: Land Processes

The overall GLAS mission requirement for narrow-beam laser altimetry, a requirement that is driven by the cryosphere applications, provides the fundamental constraint for establishment of specific GLAS land topography requirements. A narrow-beam laser altimeter operating in the GLAS Mission can be responsive to the goals for landform studies as stated in Section 2.2.

Evidence for this assertion is found in the data record from the flight of the Shuttle Laser Altimeter (SLA-01) in January of 1996. The SLA-01 data analysis reveals meter-quality surface elevation accuracy is achievable for ocean surface topography and low slope terrain from low Earth orbit (Garvin et al, 1997). The SLA-01 laser altimeter employed beam-limited (~ 100 m diameter) short-pulse (10 nsec) measurements at 1064 nm wavelength. It operated in a nadir-profiling mode with pulse measurements separated on the Earth's surface by ~ 740 m. These pathfinder data combine with the cryosphere application constraints and the GLAS land-science mission goals to set the GLAS land science requirements

The GLAS science requirements for land as given in this Section result from the combination of our landform study goals and the constraint of a single-beam, profiling laser altimeter with approximately 100 m beam-limited footprints. Land topography requirements for the GLAS Mission can be expressed in the following two categories: (1) ground control points and (2) narrow swath mapping.

3.5.1 Ground Control Points

In narrow-beam laser altimetry the generation of ground control points is driven by the overall requirement for individual laser pulse measurements that are made with sufficient vertical accuracy at sufficiently well known spatial locations to contribute to the vertical control of topography maps and/or digital elevation models. This means we need 10 meter or better vertical accuracy and 100 meter or better spatial accuracy. The value of a GCP from the GLAS Mission arises from the full resolution and accuracy of georeferencing in all three dimensions; an accuracy which is obtainable only for individual pulses. The principal reason for the single pulse requirement is the separation between adjacent footprints that is present in both the along-track and the across-track directions during the acquisition of GLAS narrow-beam laser altimetry range data. Thus, it is not possible to average over multiple laser pulse data in order to derive a GCP. The role of GLAS-derived GCPs in control of topographic imagery, such as that to be derived from SCANSAR data, suggests that several tracks of GLAS data across 100 km square images are required for long-wavelength baseline tilt corrections and mosaicing of adjacent images.

The following *Level 1E-1 Requirements* pertain to the land science goals and express the specific needs for useful ground control points:

- *Operate the GLAS laser altimeter in a continuous data acquisition mode over the Earth's landforms.*

- *Measure land surface elevation to 10 m or better vertical accuracy on a single laser pulse basis for footprint-scale slopes of less than or equal to 30 degree, improving to 1 m or better vertical accuracy for slopes of less than or equal to 3 degree. Slope angle is defined as the angle of incidence between the laser pulse direction and the normal to the Earth's surface in the laser footprint.*

- *Record the time history of individual, landform pulse echoes with sufficient amplitude dynamic range, temporal resolution, and temporal duration to reveal the signature of the* *vegetation-removed land surface when the vegetation canopy closure within a single laser footprint is 90% or less.*

• *Obtain an average density of 100 ground control points per 100 km square area at the equator for each mission year.*

3.5.2 Narrow Swath Mapping

In narrow-beam laser altimetry the global mapping of topography at high resolution and high accuracy is quite limited in coverage due to the relatively small laser footprints on the Earth's surface and the along-track and across-track separation between footprints. Nevertheless, it is possible to utilize GLAS narrow-beam laser altimetry data to maximize knowledge of Earth topography in narrow strips and limited areas, i.e. narrow swath mapping. It proceeds by orienting the GLAS sensor footprint ground track such that data are acquired in the interior of 1 km wide strips over landform areas, and doing this at an average density of 1 strip per 100 km at the equator. This action will require mrad-level control of spacecraft pointing with a maximum pointing angle bias of 5 degree off nadir. Since the overall GLAS Mission requirements, as driven by cryosphere requirements, call for a 94 degree inclination, 183-day repeat track, and 25-day near-repeat track orbit, it is possible to focus topographic measurement coverage in 1 km strips which have numerous crossing points as a function of latitude on a global basis. Data density builds up in these tracks through revisits every 25 days of the sub-cycle and the whole cycle of 183 days sets the distribution of crossing points.

By concentration of GLAS topography data acquisition in the 1 km wide strips, the crossing points of these strips have the potential for a factor of 10 or higher resolution and/or data density than single along-track profiles of the GLAS instrument. The availability of topography data over a ~ 1 km square area at each crossing point, provides some measure of across-track slope and aspect determination to characterize topography at the scale of DTED Level 1, i.e. to make a small map with on the order of 100 m spatial resolution and up to an order-of-magnitude greater vertical knowledge than DTED Level 1 specifications. Not only will these areas be prime spots for comparison studies with digital elevation models and calibration and validation activities for the GLAS Mission and other EOS missions, they are essential for change detection studies. It is only at the crossing points where multiple, time-separated observations of a given Earth surface area are possible. The 183-day repeat track cycle gives a topography monitoring capability of 10 cycles over 5 years with synchronization to seasonal variably, so essential for land cover and ecological studies.

The following *Level 1E-2 Requirement* for narrow swath mapping follows from the preceding discussion:

• *The GLAS spacecraft shall have the capability to control pointing of the sensor ground track of the GLAS laser altimeter in order to focus coverage over the Earth's landforms into narrow strips of 1 km width at the equator.*

3.6 Level 1F Requirements: Atmosphere

The Level 0 science requirements needed from the GLAS observations involve the direct height measurements of boundaries and variables which relate to the radiation and other influence of clouds and aerosols. The height of cloud boundaries are a direct measurement result from lidar profiling. The basic parameter which defines the integrated radiative influence of a layer is optical thickness. The resolution of the vertical resolved structure of radiative forcing, or the relation to physical parameters, requires that the total, or extinction, cross section be obtained. Both the cross section and optical thickness are derived parameters which involve the height resolved laser scattering data and appropriate retrieval algorithms. As mentioned in the level 0 science requirement, the optimal algorithms for optical thickness involve a measurement of the background radiance at the lidar wavelengths and a thermal IR background. For boundary layer height levels, the heights are derived values from analysis of the aerosol and cloud scattering structure. In all cases the accuracy of the derived parameters set accuracy requirements on the GLAS atmospheric profile measurement.

Since the measurements for optical thickness and for the height derived parameters are dependent on the instrument signals and retrieval algorithms, there is an important requirement for validation of observations and for intercomparison to other EOS cloud and aerosol measurements. It will be necessary at the beginning of flight operations for an extended period where the instrument is flown in the near orbital plane of the EOS AM and PM platforms. There will also be a need for ground based or aircraft validation activities.

The signal accuracy is dependent upon the backscatter cross section of clouds and aerosols and the ambient background light conditions. In general, as the measurement accuracy requirement increases, the spatial resolution which is obtainable decreases because more lidar shots must be averaged together to increase the signal to noise ratio. Table 4 lists the measurement requirements for the direct GLAS atmospheric observations by specifying a spatial requirement and an accuracy requirement for each atmospheric measurement. The accuracy is intended in this case to be the precision of the measurement of the non calibrated atmosphere signal after correction for background and detector effects. The stated requirement are to apply for both night and day time observations. Also listed is the known range of backscatter cross section associated with each measurement. The spatial requirement is presented in terms of the minimum acceptable horizontal and vertical resolution for that measurement. The accuracy requirement specifies to what degree of accuracy the measurement must be made in order to be scientifically useful and is expressed as a percentage standard deviation error.

Table 4. GLAS Level 1F Requirements for Cloud and Aerosol Profiling

Measurement	Spatial Horizontal	Requirement Vertical	Cross Section Range $(m\text{-}sr)^{-1}$	Accuracy Requirement
Dense Clouds	0.2 km	100 m	10^{-4} - 10^{-2}	10%
Cirrus	1-20 km	300 m	10^{-6} - 10^{-4}	10%
Thin Cirrus PBL Aerosol	20-50 km 1-50 km	300 m 150 m	10^{-7} - 10^{-5} 10^{-7} - 10^{-4}	10% 10%
Upper Trop. Aerosol	100-1000 km	500 m	10^{-7}-10^{-6}	10%
Strat. Aerosol	1000 km	1000 m	10^{-7}-10^{-6}	2%
Molecular Return Background	5000 km 1 km	2000 m ______	10^{-8}-10^{-7} ______	2% 1%

The actual accuracy obtained will vary depending on the background light conditions, with the highest resolution and accuracy associated with low background or nighttime conditions. The measurement requirements listed in table 2 must be met during the worst daytime background conditions. A prime instrument requirement for the GLAS atmospheric channel is to not reach signal saturation for daytime background conditions over thick clouds. The solar background signal is additive to the atmospheric scattering signal and must be accurately subtracted. In addition the measurement of the solar reflected radiance is needed to improve the retrieval of optical thickness. An important requirement is to measure the background radiance in the receiver channels during daytime to within 1 percent non calibrated, or relative, accuracy.

Dense clouds will provide the highest signal returns which will enable their measurement at the highest spatial resolution and accuracy. These include stratus, cumulonimbus and fair weather PBL cumulus clouds. In general, a cloud can be considered dense if its backscatter cross section is greater than about 10 -3 (m-sr)-1. The height of dense cloud layers will be determined on a shot to shot basis, which corresponds to a horizontal resolution of 175 meters. The accuracy requirement of 10 percent will be met with uncertainties in cloud top height not exceeding 150 meters. Cirrus clouds are less dense and give smaller signal return, but signal strength need to be large enough to obtain spatial variability down to 10 km or less under optimal conditions. The measurement of thin cirrus will be accomplished only with signal averaging of lidar shots. To meet the spatial requirement of 20 km, the averaging of roughly 100 lidar shots will be available, for signal accuracy of 20%. The backscatter cross sections for PBL aerosol are similar to those of thin cirrus clouds. However, for PBL measurements, it is desirable to resolve scales down to about 2 km since this is typical of PBL clear air convective cells. While this is not a requirement, this resolution may be possible under optimal conditions. In order to estimate near surface moisture, we will need good statistics on the height of PBL cumulus with a measurement accuracy of 150 meters in the vertical and a horizontal resolution of 200 meters. Further statistics on the vertical distribution of convective cells within the PBL can be used to estimate the profiles of moisture through the depth of the PBL.

Upper tropospheric aerosol and episodic stratospheric aerosols are associated with very low backscatter cross sections but observation at high spatial resolution is not required. Many shots can be averaged together to increase the signal to noise ratio while still obtaining the necessary resolution. In order to measure the stratospheric aerosol layer it is necessary to measure the atmospheric signal to an altitude above where the aerosol signal can be a significant component of the signal, or well above 35 km. The horizontal resolution required will be no greater than that shown, but may in practice be much larger.

Multiple scattering is a significant factor for the atmospheric signals. Forward scatting into the FOV will reduce the apparent attenuation by a factor of two or greater in the case of cloud scattering. One effect of the multiple scattering is to produce a delayed return signal that is apparent even after the earth surface is encountered. Another source of a return signal from below the surface is scattering of the laser pulse in water. Both cases give rise to a need to measure the return signal for several kilometers below the apparent surface.

The calibration of the lidar signal is most basically the ratio of the signal to the product of the atmospheric total backscatter cross section times the path transmission, know as the attenuated backscatter cross section. In the stratosphere and upper troposphere for typical background clear atmospheric conditions the attenuation is less than a 1% factor. In order to sufficiently calibrate the atmospheric channels and obtain a normalization for the stratospheric aerosol retrieval, the measurement of the molecular backscatter return in the upper troposphere is required to an accuracy of 2 percent.

With these statements and considering the Level 0 Requirements, the Level 1F Science Requirements are:

• *Profile all cloud and aerosol structure of the atmosphere from -5 km to 40 km altitude at the resolution and accuracy requirements in Table 2 throughout all orbital conditions and times.*

• *Measure the background radiance signal at the lidar wavelengths to the precision and resolution given in Table 2. Measure the background infrared radiance at 11 μm at the location of the lidar footprint to 1 km resolution.*

• *In the initial 40 days of the mission the orbit will be in a plane to optimize the co-incidence of measurements with the EOS AM and PM platforms for validation activities and additional validation activities will take place at two year cycles.*

3.7 Level 1G Requirement: Atmospheric Lidar

Both the atmospheric measurement requirement and the cryosphere measurement requirement give rise to the need for an atmospheric lidar measurement requirement for GLAS. In order to fulfill the science requirements, GLAS must be able to make a given measurement at the required accuracy and spatial scale. Both the obtainable measurement accuracy and horizontal and vertical resolutions depend upon instrument configuration and the atmospheric cross section. The basic measurement requirements for GLAS can thus be summarized as a function of scattering cross section. Table 5 summarizes the requirements of the GLAS direct measurements in terms of spatial resolution and accuracy based on the magnitude of the atmospheric cross section. The cross section is the observed cross section which includes the effect of attenuation. Less horizontal and vertical resolution are required as the atmospheric backscatter cross section becomes smaller. In essence, both horizontal and vertical averaging of data is available to make a given measurement when atmospheric cross sections are 10-4 (m-sr) -1 or smaller.

Table 5. Summary Level 1F Accuracy and Resolution Requirement

Cross Section (1/m-sr)	Vertical Resolution	Horizontal Resolution	Measurement Accuracy
$> 10^{-4}$	75 m	200 m	5%
$10^{-4} - 10^{-6}$	300 m	10 km	10%
$10^{-6} - 10^{-7}$	300 m	50 km	20%

The measurement accuracy involves more that just the signal noise and signal averaging. The detection of the signal must be linear and not be biased by the polarization of the signal. The return signal depolarization can be a great as 100% for some cases of cloud scattering. The background signal must be accurately subtracted.

It is necessary that the atmospheric scattering measurement cover the full dynamic range of the observed cross sections. To avoid saturation and non-linearity's, the requirements for the signal dynamic range, which varies by over four orders of magnitude, leads to a need for two atmospheric channels. One channel should sample the analog signal from the altimetry channel at 75 m resolution. In order to provide the cloud presence and height of dense clouds at sufficient scale, a signal for each pulse should be reported. The full height range of -5 to 40 km is not needed, only where there is a significant signal. A second channel is needed with the accuracy to respond to low cross section signals. Based on the known limitations of analog signal detection the high accuracy channel should be photon counting. Data from the high accuracy channel does not need to be at the highest resolution. A horizontal resolution higher than 1 km is not needed for the atmospheric science requirement. For surface ranging, a higher resolution could be considered to improve the coverage of data. The question is whether the elimination or correction of surface returns based on four pulse averages as stated in section 3.2 is sufficient, or if it would result in too great a loss of data. The issue requires further consideration after simulation studies are carried out. The wavelength of the two atmospheric channels does not have to be the same since cloud scattering is in general wavelength independent to first order.

The Level 1G-1 requirement is given as follows based on the above statements.

- *The instrument will measure the observed atmospheric scattering cross section to the sampling and cross section dependent accuracy as specified in Table 3 over to full range of atmospheric scatters.*

- *The atmospheric signals will be retrieved over the full dynamic range without saturation and with sufficient linearity to meet accuracy requirements. This requirement gives need for two channels - an analog channel for detection of strong cloud signals and a high accuracy photon counting channel.*

- *The vertical sampling resolution of the atmospheric signal will be 75m. Signals will be obtained over a range of -5 to 40 km.*

- *The strong signal channel will be recorded on a single pulse basis and over the altitude range where cloud signals are present.*

- *The high accuracy channel will be recorded on a horizontal resolution greater than 1 km. Given a 40 pulse per second rate as stated in Section 3.4 a four pulse average or greater would be acceptable. A caveat on this sampling requirement is that further study of the problem of surface ranging bias due to cloud scattering may indicate a need for greater resolution.*

- *The polarization bias of the retrieved atmospheric signal should be no greater than 2%.*

- *The background signal for each laser pulse must be measured to 2% accuracy for each atmospheric channel.*

3.8 Level 1H Requirements: Other Considerations

Verification, calibration and data product validation are essential to the scientific analysis of data acquired by GLAS. Some issues have been addressed by preceding requirements, but this section describes additional considerations.

One approach for the verification of the pointing accuracy is the intentional off-nadir pointing of the laser over a flat surface with known topography, such as the ocean. Based on the high accuracy required for the orbit position knowledge, a few degree off-nadir pointing will enable determination of a bias in pointing knowledge. The minimum off-nadir angle should be 2°, but larger angles up to 5° would further aid in resolving such biases.

The off-nadir pointing ability will enable sampling of points within the region around the poles that are excluded by nadir-only pointing. With the 94° nominal inclination, there is a 4° “hole” at the poles where no measurements can be acquired by a nadir-pointing altimeter. With off-nadir pointing capability, some data will be acquired in this region. With an off-nadir angle of 5°, measurements can be acquired up to 60 km in the cross-track direction, thereby reducing the size of the "hole."

The atmospheric science component of GLAS requires nearly coincident measurements with an imaging instrument, such as MODIS. Both the EOS-AM and EOS-PM platforms will carry a MODIS instrument, but the altitude of these platforms is 705 km and the inclination is sun-synchronous (98°). Analysis by Schutz (1996) shows that GLAS can be within the MODIS swath in mid-latitude regions for about 40-days. During this period, about xx hours of nearly coincident measurements can be acquired. During the GLAS lifetime, the EOS platform orbit planes will naturally drift into alignment with the GLAS orbit. To assure early data, the GLAS launch should take place when the launch site is appropriately aligned with respect to one of the MODIS instruments so that coincidences will occur during the GLAS Initial Verification Phase. To accomplish this, a daily launch window will exist with a duration of about one hour.

With these considerations, the *Level 1H Requirements* are:

- *The GLAS spacecraft should be capable of pointing 2° off-nadir, with a desired angle of 5° or more.*

- *The GLAS launch should take place when a MODIS platform is appropriately aligned with the launch site to enable maximum periods of coincident observations during the Initial Verification Phase.*

3.9 References

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APPENDIX A

Rationale for Ice-Sheet Science Requirements

A.1 Primary Objectives

The primary objectives of the laser-altimeter mission over Antarctica and Greenland are:

1) to determine the contributions of the ice sheets to sea-level change by measuring their changes in volume through time;
2) to measure interannual variability of the surface elevation in sufficient spatial and temporal detail to enable long-term trends to be identified and to help explain those trends;
3) to identify dynamic imbalances within the ice sheets by measuring elevation changes, and hence redistribution of ice, within the basic dynamic units - the drainage systems;
4) to help provide high-resolution ice-surface topography in support of almost all glaciological research on the ice sheets.

The first objective represents the major goal of the mission, but the second and third objectives are the most crucial: short-term variability must be measured in order to reveal long-term trends, and improved understanding of ice-sheet dynamics is essential to enable future ice-sheet behavior (and thus sea-level change) to be predicted. Interannual variability will result in changes in ice-sheet volume over the lifetime of a satellite mission that are not related to the long-term balance, which is the component of interest in evaluating the contribution of the ice sheets to sea-level change. Thus it interferes with the evaluation of long-term changes from a 3- to 5-year mission.

A. 2 Measurement Requirements

We will apply three different approaches to determine GLAS measurement requirements:

A.2.1. In order to determine a quantitative science requirement for secular change, we assume that the long-term changes are “contaminated” by shorter-term variability. We then apply the analysis of Van der Veen (1993) to calculate the magnitude of an elevation change, measured over a GLAS mission lifetime (assumed to be 4 years), that is likely to signal a long-term change. We assume that, during the 4-year mission, the interannual variations in snow accumulation rate are randomly distributed in time with a standard deviation of plus or minus 25% (Giovinetto, 1964), and that the mean density for near-surface snow is 40% that of solid ice. Van der Veen's (1993) analysis then indicates that the total change of surface elevation during the mission, Δh, must exceed 170% of the annual accumulation (A), expressed as its equivalent thickness of solid ice, for there to be a 90% chance that it was due to a “real” (i.e. long-term) change. If Δh is only 60% of A, however, there is only a 68% chance that it is “real”. There is little purpose in trying to evaluate the long-term change rate with a probability of less than 68% (one standard error), so the minimum requirement for measuring Δh from the full 4-year data set is 0.6A.

The above analysis applies to regions of net snow accumulation. For ablation regions with a net annual surface melting rate of B, the equivalent requirement for Δh is 0.24B.

These are the measurement accuracies required to infer long-term ice thickness changes from 4 years of GLAS data. The area over which these estimates should be averaged varies from 2,500 km^2 for Greenland ablation regions to 200,000 km^2 for Antarctic catchment basins.

A.2.2. Secondly, we take into account existing approaches to the estimation of snowfall on the ice sheets to estimate how accurately GLAS must measure short-term surface-elevation changes to offer significantly improved estimates of interannual variability. Recent analyses of moisture flux divergence, from satellite observations controlled by rawinsonde measurements at a few surface stations, yield annual mass inputs that, for averages over the whole ice sheets, are now accurate to a few percent of the annual accumulation (A) for Greenland (Chen et al, 1997; D H Bromwich, personal communication, 1996), and are expected to be capable of attaining an accuracy of 10% for Antarctica (D H Bromwich, personal communication, 1996). However, regional estimates (for areas of 50,000 sq km) are considerably less accurate (worse than 10% for Greenland, and considerably worse for Antarctica [D H Bromwich, personal communication Oct 96]). GLAS will provide an independent check on the interannual variability of snow-accumulation rates derived from these estimates if it can measure changes in surface-elevation equivalent to 5% of the annual accumulation expressed as a thickness of surface snow with a density of 40% that of solid ice. This imposes a requirement on GLAS of measuring annual elevation changes averaged over areas of 50,000 km^2 to better than 0.13A. This is a more stringent requirement than that derived in A.2.1 for long-term changes, but it is particularly important that it be met. The detailed information that it will provide will significantly improve confidence in our estimates of long-term thickness changes and will help reveal their causes.

A.2.3. Finally, we consider the magnitude of existing estimates of ice thickening/thinning rates given in Table 1. Most of these are considerably larger than 0.1A per year, and would be readily measured by GLAS with the requirements derived above. As examples, we consider five regional groupings with similar accuracy requirements in which the detection of change will be particularly important: (a) the ice-stream area of western West Antarctica (79° S to 85° S); (b) the high interior plateau of East Antarctica (80° S - 90° S); (c)) the northeast Greenland plateau (75° - 80° S) and the plateau in Antarctica between 70° and 80°; (d) coastal Antarctica (65°-70° S) and most of the Greenland plateau (70° - 80° N); and (e) southern Greenland between 61° and 65° N and the Greenland outlet glaciers.

A.2.3.1. To detect dynamic imbalances within individual West Antarctic ice streams, which is necessary because neighboring ice streams are known to behave very differently, we must be able to attain the measurement accuracy for long-term changes (derived in A.2.1 above) over regions 10^4 km^2 in area. The local accumulation rate is about 100 mm/yr, yielding a measurement accuracy on Δh over a 4-year period of 60 mm. For measurement of the interannual variability (described in A.2.2) of accumulation rates, the accuracy requirement for measuring annual elevation changes averaged over areas of 50,000 km^2 becomes 13 mm.

A.2.3.2. In central East Antarctica, the accumulation rate is lower still, averaging only about 30 mm/yr over a broad region (80° S - 89° S). Here, however, it is acceptable to average over an area of 200,000 km^2, leading to a measurement accuracy for Δh over a 4-year period of 18 mm, and of 4 mm over one year. Fortunately, both the West-Antarctic-ice-stream and central-East-Antarctic areas are near the highest latitudes to be covered by GLAS, where there are the largest numbers of orbit crossovers and surface slopes are very small (see GLAS error analysis).

A.2.3.3. Much of Antarctica between 70° S and 80° S, and the northeast part of the Greenland ice sheet (75° - 80° N), have accumulation rates of about 100 mm ice equivalent per year, with surface slopes nearly everywhere <.005 radians (0.3°). Accuracy requirements for Δh are approximately 60 mm over a 4-year period, and 13 mm for one year. These are identical to the requirements from A.2.3.1, but for areas of at least 50,000 km^2.

A.2.3.4. Near the coast of Antarctica, between 65° S and 70° S, and over most of Greenland north of 70° N, surface slopes are generally less than 0.01 radians (0.6°), and a typical accumulation rate would be 300 mm/yr. In these areas, by our analysis, the accuracy on Δh averaged over 10,000 km^2 can be relaxed to about 180 mm over a 4-year period and 40 mm over one year.

A.2.3.5. In southern Greenland and over most Greenland coastal regions, accumulation rates are approximately 0.4 meters of ice per year, rising to more than 1 meter of ice per year in southeast Greenland. Ablation rates over the outlet glaciers can be several meters per year. This leads to accuracy requirements for Δh of 250 to > 600 mm over a 4-year period, and 50 to > 130 mm over a 1-year period. However, there are very few orbit crossovers at these low latitudes (see GLAS error analysis), surface slopes on the outlet glaciers exceed 1/100, and Δh must be averaged over areas as small as 2,500 km^2.

A.3. These requirements do not cover the floating ice shelves, into which most Antarctic ice flows en route to the ocean. Here, changes in ice thickness will be difficult to measure with GLAS because the change in surface elevation is only about 10% of the change in ice thickness. However, the location of the grounding line, separating the ice shelf from the grounded ice sheet, is likely to be very sensitive to such thickness changes. It is marked in many places by a distinct change in surface slope, and will be mapped very accurately by GLAS.

A.4. GLAS errors will be strongly dependent on the magnitude of ice-surface slopes. Fortunately, the regional slopes over more than 85% of the Antarctic ice sheet and more than 70% of the Greenland ice sheet are considerably less than 0.01 radians (0.6°), with undulations that can increase local surface slope to about double the regional slope. Near the coast, regional surface slope increases, but seldom to more than 0.03 radians (1.7°) for more than very small distances (on the order of 10 km); in these areas, undulations can increase local slopes to 0.05 radians (3.2°). Even with 1 arc-second pointing accuracy, GLAS slope-induced errors will be large in such areas (ref to error analysis), but fortunately these areas are generally where the ice is most dynamic and/or where surface ablation rates are very high, so changes are likely to be rapid.

References

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APPENDIX B

Single-Shot Error Budget

TABLE B-1. ALTIMETER MODE ERROR BUDGET: CRYOSPHERE
Single Laser Pulse

Error Source	Contribution
• Level 1A Instrument error sources (assume: 1° surface slope)	100 mm
Slope and surface roughness influence on precision, including biases (Instrument range precision per pulse)	
• Platform requirement	
Determination of altimeter reference point relative to orbit determination reference points (GPS phase center and SLR array)	5 mm
• Level 1B error sources (assume: 1° surface slope)	
Radial orbit error (based on GPS, error assumed random)	
Assume: 50 mm for GLAS altimeter reference point	50 mm
Horizontal orbit position error (based on GPS, assumed random)	
Assume: 200 mm	10 mm
Attitude/pointing error as a function of slope (50 mm/″ pointing/° slope)	
Assume: 1″ attitude on 1° slope	50 mm
Atmosphere delay error (Ref: Marini-Murray model)	
Surface pressure 2.3 mm/mb)	
Assume: 10 mb surface pressure error	20 mm
Surface temperature (9 mm/50°K)	
Assume: 25°K error	<10mm
Surface relative humidity (0.5 mm/50%)	
Assume: 100% error	0 mm
Clock synchronization:	
Assume: < 10 μs with respect to GPS time (consistency with GPS-derived ephemeris: height error is 4 mm for 10 μs)	< 10 mm
Other error sources (expected to be < 10 mm, but currently under study)	< 10 mm
Solid tides and ocean loading over ice sheets	
Ice sheet loading/rebound	
RSS	130 mm

Note: long term systematic (time scale: 5 years) error contributions: <10 mm

If the surface slope is 3°, the corresponding attitude/pointing error in the above changes from 50 mm to 150 mm, and the overall RSS becomes 210 mm.