ICESat Land Working Group

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ICESat Science Team Ad Hoc Meeting
January 14, 2004
Report Objectives

Two purposes for our recommendations
Maximize land science accomplished with ICESat-1 data
Demonstrate capability that motivates follow-on missions
  ICESat-2
  Other future laser altimeter missions

Three categories of science considered
Construction of ICESat land DEMs at high latitude
Sampling of land topography and vegetation cover
Change detection from repeat observations
Sampling Approaches

Accomplishments that can be met with ICESat-1

Validation/calibration of DEMs, particularly SRTM
  - cross-track data density insufficient for ICESat-only DEM production, even at high latitudes

Vegetation height characterization
  - forest biomass inventory
  - aerodynamic resistance input to global circulation models
  - both require DEMs for relief contribution to pulse width
Change Detection Approaches

Exact-repeat reference tracks at latitudes greater than 59° and selected mid-latitude targets

Accomplishments that can be met with ICESat-1
Mountain glacier dynamics

Capability demonstrations motivating future missions

Vegetation
seasonal cover: leaf off vs leaf on
pre- and post-burn biomass loss
crop growth monitoring?

Inland water height monitoring
seasonal changes (river discharge, annually inundated forests)
flood events

Seasonal snow pack depth

Natural hazard topo change if any occurs during observing
volcanic eruption or major earthquake
Issues Addressed

Optimal repeat orbit and duration

Data acquisition

On-board compression for truncated broad waveforms

Data processing

DEM used for reporting land elevation

Ancillary data in GLA14 for footprint location

Range correction for saturated returns

Test of Xiaoli correction for Uyuni Playa
**Recommendations (1)**

Optimal repeat orbit and duration

8 day repeat cycle followed by 33 day subcycle

No compelling land reason to do 91 day cycle
- would increase amount of coverage but still only sampling
- could target anywhere with 5° off-pointing; not so from 33 day subcycle

Do every 3 months to observe seasonal land cover changes
- match 33 day subcycle to last 33 days of initial Laser 2 ops

**Rationale for starting with 8 day cycle**

Complete globally-distributed repeat tracks achieved at outset
- a hedge against laser or other system failure

Along-track change complements cross-over change detection
- measures change at smaller spatial scales related to specific landforms
- profiles of change communicate to general population and program managers
- much higher probability of coincident repeat footprints for waveform change

Inter-comparison with Laser 1 Cycle 4 & 5 and Laser 2 Cycle 29
- reveals slope-induced calibration errors
- increases value of Laser 1 data
- enables along-track change observations over one year
Recommendations (2)

Data acquisition

On-board compression for truncated broad waveforms

Prior suggestion for 1° acquisition mask revision not optimal
- spatial scale of pulse-width variation too small
- consensus on what 1° cells to compress difficult to reach

Better approach is to only compress very broad waveforms
- selected filter is available on shot-by-shot basis
- requires development of software patch
  - Jan McGarry is assessing feasibility and impact with software team
  - initial approach is compression lookup table for each selected filter
  - table could easily be modified by parameter uploads
  - could simply replace surface type input to current lookup table with selected filter input, and use for all surface types
Recommendations (3)

Data processing

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To facilitate evaluation of SRTM data
From SRTM 90 m continental products
- North and South America, Eurasia currently available
- Africa, Australia, major ocean islands to be completed

Ancillary data in GLA14 for footprint location

To facilitate interpretation of waveforms
From 3x3 array of SRTM 90 m elevations
- relief (combining slope and roughness)
- slope orientation and magnitude
- roughness (rms departures from best-fit slope plane)
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- UMD woody vegetation percent cover
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**Shuttle Radar Topography Mission**

C-band (5.6 cm wavelength) radar interferometry in 225 km wide swaths

- US DEM: 30 m grid; Non-US DEM: 90 m grid
- Reported elevation: phase center of C-band radar scatterers
**ICESat Groundtrack Separation vs. Latitude**
(ascending to ascending or descending to descending track separation)

- **91 day**
- **45 day**
- **~33 day**

**Groundtrack Separation (km)**

**Latitude (deg)**

- **SRTM 90 m grid**
  - ~10 m vertical accuracy to radar phase center

- **GTOP30 900 m grid**
  - ~50 m vertical accuracy

Best Publicly Available, Global Digital Elevation Models

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ICESat Track Spacing vs. Orbit Cycle

Mississippi River Delta:
29° - 34°N, 88° - 94°W

Iceland:
62° - 67°N
17° - 23°W

Svalbard:
75° - 81°N
13° - 19°E
ICESat Track Spacing vs. Orbit Cycle

Iceland: 62°-67°N, 17°-23°W
Svalbard: 75°-81°N, 13°-19°E
Vegetated Landscape Waveform Elevations

Height Distribution of Reflected Laser Energy

Digitizer vertical sampling = 0.15 m,  Pulse width + receiver vertical resolution ∼ 1.5 m

1064 nm Laser Pulse

Threshold

Travel Time

Return Amplitude

ICESat Elevation Products

Signal Start
= highest detected elevation

Gaussian Fit to Largest Peak
= standard ice sheet elevation

Centroid of Signal Start to End
= average detected elevation

Signal End
= lowest detected elevation
ICESat Signal Start vs. SRTM

GLA06 Track ICESat 43-002 vs. 30m SRTM in US

Ground Return: E-W Shift: 42.06 m, N-S Shift: 30.83 m

Canopy Top Return Profile (red) for accepted shots and SRTM-50.m (green)

Canopy Top Return Profile - SRTM Differences (red) and Average Footprint Relief (blue)

Average Footprint Relief: Mean = -0.01 m, STD = 2.65 m

Canopy Top Return Differences: Mean = 16.12 m, STD = 8.36 m

NP = 993
ICESat Signal End vs. SRTM

GLA06 Track ICESat 43-002 vs. 30m SRTM in US

RMS Contours for Shifted Sub-orbital Track

ICESat - 30m SRTM

SRTM and ICESat 43-002 Track

Ground Return: E-W Shift: 42.06 m, N-S Shift: 30.83 m

Lowest Ground Return Profile (red) for accepted shots and SRTM-50.m (green)

Lowest Ground Return Profile - SRTM Differences (red) and Average Footprint Relief (blue)

Average Footprint Relief: Mean = -0.01m, STD = 2.65m

Lowest Ground Return Differences: Mean = -11.72m, STD = 8.55m
ICESat Largest Peak vs. SRTM

GLA06 Track ICESat 43-002 vs. 30m SRTM in US

Ground Return E-W Shift: 21.03 m, N-S Shift: 30.83 m

Ground Return Profile (red) for accepted shots and SRTM-50.m (green)

Ground Return Profile - SRTM Differences (red) and Average Footprint Relief (blue)

Average Footprint Relief: Mean = 0.02m, STD = 2.71m

Ground Return Differences: Mean = 6.85m, STD = 7.24m

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Shuttle Laser Altimeter Evaluation of GTOPO30 Errors

Africa SLA–01 vs. GTOPO30 DEM

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South Asia SLA–01 vs. GTOPO30 DEM

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black = SLA–01 – SLA–01 (m); distance < 200 m & relief < 50 m

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Accomplishments that can be met with ICESat-1

Validation/calibration of DEMs, particularly SRTM
- cross-track data density insufficient for ICESat-only DEM production, even at high latitudes

Vegetation height characterization
- forest biomass inventory
- aerodynamic resistance input to global circulation models
  - both requires DEMs for relief contribution to pulse broadening
Forest Canopy Information from ICESat Waveforms

Three Representative Return Pulse Waveforms

Canopy Height = Distance from Start of Signal to Last Peak, $z_2$
Crown Depth = Width of Upper Part of Canopy Return, $z_2 - z_1$
Roughness of Outer Canopy = Leading Edge Slope from $z_2$ to $z_c$
Canopy Closure $\sim \frac{\text{Ground Return Energy}}{\text{Total Return Energy}}$
Estimation of Forest Stand Above Ground Biomass

SLICER waveform mean canopy height squared (MCH²) vs. field observations of above ground forest biomass
- linear relationship to high biomass levels
- accounts for 80 to 90% of variance
- applicable to a diversity of forest types
- MCH² proxy for height x stem diameter (a measure of tree volume)

Lefsky, et al., 2002, Global Ecology and Biogeography

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Canopy and Ground Aerodynamic Resistance
SiB2 model from Sellers, et al., 1996

- $z_2$ canopy top height
- $z_c$ leaf-area density inflection height
- $z_1$ canopy base height
- $z_{gs}$ ground roughness length
- $l_w$ leaf width
- $l_l$ leaf length
- $L_L$ leaf-angle distribution factor
- $L_T$ total leaf area index (time variable)
- $z_0$ roughness length
- $d$ zero plane displacement
- $C_1$ canopy resistance coefficient
- $C_2$ ground to canopy air-space resistance coefficient

GCM aerodynamic resistances:
- $r_a$ canopy air-space to ref. height
- $r_b$ canopy to canopy air-space
- $r_d$ ground to canopy air-space
Puget Lowland High-Res Airborne Laser Mapping

Mapping by TerraPoint, LLC for Puget Sound Lidar Consortium
1 laser pulse per sq m with up to 4 discrete returns per pulse
Vertical accuracy ~ 20 cm RMSE
Returns classified as ground, vegetation, & structures
Data acquired in winter, 2000 - 2003, comparable to ICESat laser 1

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Waveform Matching to High-Resolution Canopy DEM

Laser Profiling Array (LPA) Image of Footprint Spatial Energy Pattern

1064 nm Receiver FOV Transmissivity

1.8 m DEM from Airborne Scanning Laser Altimetry

Spatial Convolution = Height Distribution of Reflected Laser Energy Within Footprint

Receiver Response for Transmit Pulse

~ 120 m x 50 m full-width ellipse

500 m full-width diameter

Waveforms at Location Of Best Fit

Spatial Shifting to Maximize Correlation Between Observed and Simulated Waveforms

Temporal Convolution = Simulated Waveform

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Identification of Ground from Bald Earth DEM

Laser Profiling Array (LPA) Image of Footprint Spatial Energy Pattern

1064 nm Receiver FOV Transmissivity

1.8 m DEM from Airborne Scanning Laser Altimetry

~ 120 m x 50 m full-width ellipse

500 m full-width diameter

Spatial Convolution = Height Distribution of Reflected Laser Energy Within Footprint

Receiver Response for Transmit Pulse

Energy Distribution
Ground Waveform
Observed Waveform

Energy Distribution
Simulated Waveform
Observed Waveform

Ground Elevations at Best Fit Location

Identify Waveform Best Fit Location from Canopy DEM

Temporal Convolution = Simulated Waveform

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Simulated and Observed ICESat Waveforms

Best fit shift from Release 12 geolocation: 48 m W, 53 m N
Waveform Simulation Results

Comparison to high-resolution airborne laser mapping data demonstrates that ICESat waveforms provide detailed and accurate information on the within-footprint distribution of surface heights for forested landscapes:

Signal end = lowest ground  
Signal start = highest canopy  
Signal centroid = weighted average elevation

Where the ground has local relief within the ICESat footprint, ground and vegetation are mixed in the waveform making interpretation complex:

Signal start to end overestimates vegetation height

You need to independently contrains ground relief!
**Stand Height Retrieval from Large Footprints**

Coincident 10 and 75 m SLICER Footprints in Washington State

- **Observed 75 m footprint waveform (black)**
  - Poor signal-to-noise due to high flight altitude
  - Top of canopy not recorded due to threshold-above-noise detection scheme

- **Synthesized 75 m footprint waveform (red)**
  - Addition of 10 m footprints using 75 m Gaussian spatial weighting
  - Tail due to SLICER’s non-Gaussian pulse shape

- **Observed 75 m footprint (red circle)**

- **Centers of coincident 10 m footprints (black pluses)**
  - from 50 m wide “5-beam” SLICER transect
Conceptually, four factors are involved in determining the height of a forest stand from ICESat waveforms (plus ancillary data):

- Extent of the waveform (maximum to minimum elevation: signal start to end)
- Range of ground elevations (slope + roughness)
  - Obtained here from the SLICER 10 m waveforms
  - Operationally would need to come from a DEM sources (e.g. SRTM)
- Range of canopy top elevations (canopy rugosity)
  - Obtained here from the SLICER 10 m waveforms
  - Operationally might be derived from slope of waveform leading edge
- Covariance of ground elevation and canopy top elevation
  - Not included here

We apply statistical approaches to define the likelihood of making the retrieval, and the expected limits of its accuracy.
Mt. Rainier SLICER Dataset

8 radial SLICER transects
- Intersect at summit
- Extend to flatter, forested areas
- Includes a variety of slopes and forest stand heights
- Includes worst-case forests of low stature on high slopes
- Transects are generally parallel to maximum slope
- 2488 synthetic 75 m waveforms derived from the 10 m SLICER waveforms
Statistical Retrieval of Maximum Stand Height From 75 m Waveforms

- Independent variables
  - 75 m synthetic waveform extent (EH)
  - range of ground elevations (ELEV_RANGE10)
  - range of canopy top elevations (TOPE_RANGE10)

- Dependent variable
  - maximum height of the 10 m waveforms (GPEAK_MAX10)

- Step-wise multiple regression
  - model explains 79.6% of variance
  - EH is the most important variable
  - range variables are each about half as important

GPEAK_MAX10 = -4.761E-13 + 1 * Fitted GPEAK_MAX10

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</table>
Large Footprint Canopy Height Results

• Waveform extent, range of ground elevations, and range of canopy top elevations are all important to prediction of stand height, and explain 80% of variance.

• There is still 20% of variance left unexplained - most likely due to the covariance of canopy top and ground elevations - which may be very difficult to model.

• Further analysis suggest that replacing 10 m resolution topography from lidar with lower accuracy, lower resolution SRTM results in a prediction with 63% of variance explained.

• Removing the range of canopy top elevations variable also results in an analysis that explains 63% of variance.

• Finally, it should be noted that the dataset used here contains very few areas of low topography - where the accuracy of the ICESAT measurements should be high. In many ways, the Rainier dataset represents a “worst case scenario”.
Data processing

DEM used for reporting land elevation
To facilitate evaluation of SRTM data
From SRTM 90 m continental products
  - North and South America, Eurasia currently available
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Ancillary data in GLA14 for footprint location
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  - relief (combining slope and roughness)
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From 1 km land cover global maps
  - UMD woody vegetation percent cover
  - TBD land cover classification
Recommendations (2)

Data acquisition

On-board compression for truncated broad waveforms

Prior suggestion for 1° acquisition mask revision not optimal
- spatial scale of pulse-width variation too small
- consensus on what 1° cells to compress difficult to reach

Better approach is to only compress very broad waveforms
- selected filter is available on shot-by-shot basis
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Proposed Waveform Compression Based on Matthews Potential Vegetation 1° x 1° Global Classification

1 nsec sampling (81 m waveform extent) too short for some areas of tall vegetation and/or high relief
Solution: 2x Compression South of 59°N = 150 m waveform extent

Closed Forests  Woodlands
Grasslands with 10-40% Woody Cover
Signal Start Truncation: Amazon Rain Forest
Signal Start Truncation: Western United States
Signal Start Truncation: Himalayan Mountains
Signal Start Truncation: South East Asia
Selected Filter Measure of Pulse Width

% of these land returns with signal start offset:

> 75 m  13%
> 80 m  9%
**Signal Start Offsets for Selected Filters**

Filter 0 not shown: 0.3%

- **Filter 1** 18%
- **Filter 2** 17%
- **Filter 3** 13%
- **Filter 4** 15%
- **Filter 5** 36%
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Southern Alaska Glacier 8-day Tracks

August 9, 2003 AQUA MODIS

Bagley Ice Valley

Seward

Malaspina

Map Scale: 1:2,550,000

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Uyuni Site characteristics

Salar de Uyuni, a 9,600 km² salt lake in the Bolivian Altiplano, is the largest dry salt lake in the world.

- Surface is expansive, flat, smooth, and is a specular reflector – making it an ideal satellite altimeter target.
- Surface is composed of salt which is deposited when annual flooding (~5 months per year) evaporates each winter, and is assumed to approximate an equipotential.

Landsat images showing flooded conditions vs. dry conditions; photo to right shows surface water.
Uyuni Gridded GLAS Cal/Val surface
Survey area and grid design

Eastern part of salar is larger and flatter than the western part, and was obvious choice for our survey.
- Survey bounds further determined by surface suitability (by reconnaissance), our desire to keep the survey area rectangular, and time.

Core grid was eight 22.5 km x 13.5 km rectangles and central 24 km x 24 km square, with 12 ground control points.
- ICESat 91 day tracks shown; two TOPEX tracks passed over our survey region during its orbit manoeuvre.
- Two grids driven along ENVISAT/ERS-2 Track 139 (ascending) in west and Track 146 (descending) in east.
We retracked GLAS return waveforms in three ways:

i) centroid of a single Gauss fit

ii) deconvolution algorithm which locates the ground return

iii) threshold retracker which finds 1st bin in the return pulse > 25% of Gauss peak
● Figure shows results from Release 12 GLA06 (also uses a Gauss fit), our retrackers, and GPS interpolated points

● Both Gauss retrackers & deconvolution enhance “dip” at -20.15, coinciding with the most saturated waveforms

● Threshold follows surface but has 1.14 m bias (it picks an earlier point on the waveform)

● GLAS instrument team is currently building a saturation correction which will be applied in later data releases
GLAS “range walk” saturation correction

- Empirical saturation correction (“time walk” or “range walk”) measured by Xiaoli Sun. (Fall AGU 2003)

- 0.14ns/fJ for echo pulse energy in excess of 14fJ,

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Xiaoli’s empirical saturation correction (range walk) improves the comparison with GPS DEM.
Thick cirrus clouds induce multiple scattering in altimetry channel

Ground return signal intensity reduced and sometimes totally attenuated

High background - very bright surface

Totally clear conditions

Images courtesy of Steve Palm
GLAS waveforms track 360

These example waveforms manage to penetrate the cloud cover

These example waveforms partially penetrate the cloud cover

These example waveforms do not penetrate the cloud cover
GLAS waveforms over Uyuni

Clear atmosphere
Descending track 085

Cloudy
Ascending track 360
GLAS track 360 comparison

27 October 2003

14 November 2003

GLA06-GPS RET 1-GPS RET 2-GPS RET 3-1.14-GPS
Mean 0.081 m Mean 0.088 m Mean 0.027 m Mean 0.039 m
StDev 0.002 m StDev 0.003 m StDev 0.006 m StDev 0.001 m

GLA06-GPS RET 1-GPS RET 2-GPS RET 3-1.14-GPS
Mean 0.468 m Mean 0.477 m Mean 0.403 m Mean 0.253 m
StDev 0.009 m StDev 0.007 m StDev 0.445 m StDev 0.013 m
Ocean elevations along tracks 085 and 360, both south and north of Uyuni, appear to show a relative elevation bias similar to what is seen at Uyuni.

Track 360 is biased by about +30cm, relative to track 085.
Satellite Altimeter Tracks over Uyuni

- Black tracks: ICESat 91-day repeat orbit.
- White tracks: ERS-2 and ENVISAT
- Yellow tracks: TOPEX, during orbit shift in September `02
Eleven sites were established as ground control points (GCP)

- Central GCP (UY04) occupied at 30s for entire survey to tie into ITRF2000
- Surrounding GCPs set up as base stations for kinematic surveys: occupied for at least 24 hours - each grid had 4

GCPs: UY04 plus 3 others running at same rate as rover (3s)
- GCPs processed using RTD (Geodetics Inc)

At each GCP, antenna was mounted directly on the surface (see photo), to reduce effects of ground-reflected signal off the highly conductive salt (multipath): this significantly reduced the effect
Survey took six days (4 to 9 Sept 2002) with two cars

- Kinematic GPS data processed using TRACK (GAMIT); LC solutions
- Crossover analysis showed that internal consistency of grid heights was ~3 cm
- Heights consistent from car to car and from day to day
- Two surface DEMs made:
  i) Fourier fit (6 km wavelength; 500-m grid cells) for GLAS
  ii) Gauss-smoothed (2-km cells) for RA-2/ERS-2 comparison
Figure shows results from Release 12 GLA06 (also uses a Gauss fit), our retrackers, and GPS interpolated points.

- All profiles have increased noise, and there are several complete data dropouts.
- 532 nm images (see panel to right) show cloudy conditions, but bias is wrong sign for effect of forward scattering.
- Uncalibrated GLAS pointing biases are most likely the source of discrepancy.