# ICESat Land Working Group

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ICESat Science Team Ad Hoc Meeting

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# ***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

### 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
- 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)

From 1 km land cover global maps

- UMD woody vegetation percent cover
- TBD land cover classification

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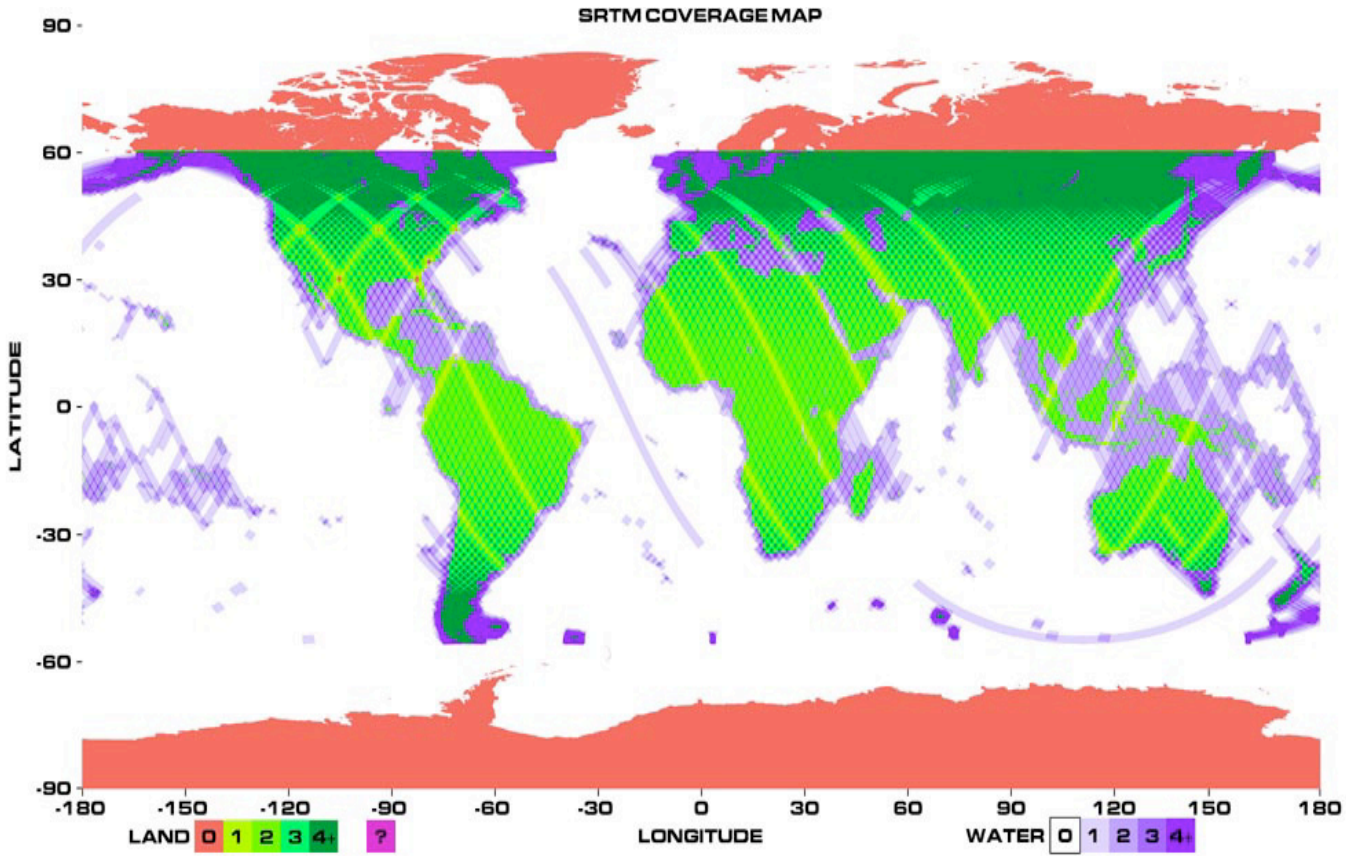
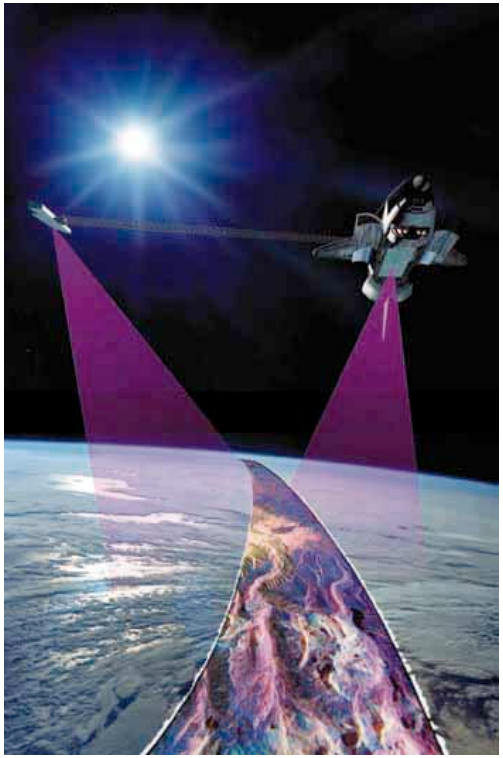
# ***Shuttle Radar Topography Mission***

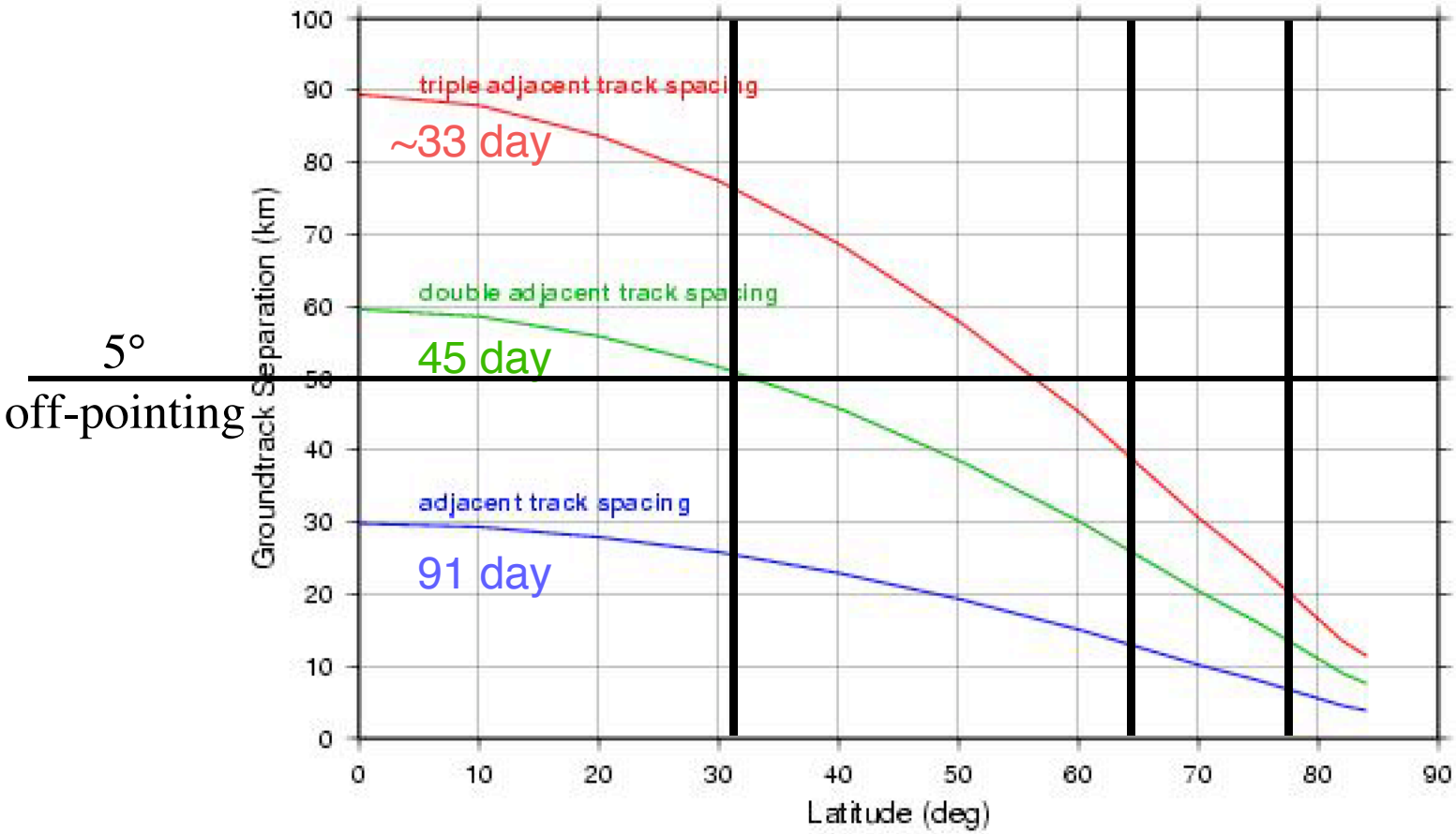
C-band (5.6 cm wavelength) radar interferometry in 225 km wide swaths
US DEM: 30 m grid;  Non-US DEM: 90 m grid
Reported elevation: phase center of C-band radar scatterers



# *ICESat Groundtrack Separation vs. Latitude*

(ascending to ascending or descending to descending track separation)




SRTM 90 m grid

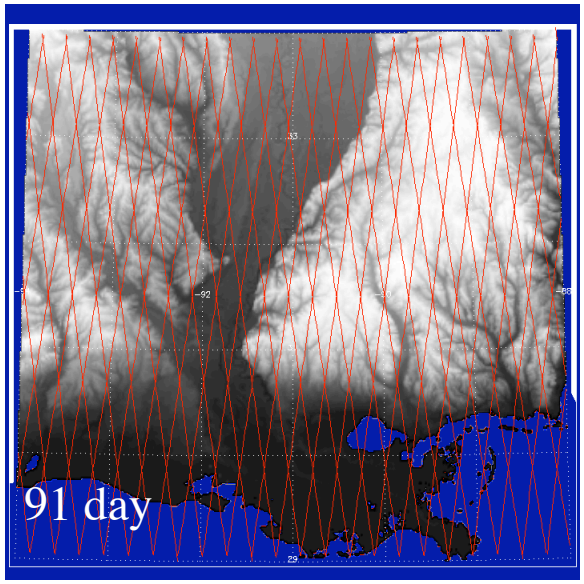
~10 m vertical accuracy to radar phase center

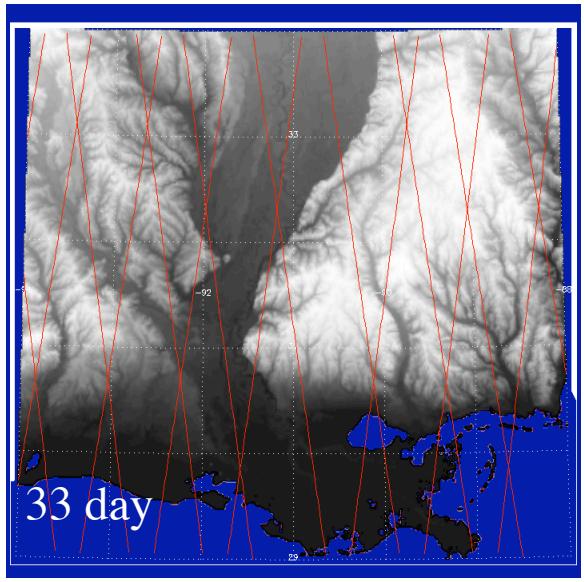
GTOPO30 900 m grid

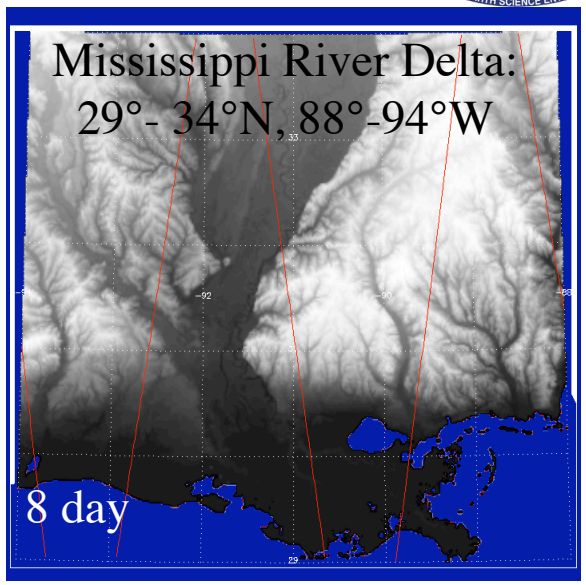
~50 m vertical accuracy

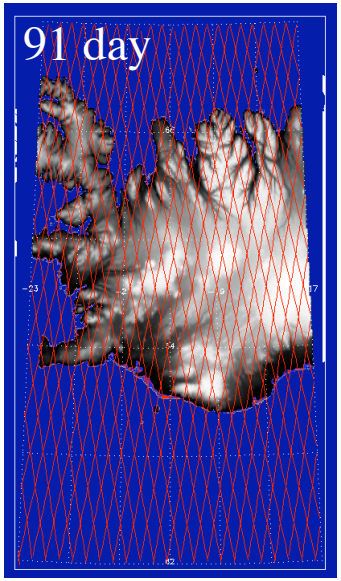
Best Publicly Available, Global Digital Elevation Models

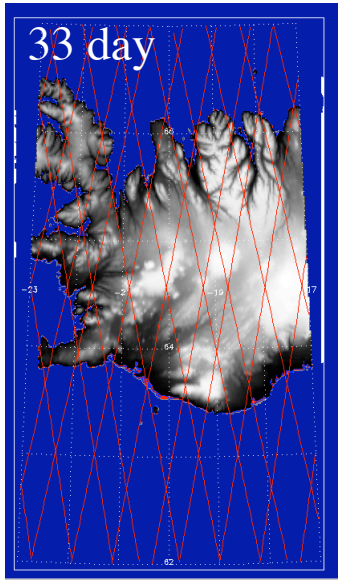
# *ICESat Track Spacing vs. Orbit Cycle*

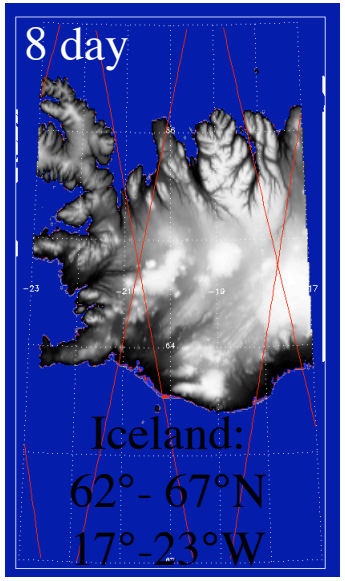


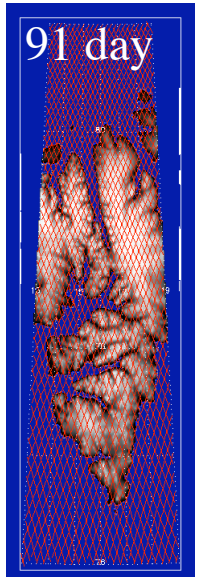



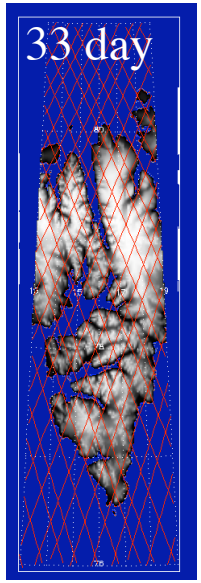



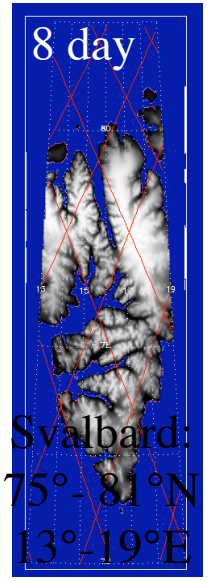



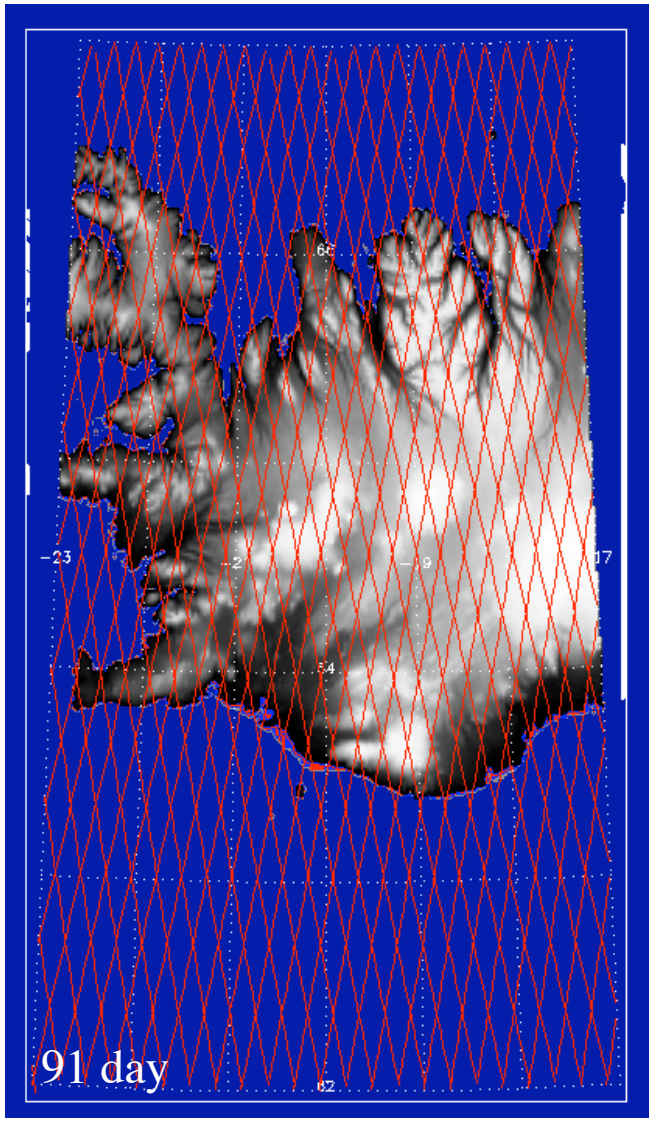



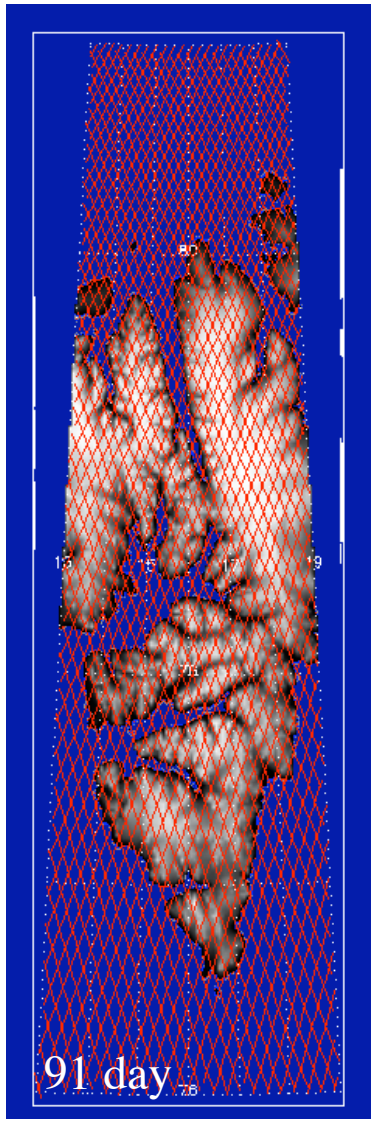



# *ICESat Track Spacing vs. Orbit Cycle*

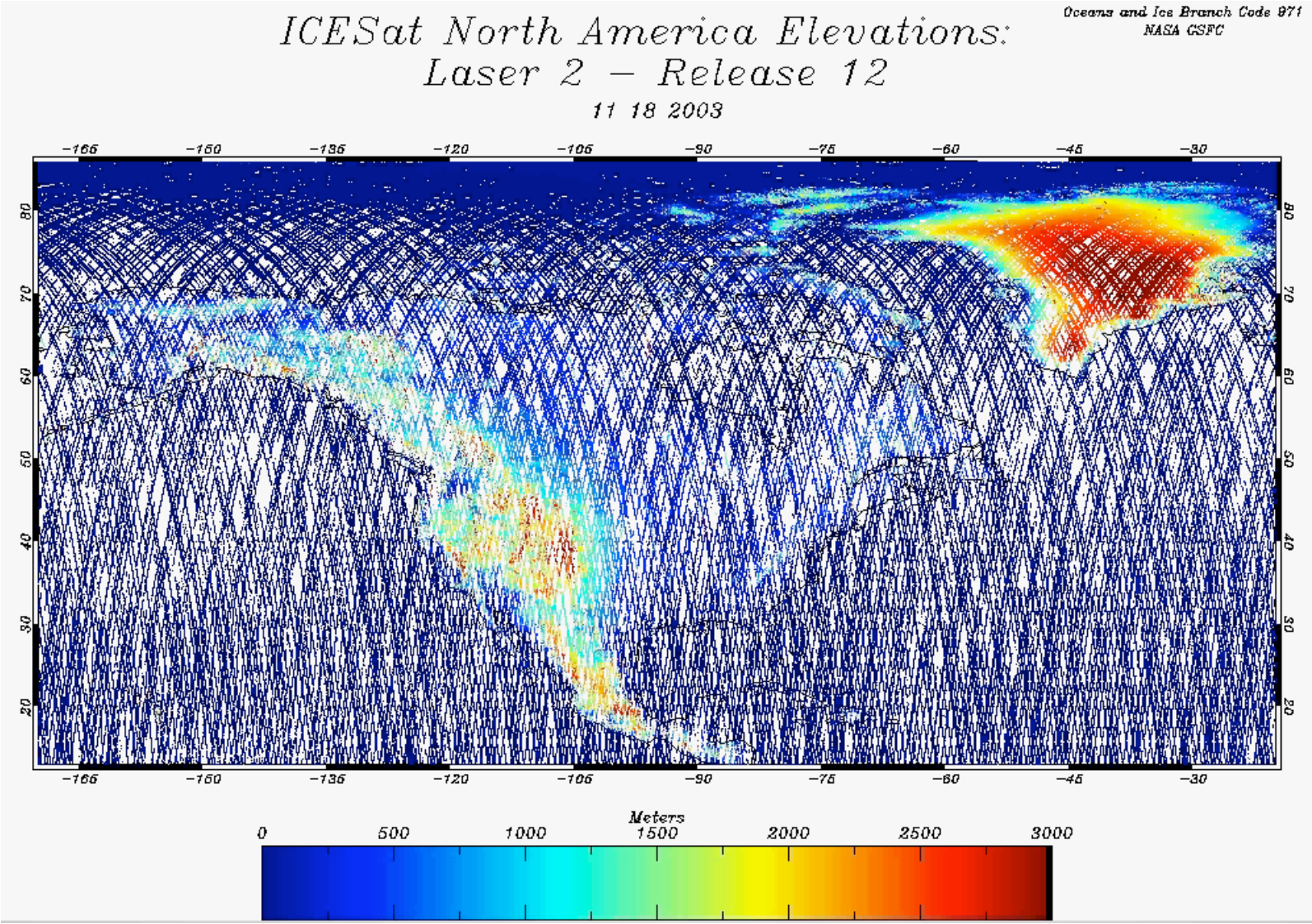
Iceland: 62°- 67°N, 17°-23°W




Svalbard: 75°- 81°N, 13°-19°E



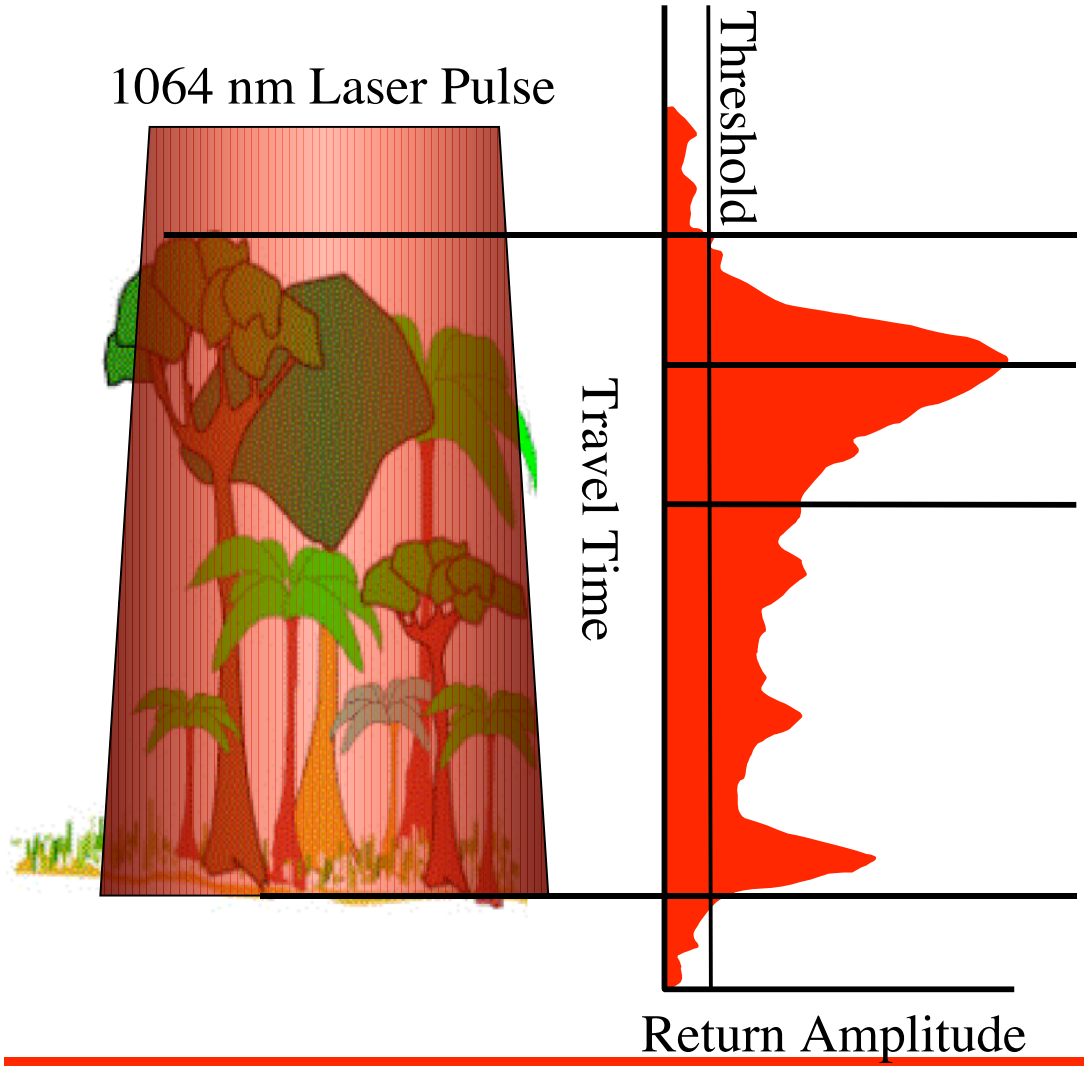
# ICESat Laser 2 North America Land Returns



# *Vegetated Landscape Waveform Elevations*

## Height Distribution of Reflected Laser Energy

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




### ICESat Elevation Products

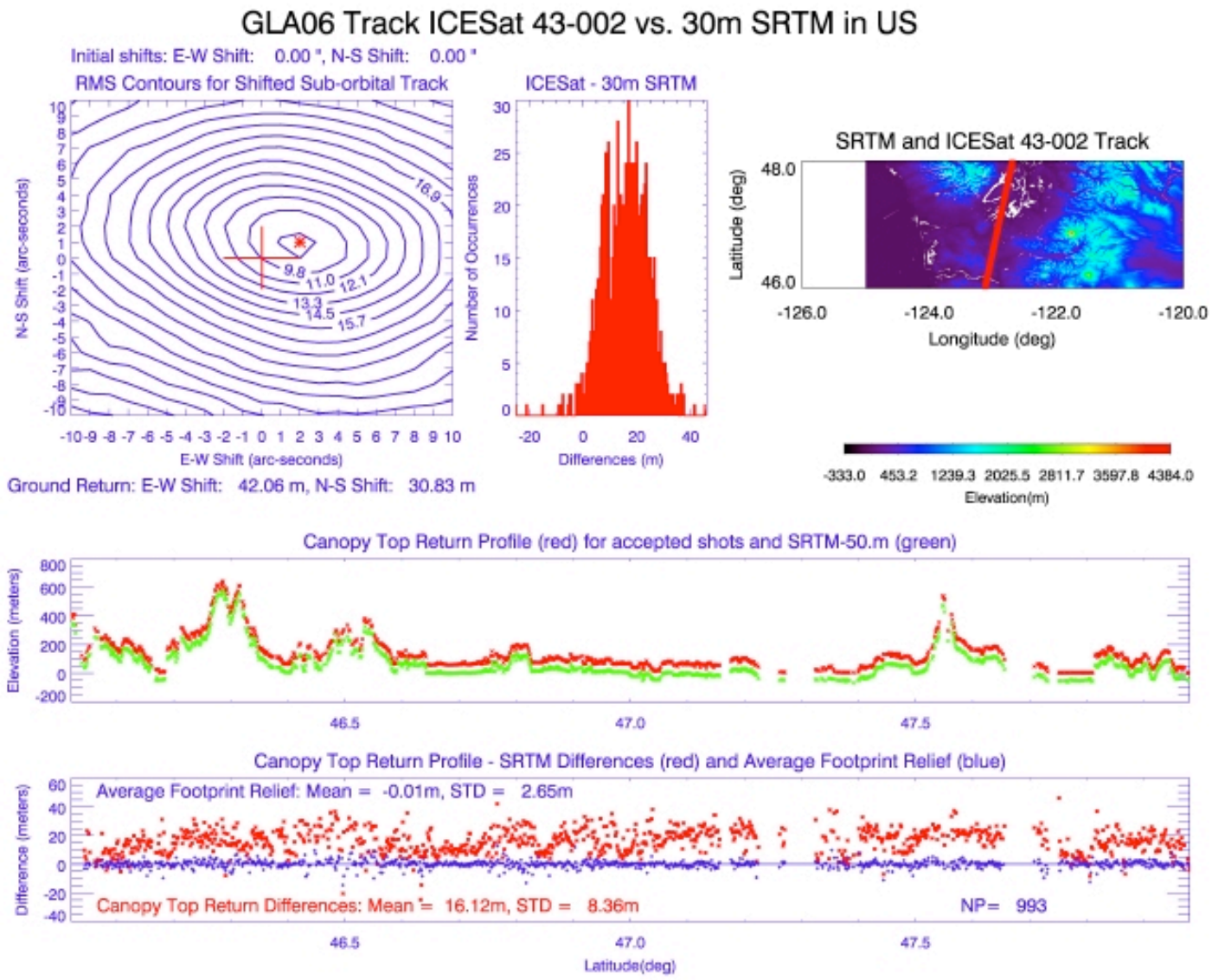
**Signal Start**
**= highest detected elevation**

**Gaussian Fit to Largest Peak**
**= standard ice sheet elevation**

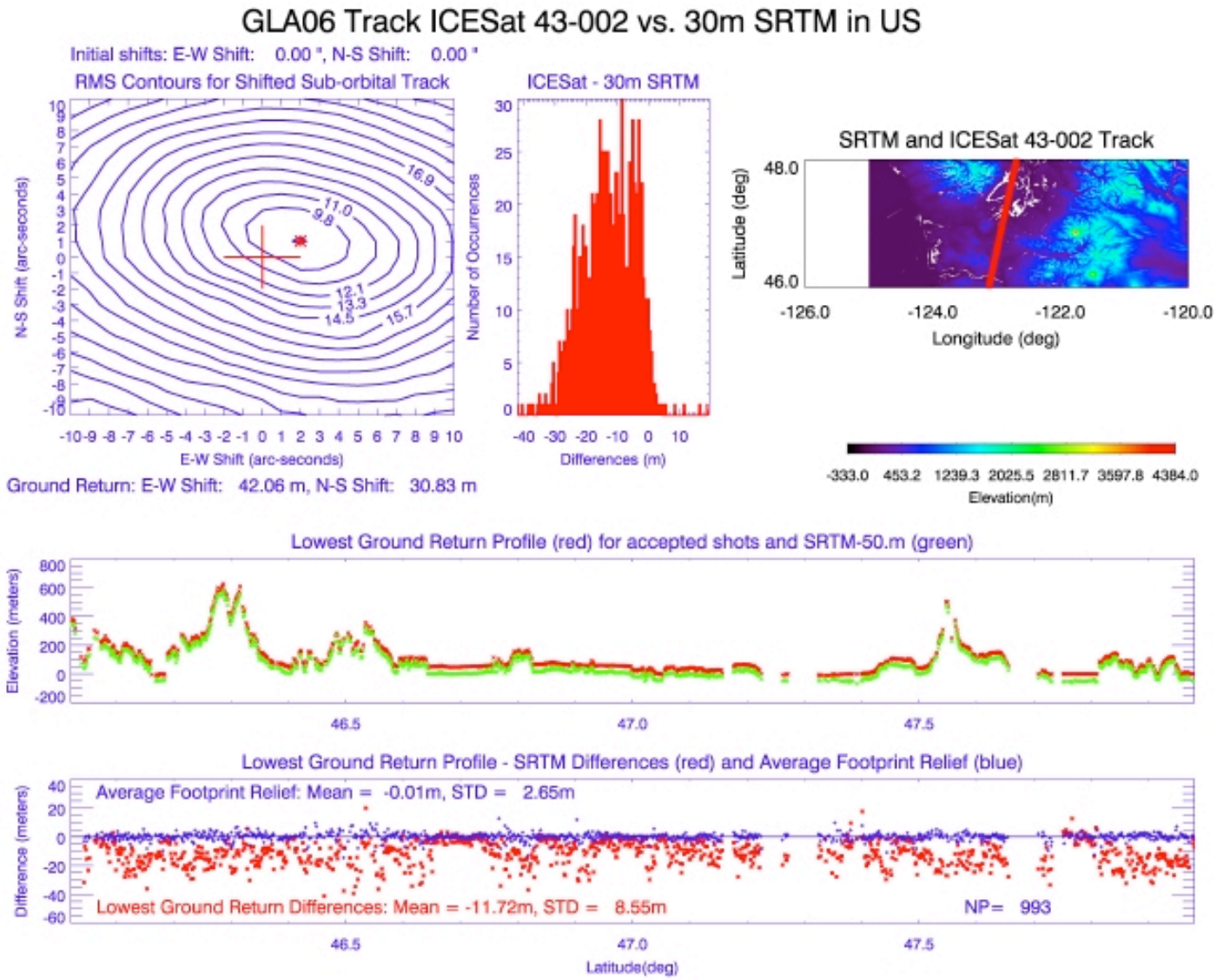
**Centroid of Signal Start to End**
**= average detected elevation**

**Signal End**
**= lowest detected elevation**

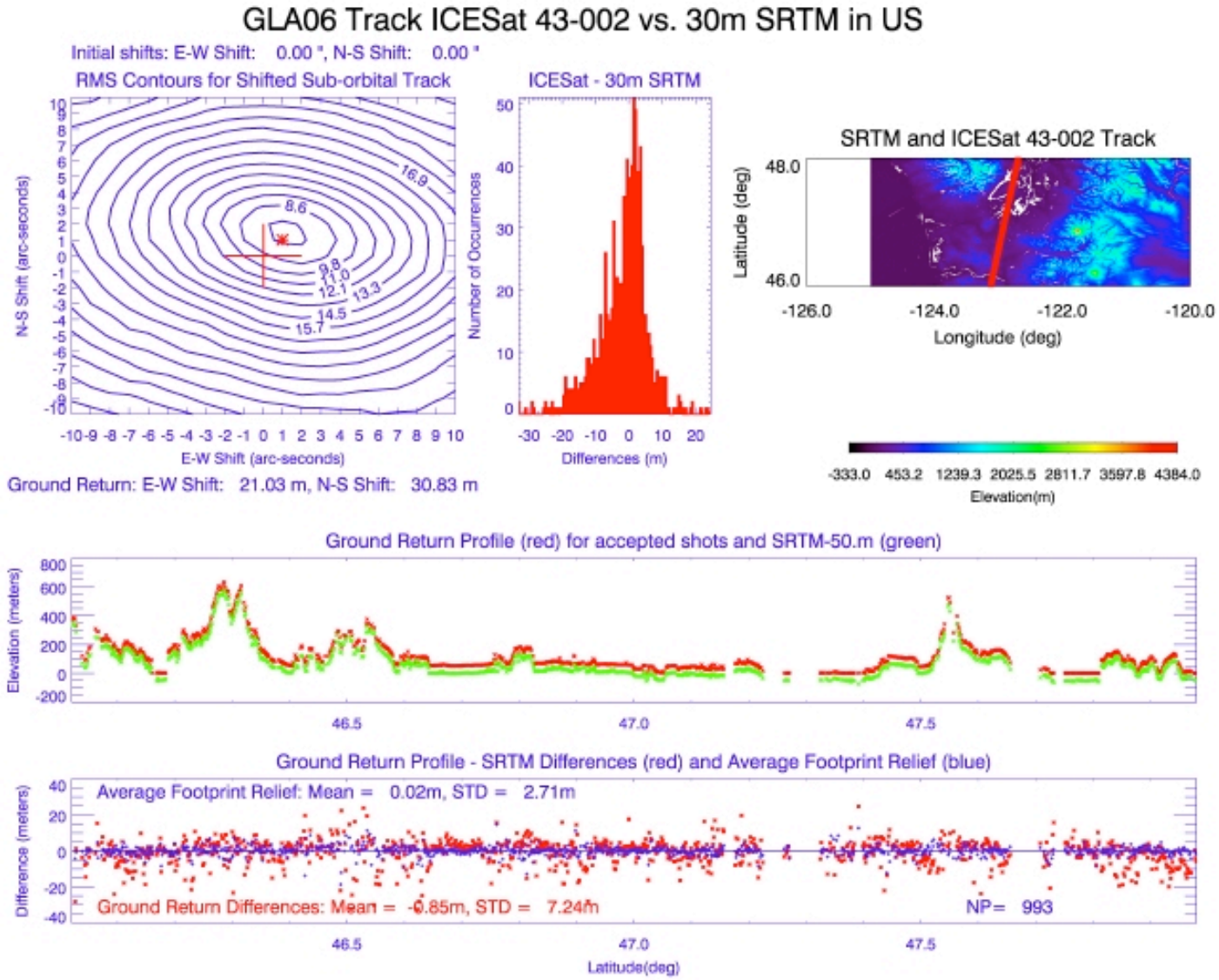
# *ICESat Signal Start vs. SRTM*



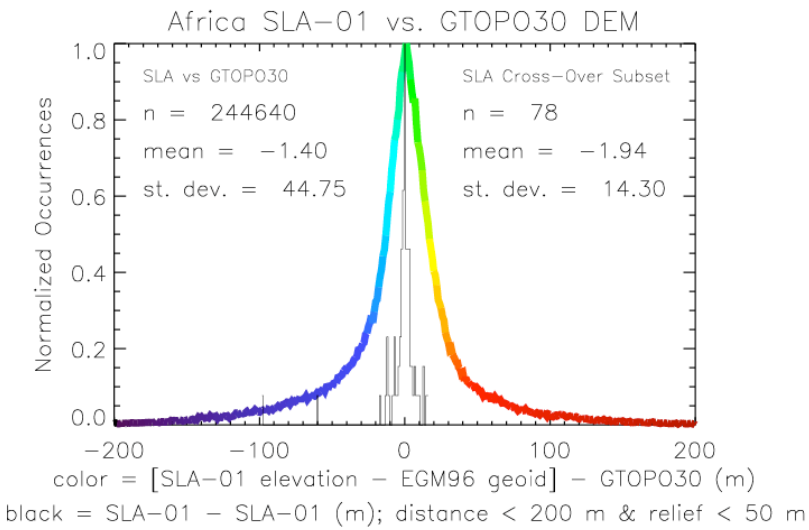
# *ICESat Signal End vs. SRTM*

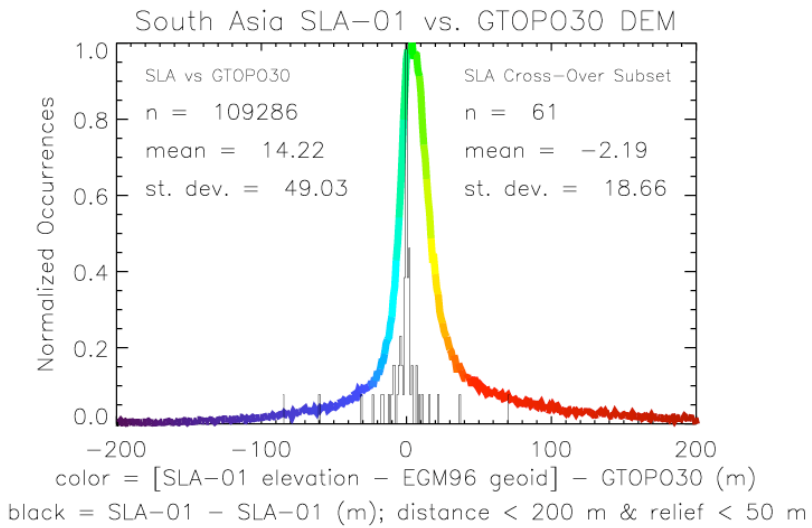


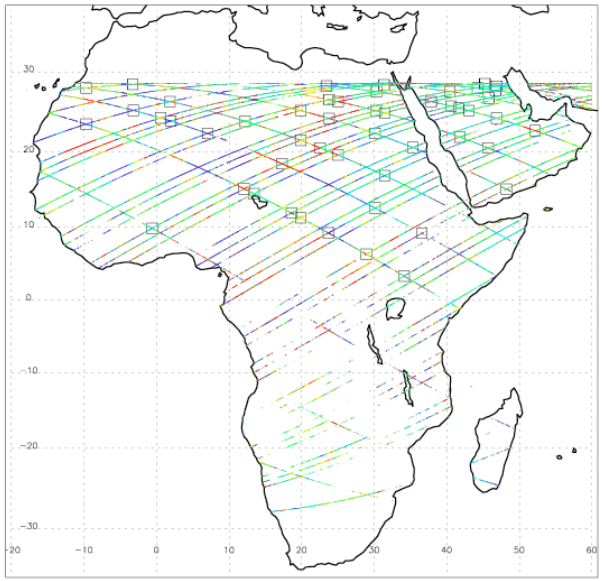
# *ICESat Largest Peak vs. SRTM*

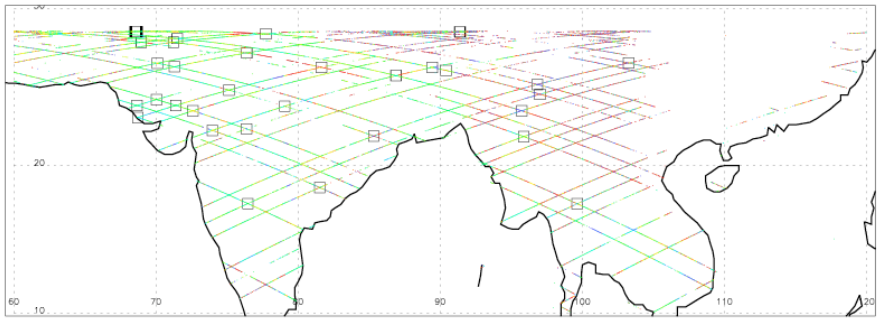


# Shuttle Laser Altimeter Evaluation of GTOPO30 Errors





# ***Sampling Approaches***

Accomplishments that can be met with ICESat-1

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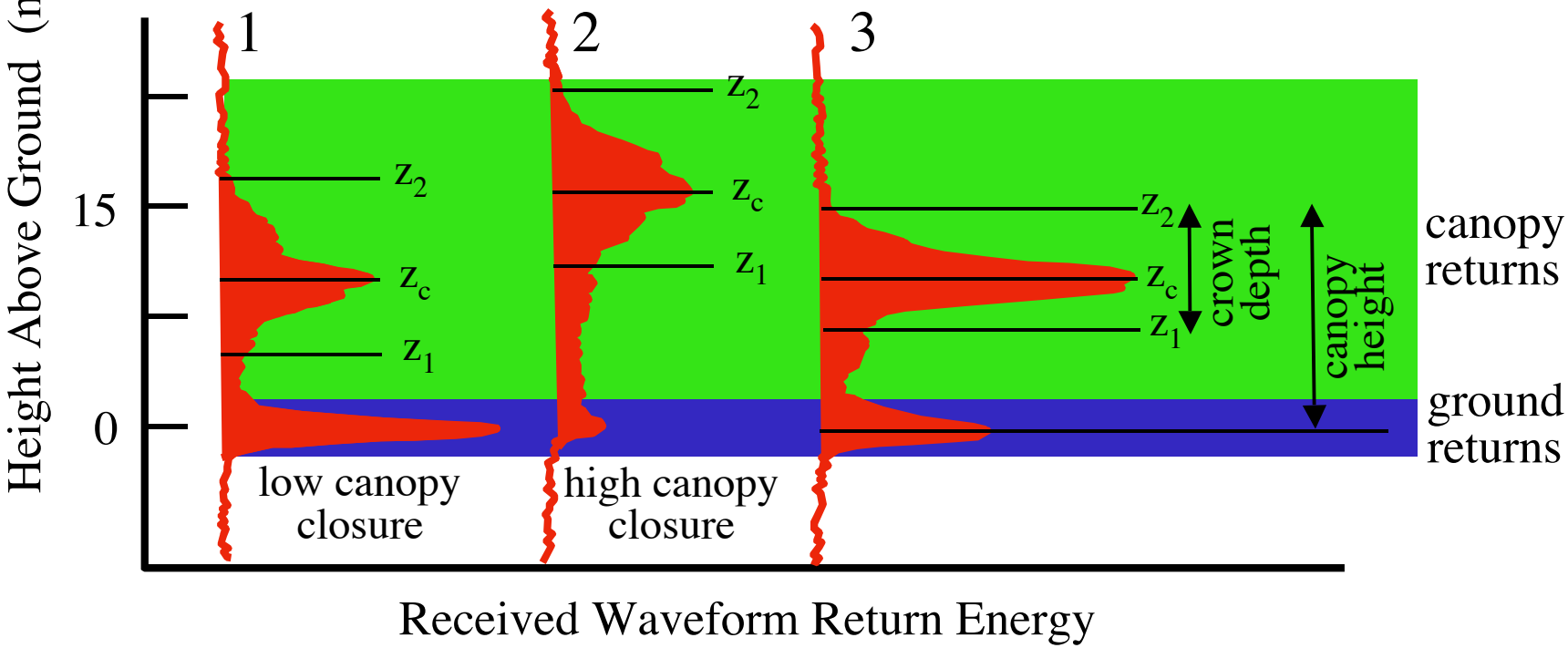
- cross-track data density insufficient for ICESat-only DEM production, even at high latitudes

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, $z_2$**

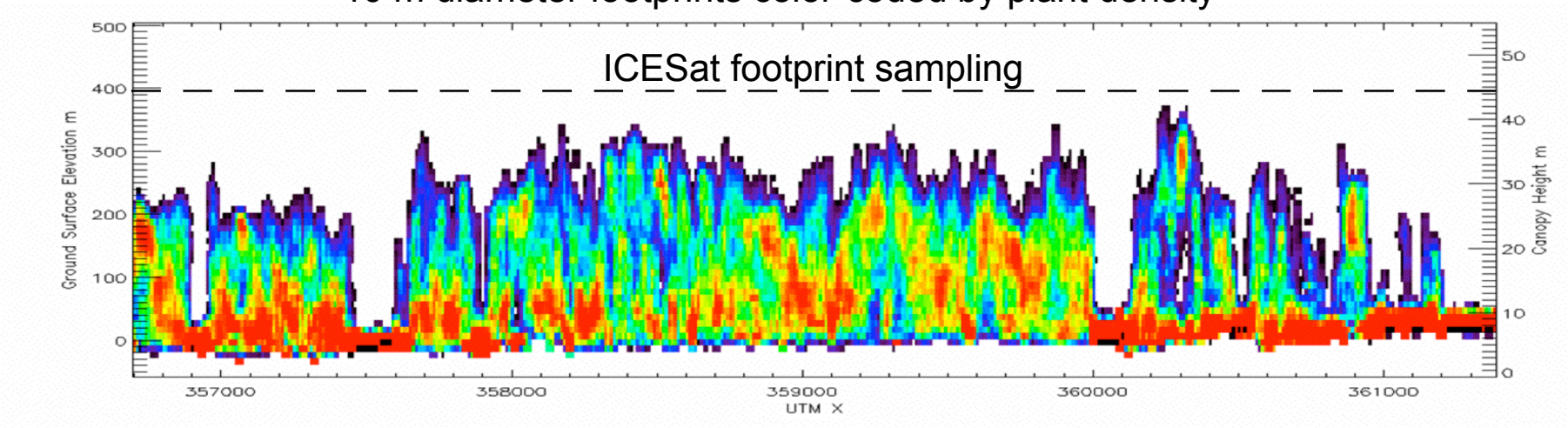
**Crown Depth = Width of Upper Part of Canopy Return, $z_2 - z_1$**

**Roughness of Outer Canopy = Leading Edge Slope from $z_2$ to $z_c$**

$$\textbf{Canopy Closure} \sim \frac{\textbf{Ground Return Energy}}{\textbf{Total Return Energy}}$$

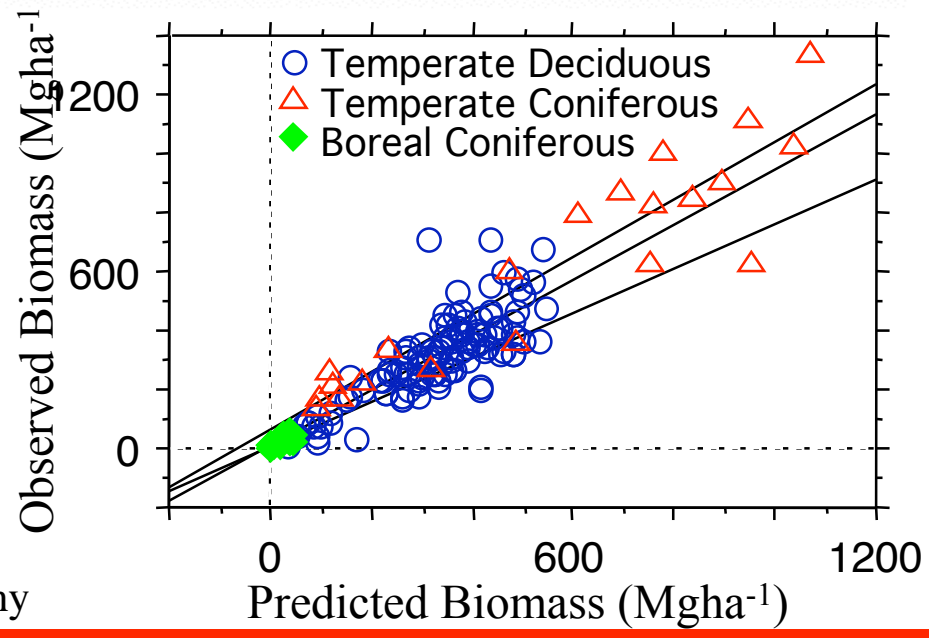
# *Estimation of Forest Stand Above Ground Biomass*

Douglas Fir 4.7 km SLICER airborne waveform transect
10 m diameter footprints color-coded by plant density




SLICER waveform mean canopy height squared ($MCH^2$) vs. field observations of above ground forest biomass

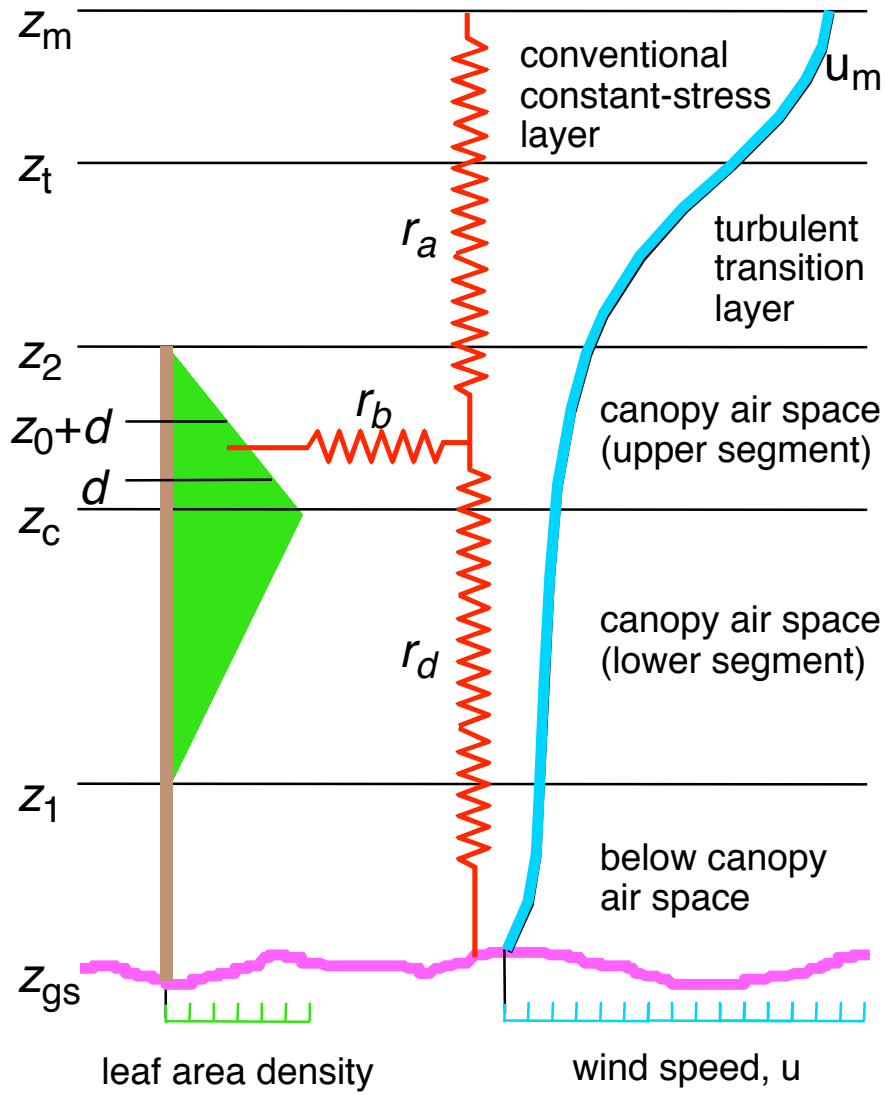
- linear relationship to high biomass levels
- accounts for 80 to 90% of variance
- applicable to a diversity of forest types
- $MCH^2$ proxy for height x stem diameter (a measure of tree volume)




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

# *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
$\square_L$ leaf-angle distribution factor
$L_T$ total leaf area index (time variable)

⬇

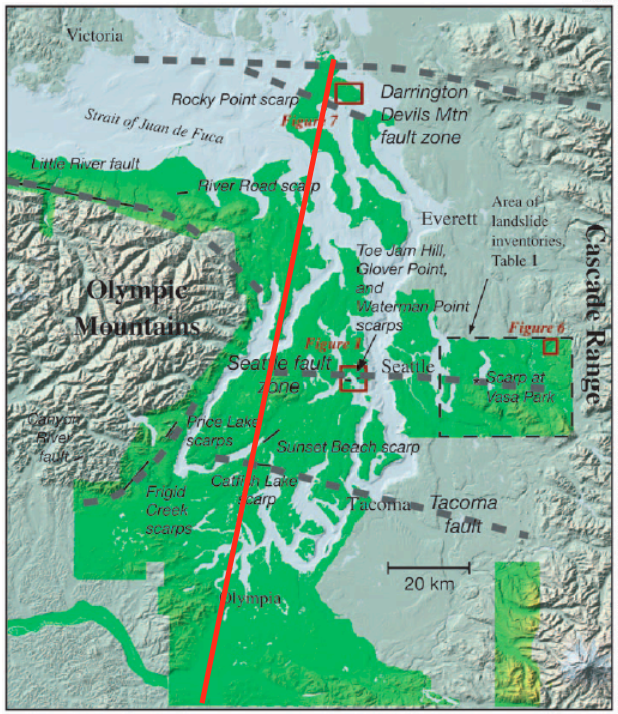
$z_0$ roughness length
$d$ zero plane displacement
$C_1$ canopy resistance coefficient
$C_2$ ground to canopy air-space resistance coefficient

⬇

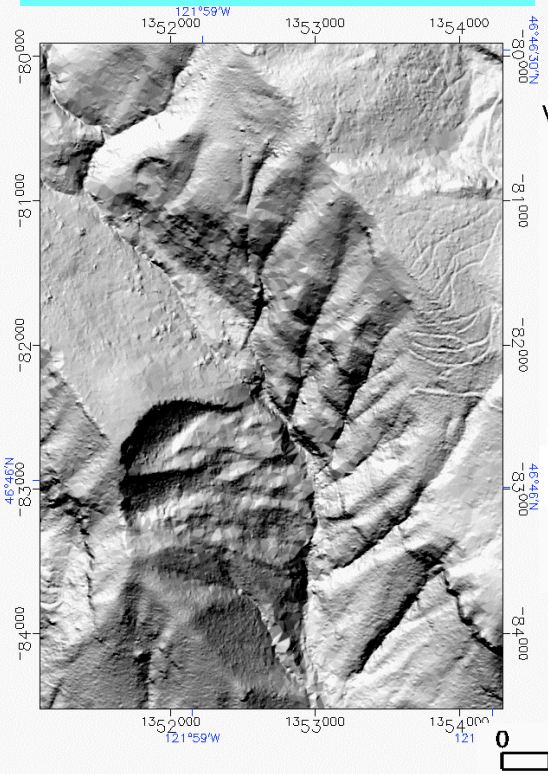
**GCM aerodynamic resistances**

$r_a$ canopy air-space to ref. height
$r_b$ canopy to canopy air-space
$r_d$ ground to canopy air-space

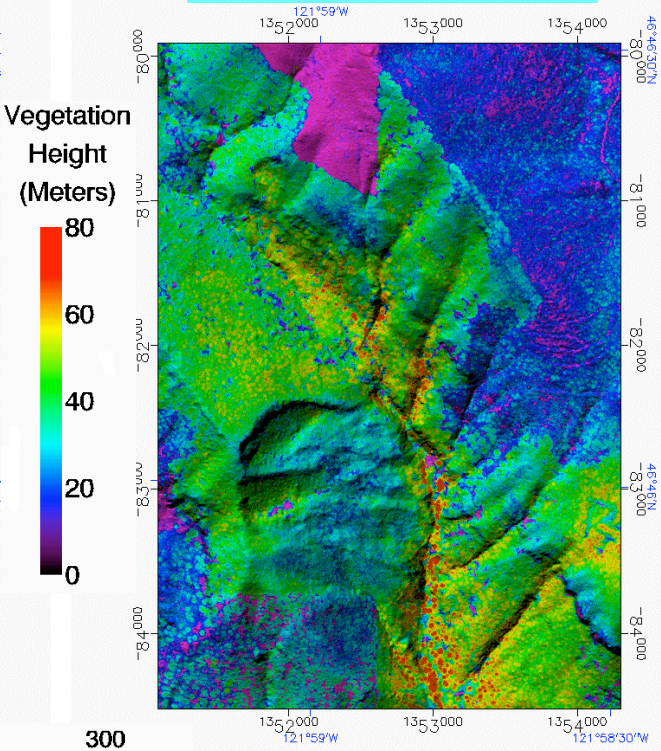
# *Puget Lowland High-Res Airborne Laser Mapping*




## Bald Earth 1.8 m DEM




## Vegetation Height

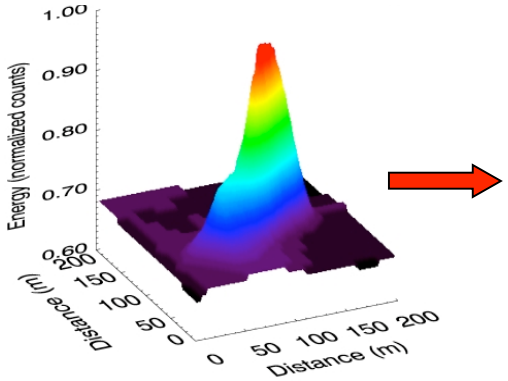



ICESat 8-day
ground track 43
180 km length
~ 1,000 footprints

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

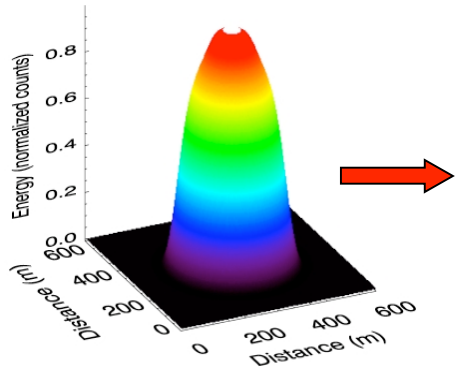
# *Waveform Matching to High-Resolution Canopy DEM*

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



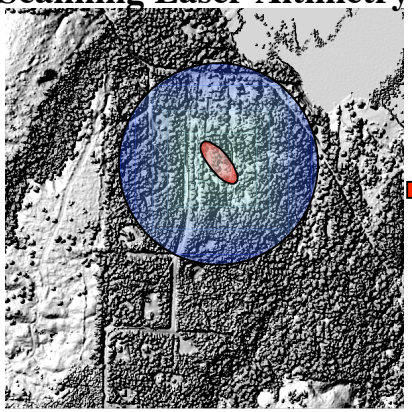

**~ 120 m x 50 m full-width ellipse**

**1064 nm Receiver FOV Transmissivity**



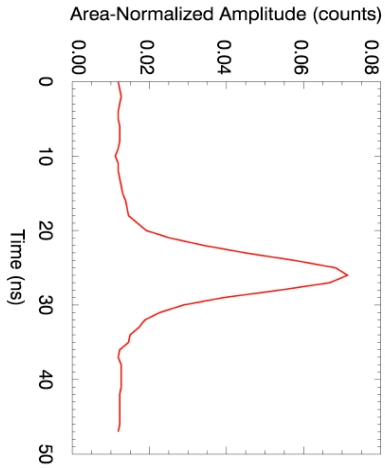

**500 m full-width diameter**

**1.8 m DEM from Airborne Scanning Laser Altimetry**

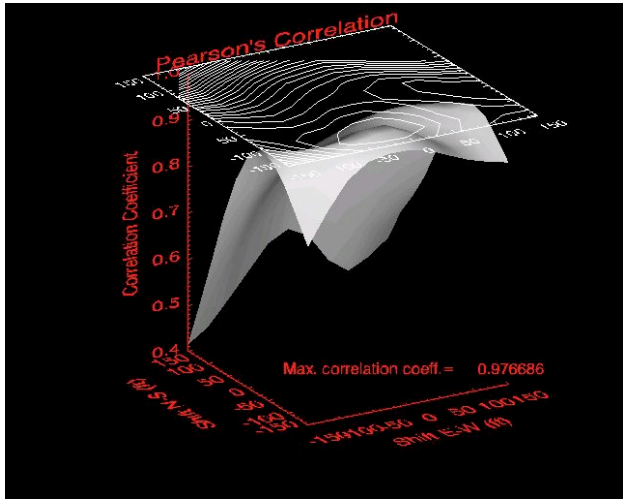


**Spatial Convolution = Height Distribution of Reflected Laser Energy Within Footprint**

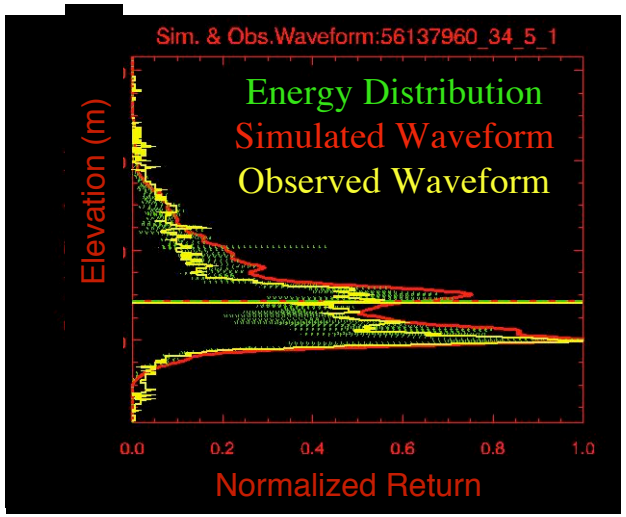
**Receiver Response for Transmit Pulse**




**Temporal Convolution = Simulated Waveform**



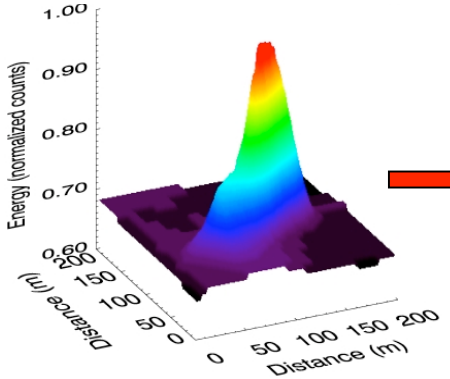

**Spatial Shifting to Maximize Correlation Between Observed and Simulated Waveforms**




**Waveforms at Location Of Best Fit**

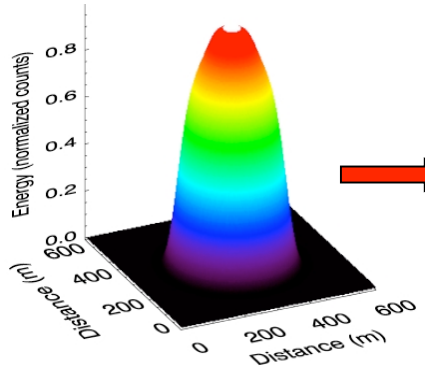
# *Identification of Ground from Bald Earth DEM*

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




**~ 120 m x 50 m full-width ellipse**

**1064 nm Receiver FOV Transmissivity**




**500 m full-width diameter**

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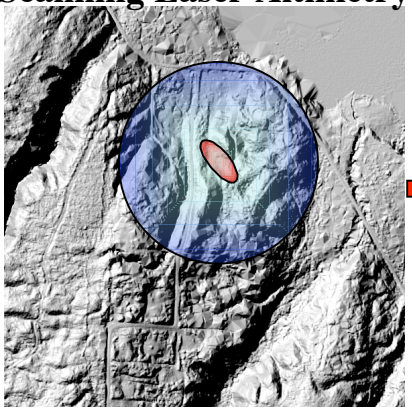
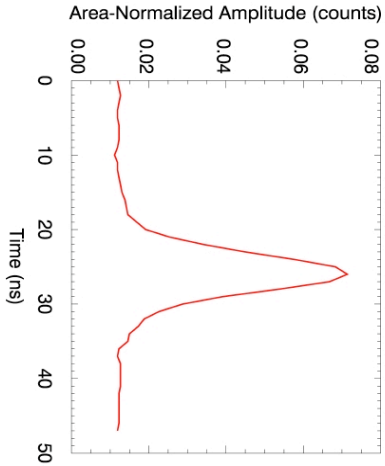
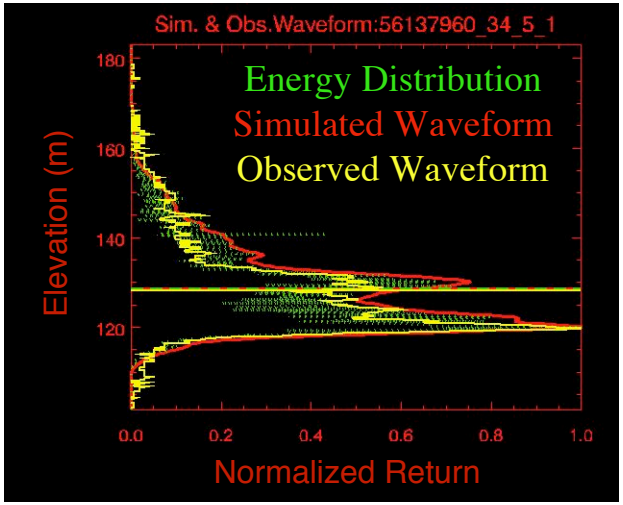


**Spatial Convolution = Height Distribution of Reflected Laser Energy Within Footprint**

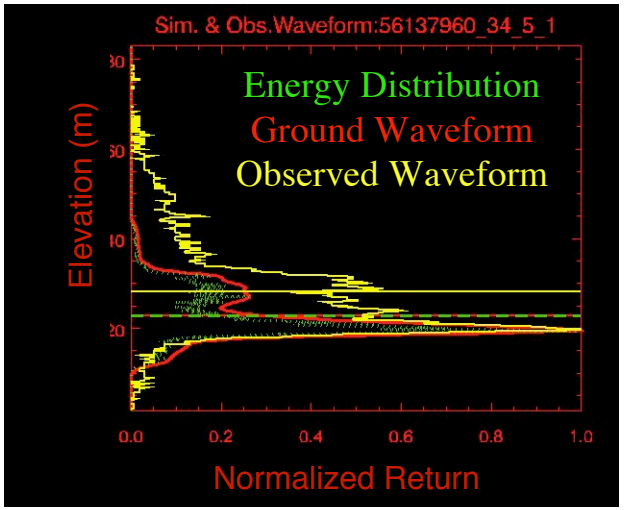
**Receiver Response for Transmit Pulse**




**Temporal Convolution = Simulated Waveform**



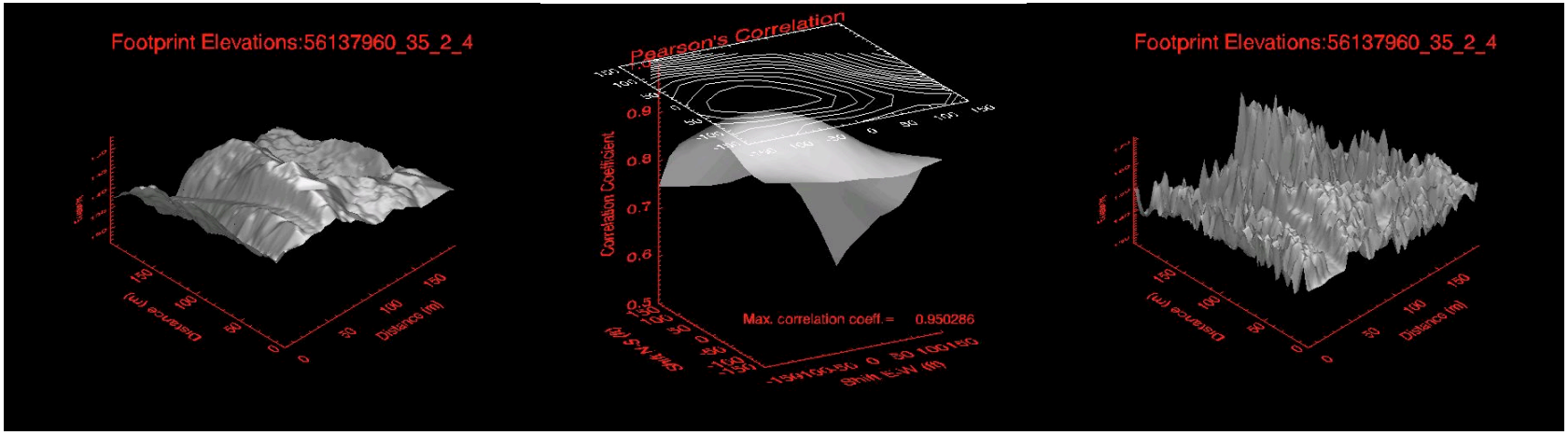

**Identify Waveform Best Fit Location from Canopy DEM**

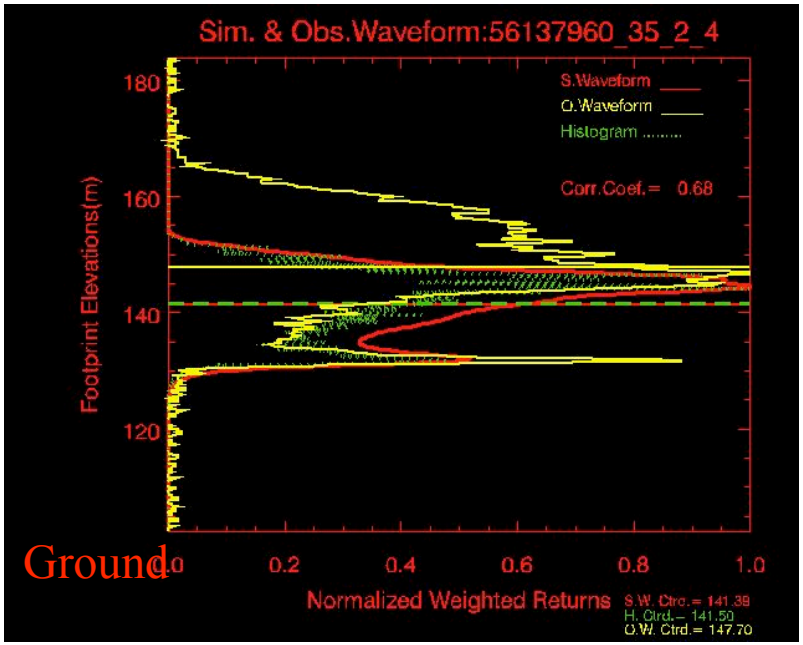


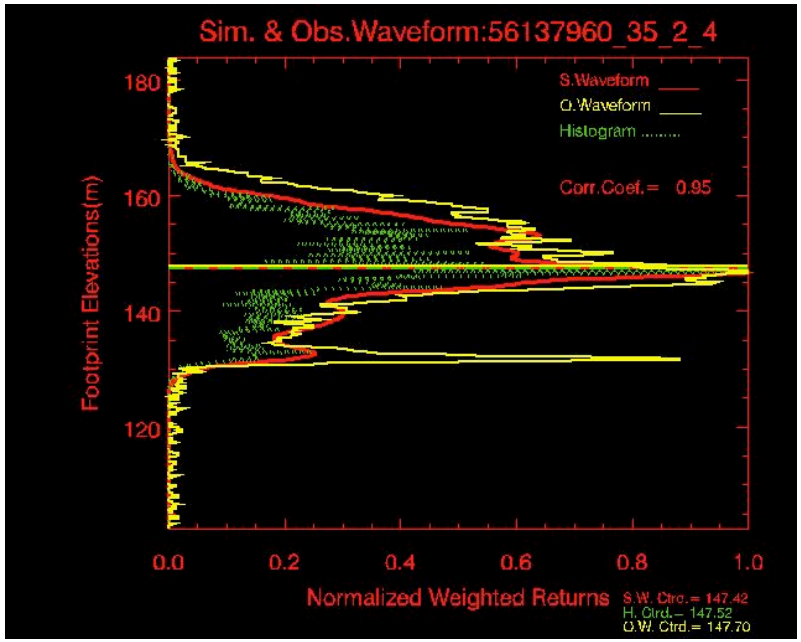

**Ground Elevations at Best Fit Location**

# *Simulated and Observed ICESat Waveforms*

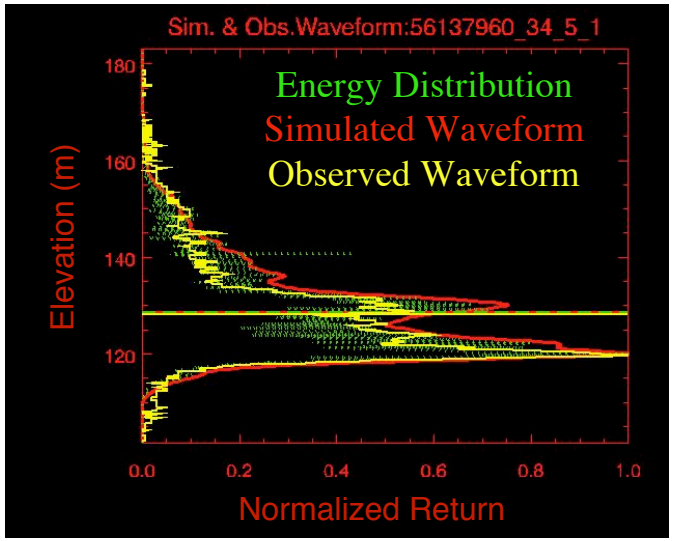
Best fit shift from Release 12 geolocation: 48 m W, 53 m N



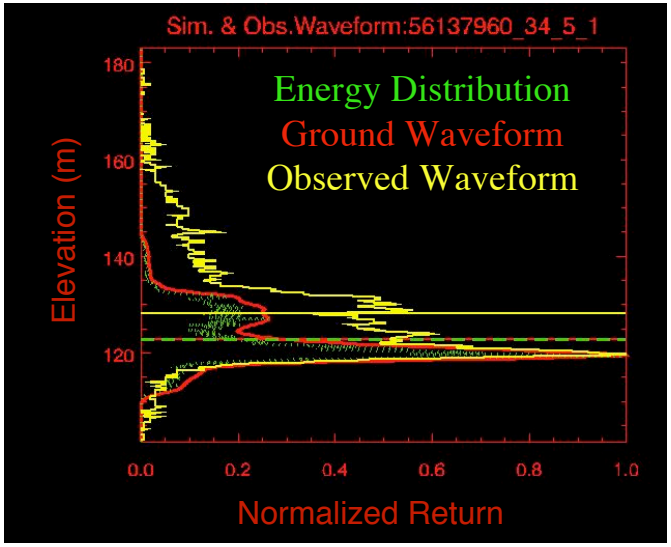



# *Waveform Simulation Results*




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*



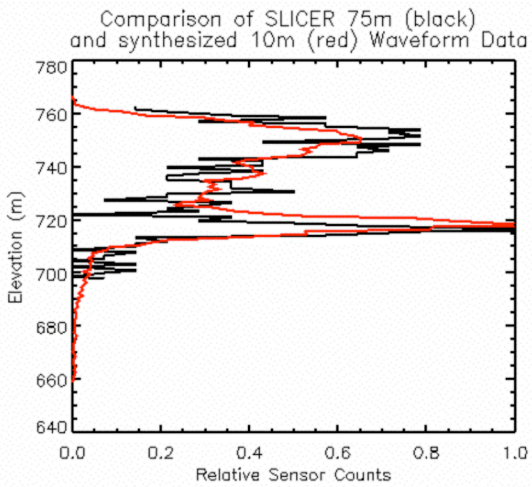

Where the ground has local relief within the ICESat footprint, ground and vegetation are mixed in the waveform making interpretation complex:

*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

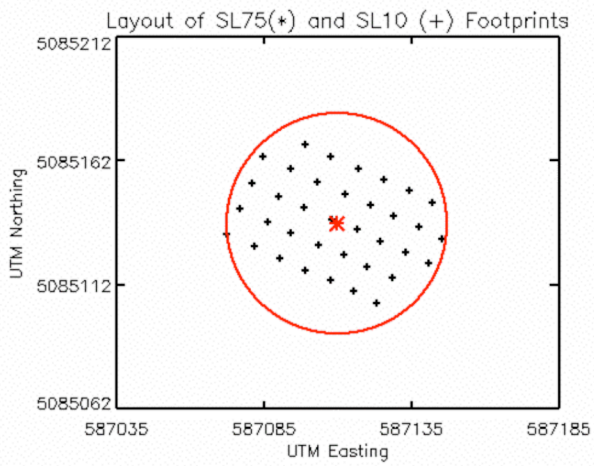



Observed 75 m footprint waveform (black)

- 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

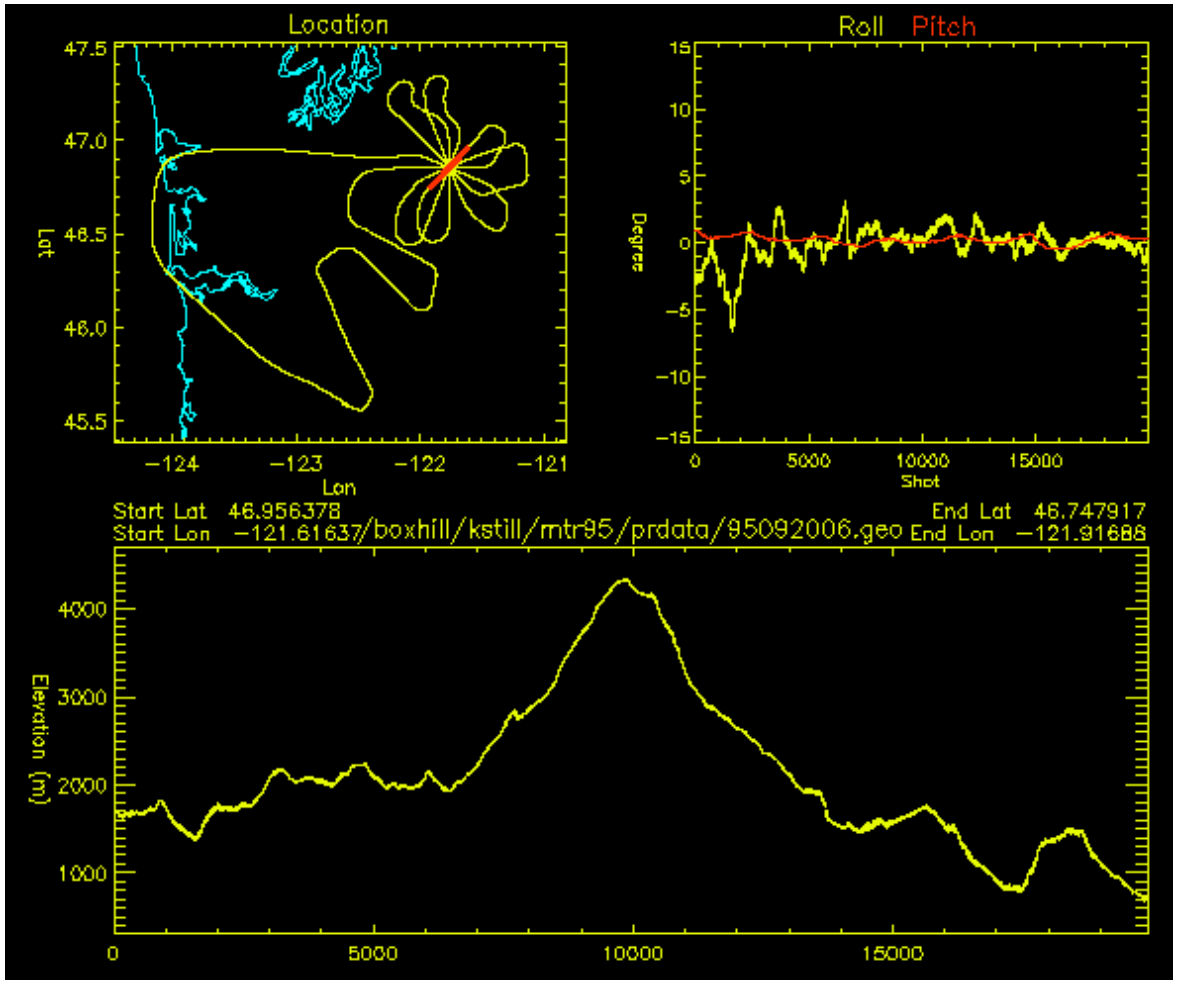
# *Stand Height Retrieval from 75m Waveforms*

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*

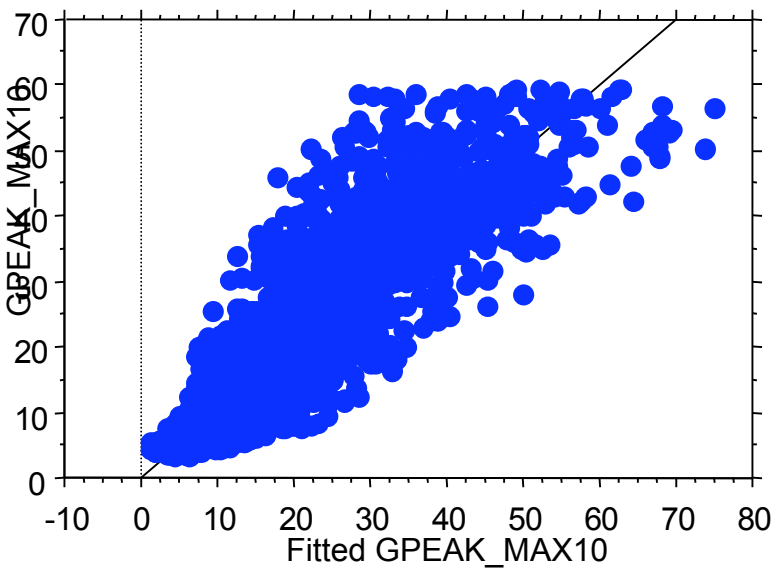



8 radial SLICER transects

- 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




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

- 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

| | |
|---|---|
| Count | 2448 |
| Num. Missing | 0 |
| R | .892 |
| R Squared | .796 |
| Adjusted R Squared | .796 |
| RMS Residual | 3.738 |

| | Coefficient | Std. Error | Std. Coeff. | F-to-Remove |
|---|---|---|---|---|
| Intercept | -1.092 | .178 | -1.092 | 37.680 |
| EH | 1.062 | .012 | 2.814 | 7952.665 |
| ELEV_RANGE10 | -.516 | .011 | -1.211 | 2170.087 |
| TOPE_RANGE10 | -.500 | .013 | -1.191 | 1571.590 |

# *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”.

# ***Recommendations (3)***

## 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
- 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)

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

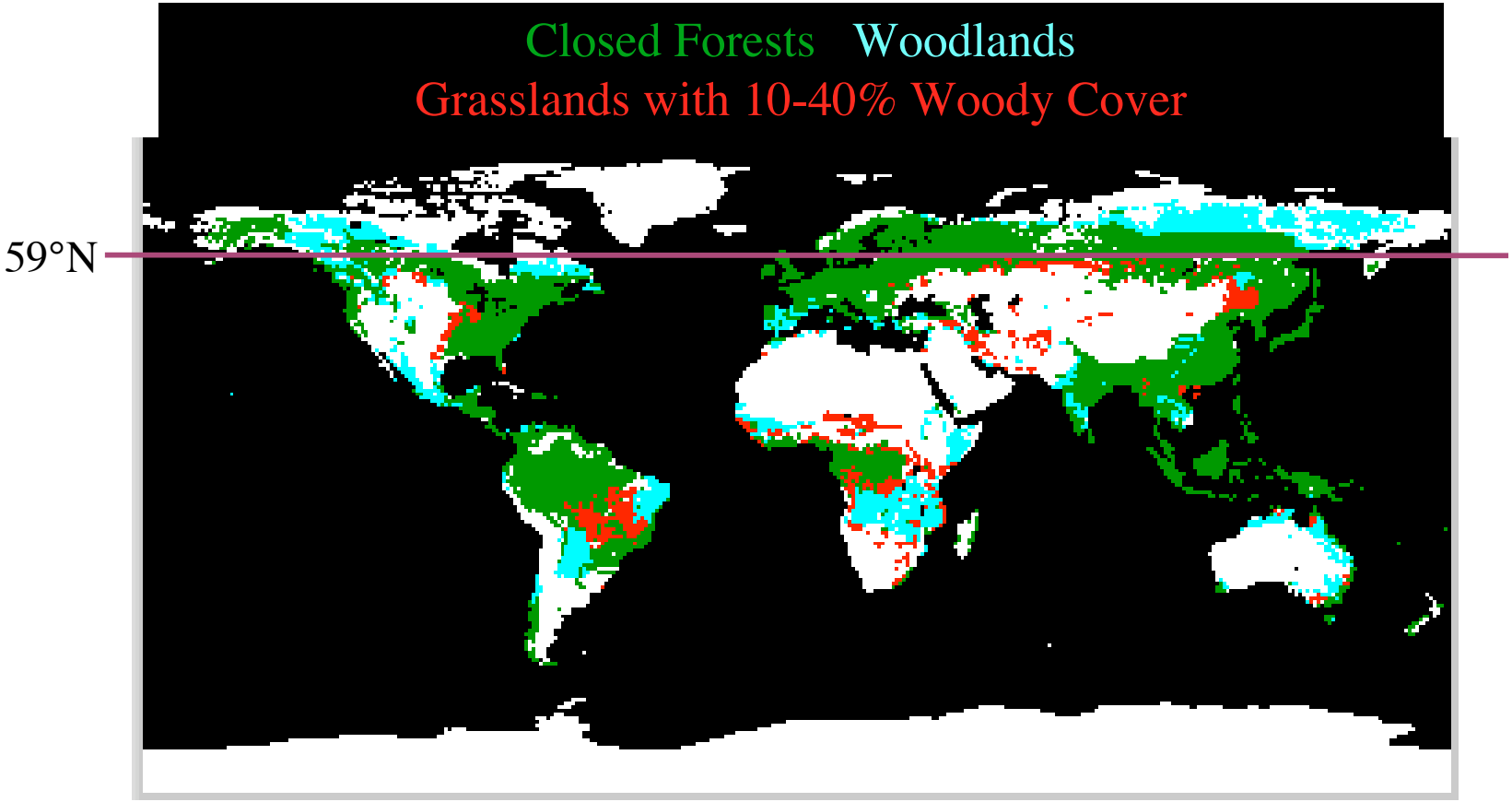
Better approach is to only compress very broad waveforms

- selected filter is available on shot-by-shot basis
- 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

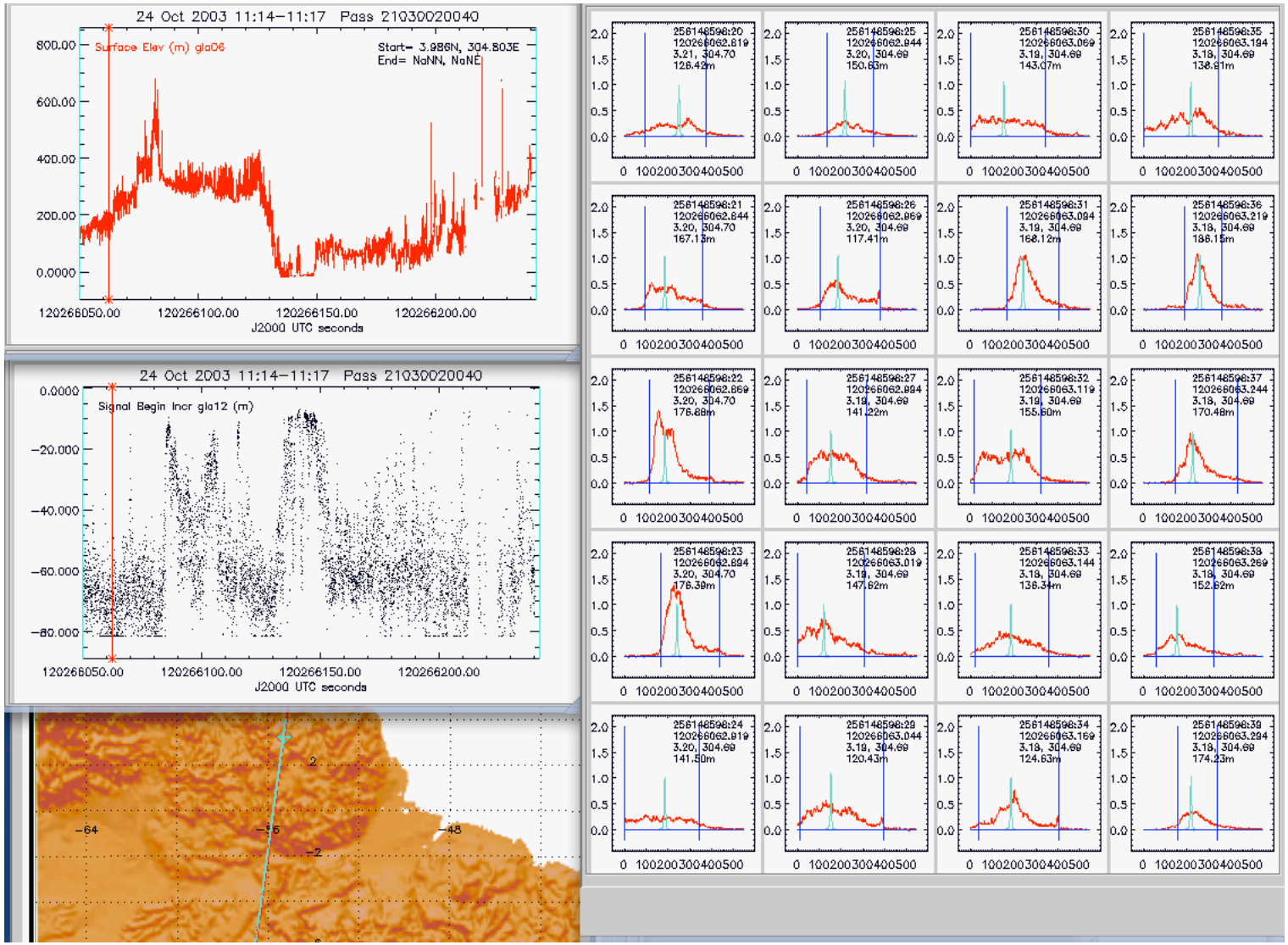
# Proposed Waveform Compression Based on Matthews Potential Vegetation 1° x 1° Global Classification

1 nsec sampling (81 m waveform extent) too short for some areas of tall vegetation and/or high relief

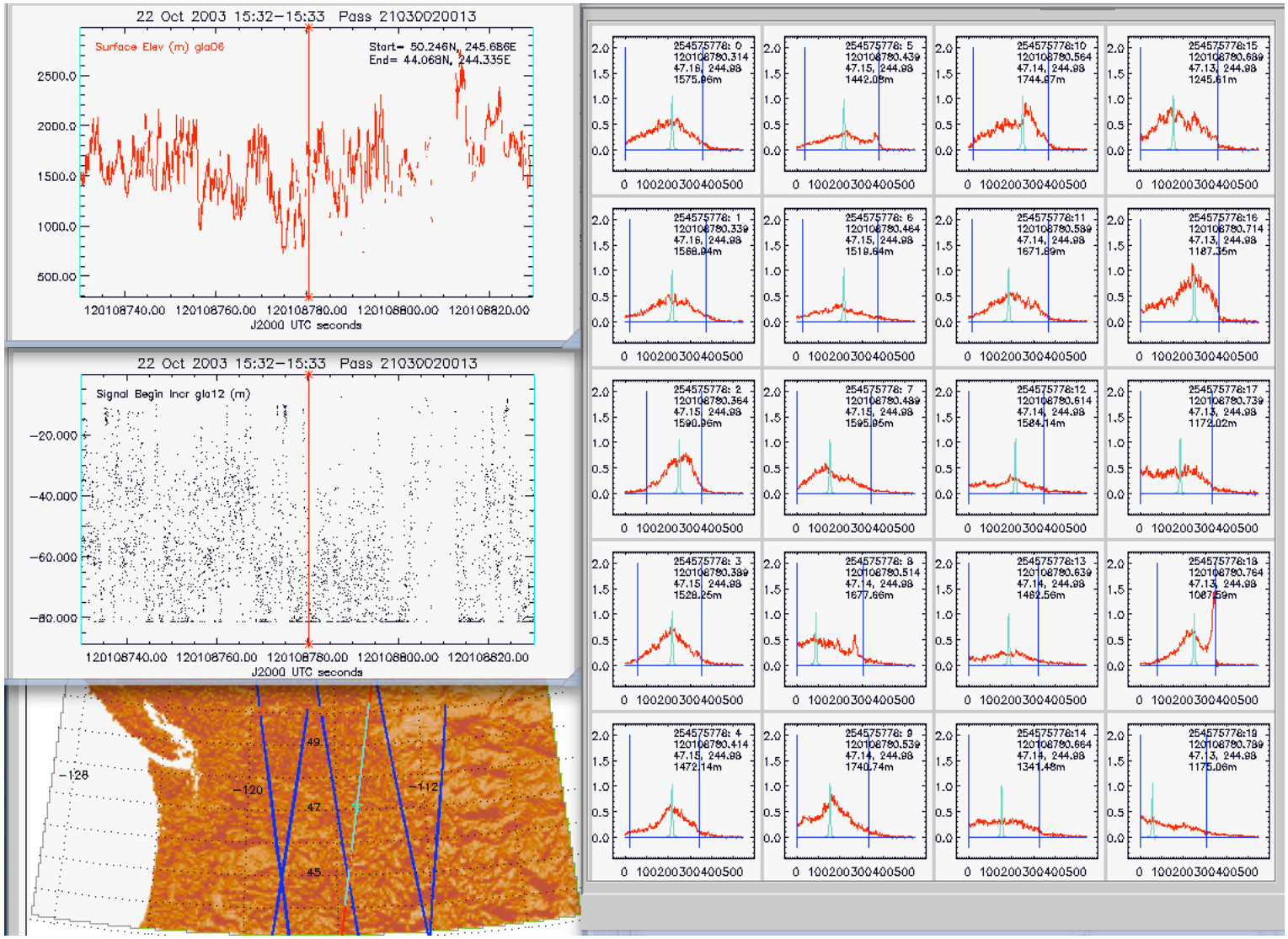
Solution: 2x Compression South of 59°N = 150 m waveform extent



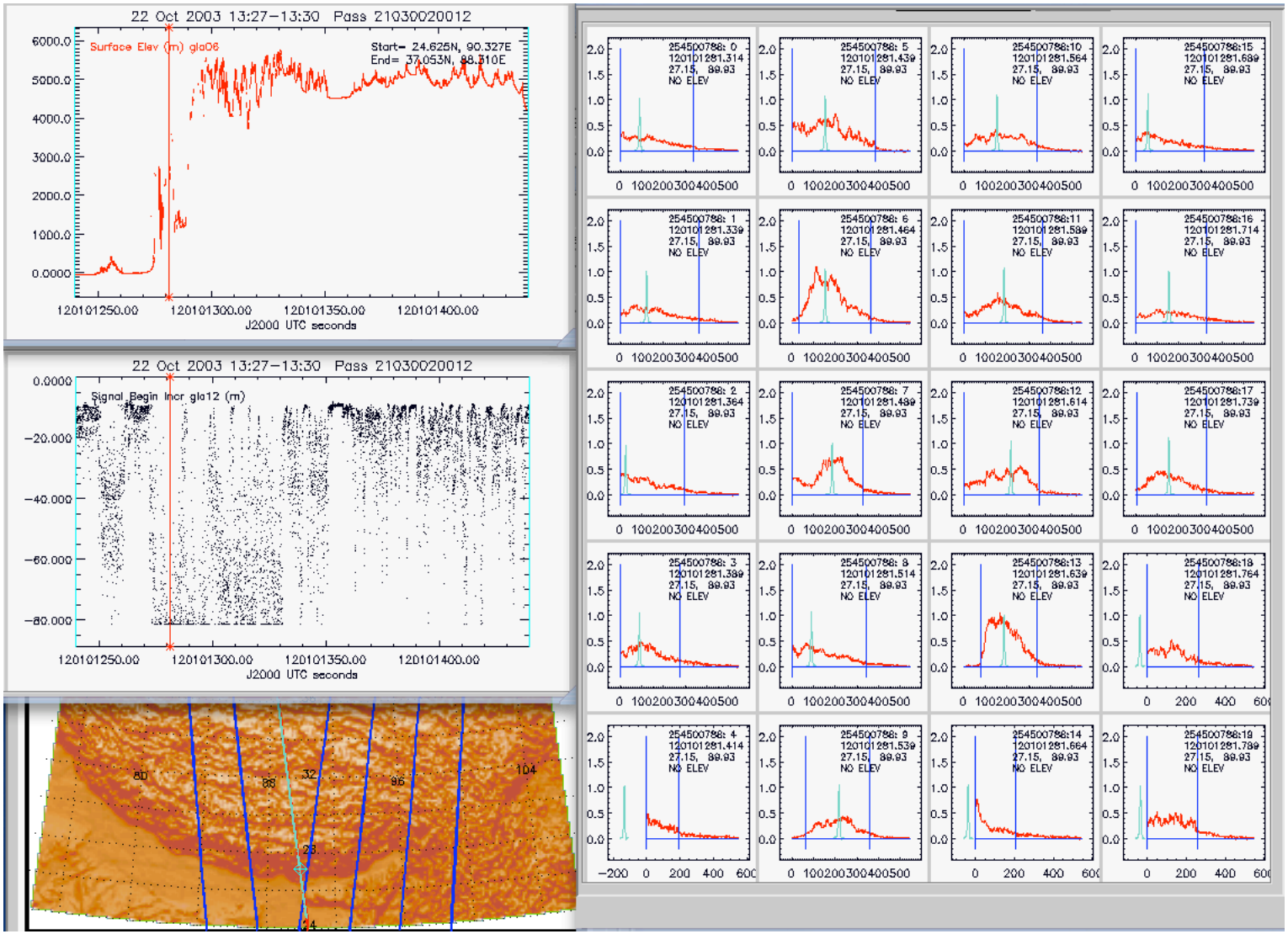
# *Signal Start Truncation: Amazon Rain Forest*



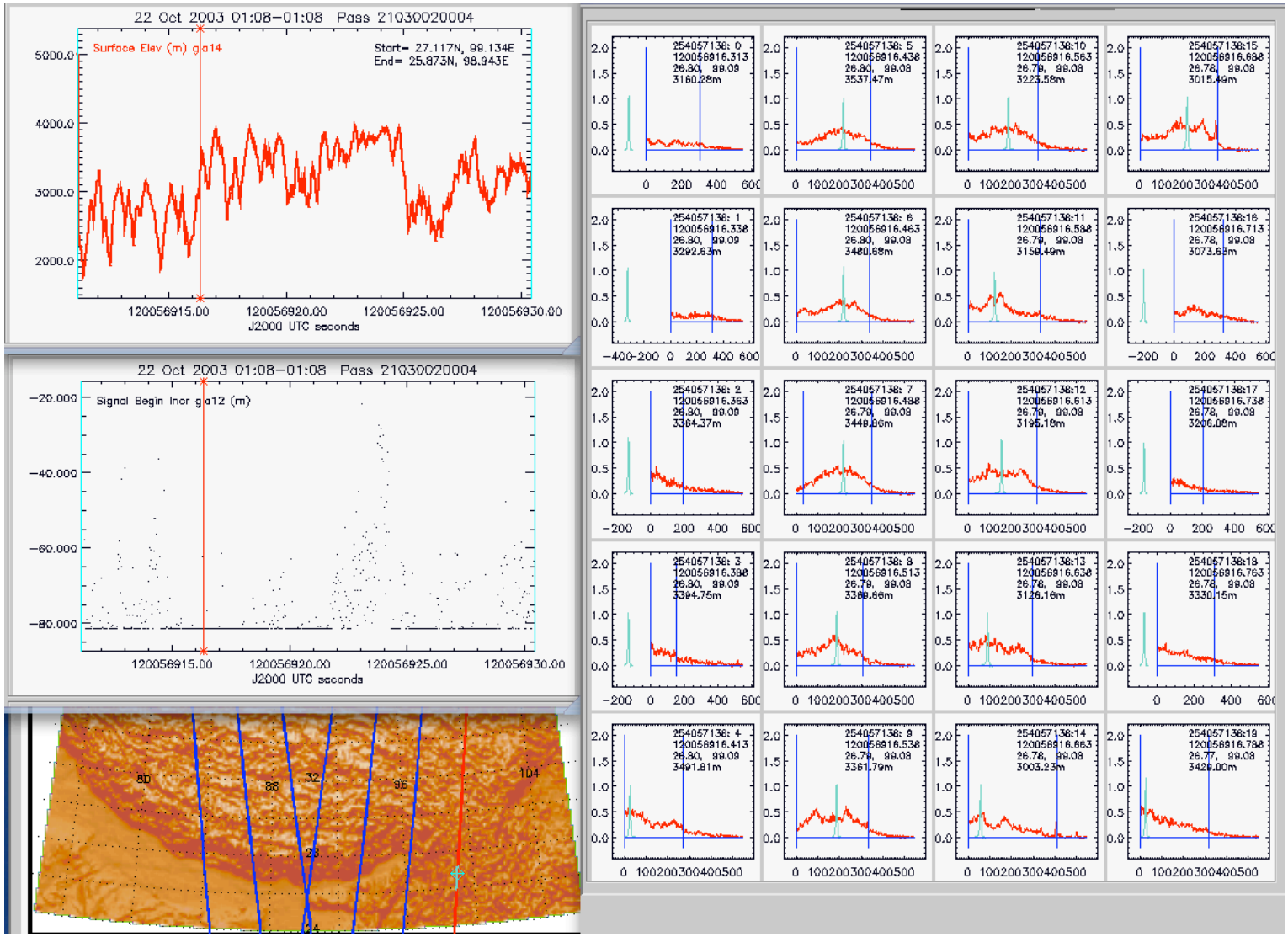
# *Signal Start Truncation: Western Unites States*



# Signal Start Truncation: Himalayan Mountains

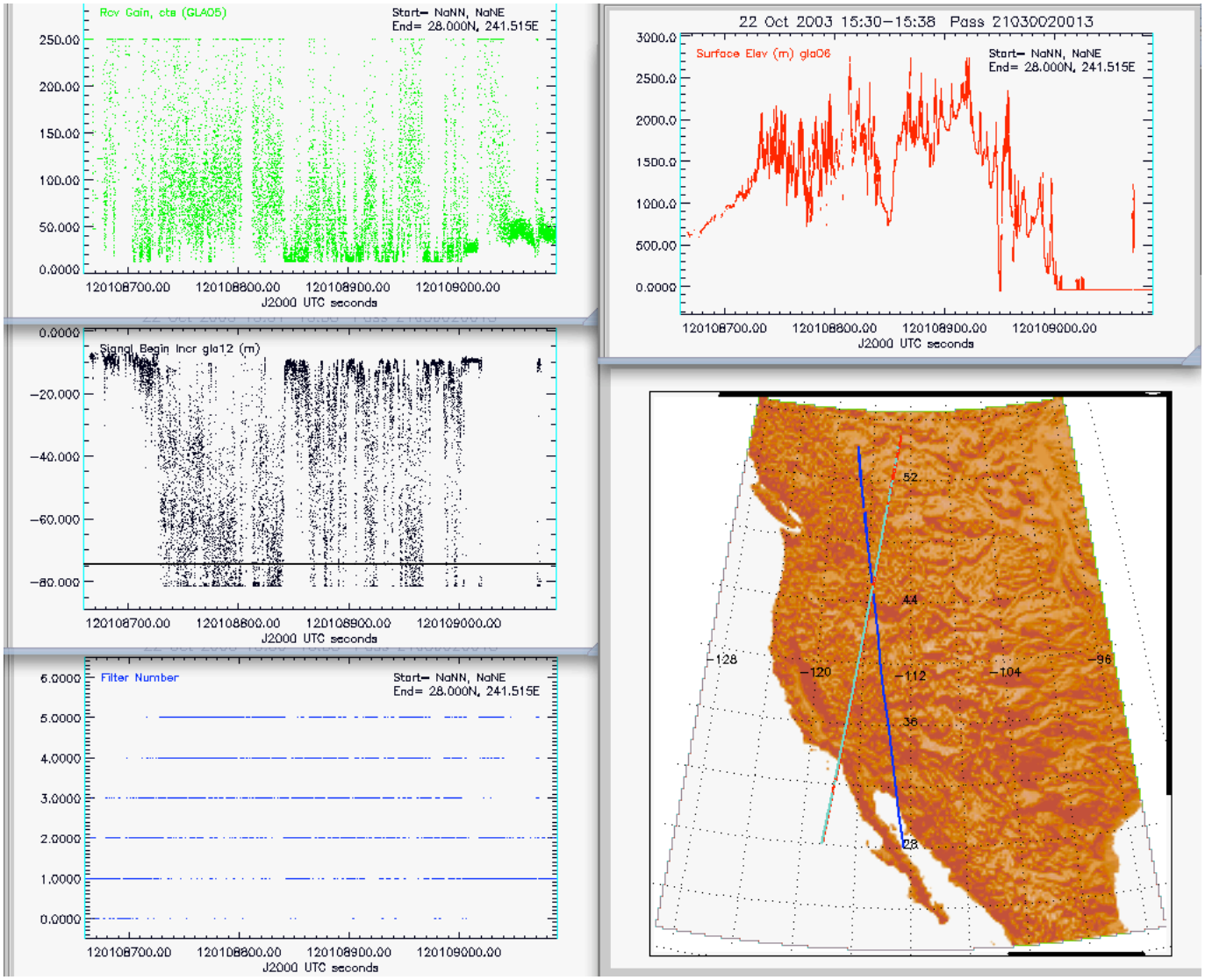


# *Signal Start Truncation: South East Asia*

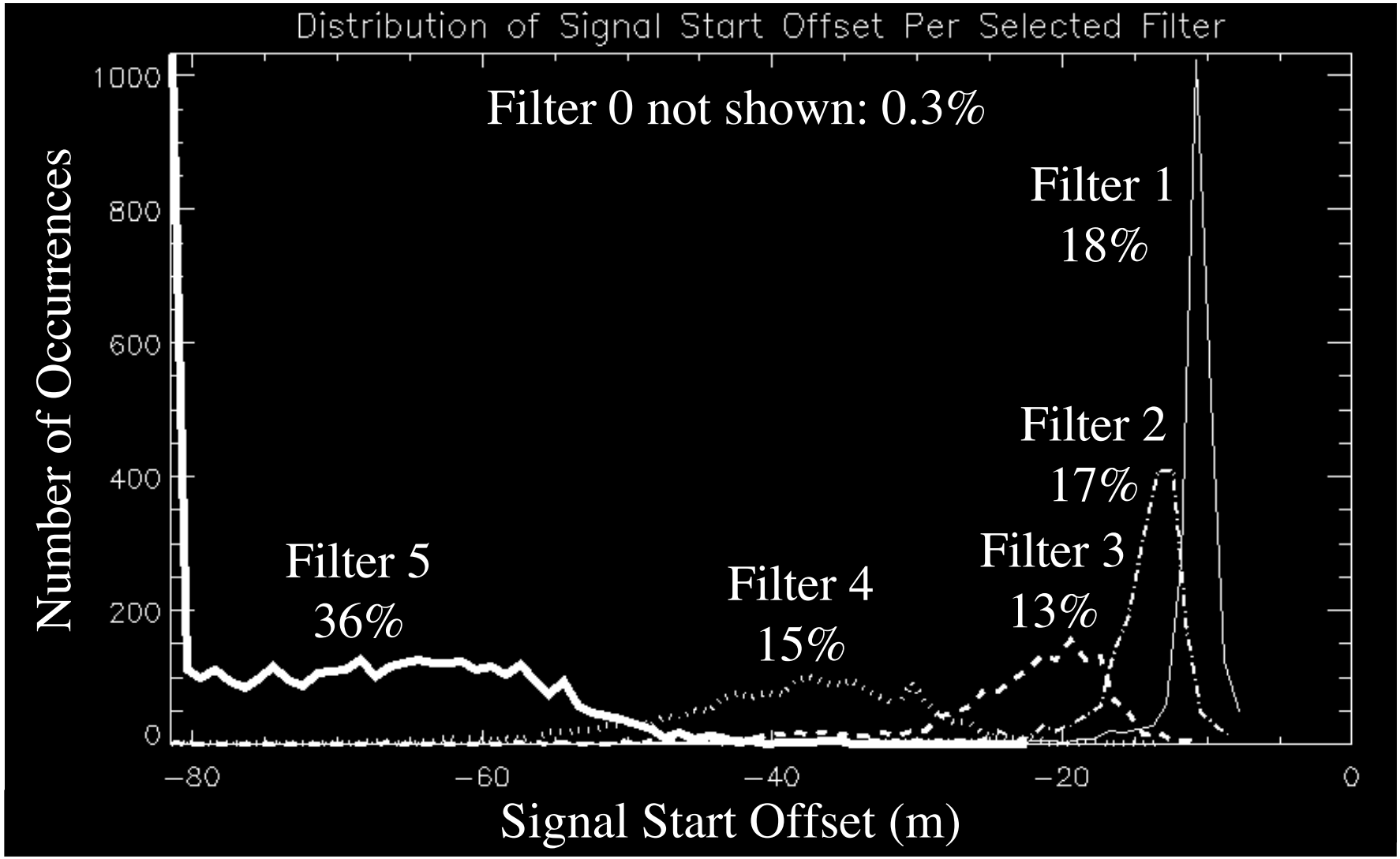


# *Selected Filter Measure of Pulse Width*

% of these land returns with signal start offset:
> 75 m 13%
> 80 m 9%



# *Signal Start Offsets for Selected Filters*



# ***Recommendations (2)***

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# *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

# ***Change Detection Approaches***

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

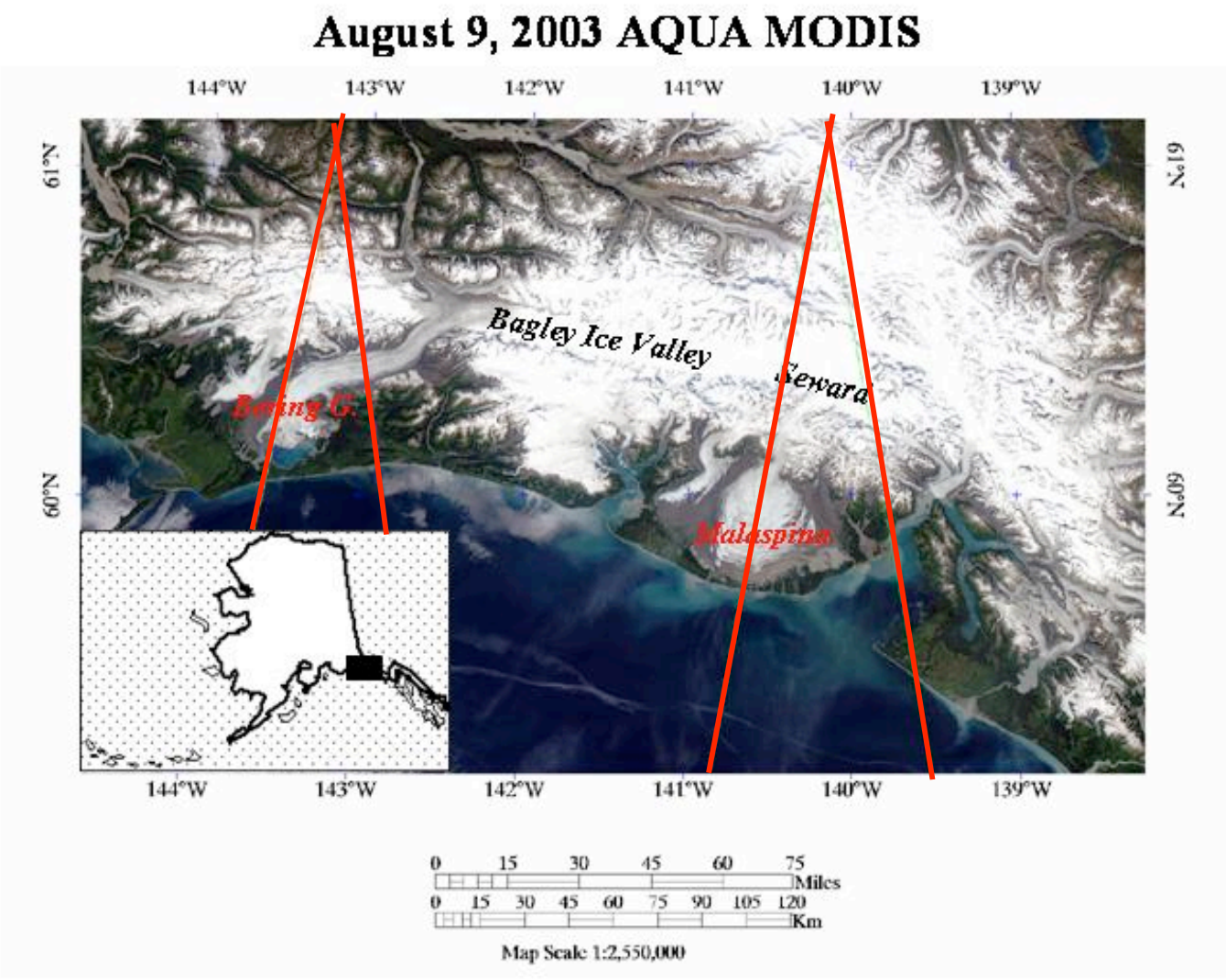
## Accomplishments that can be met with ICESat-1

- 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

# *Southern Alaska Glacier 8-day Tracks*



# ***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

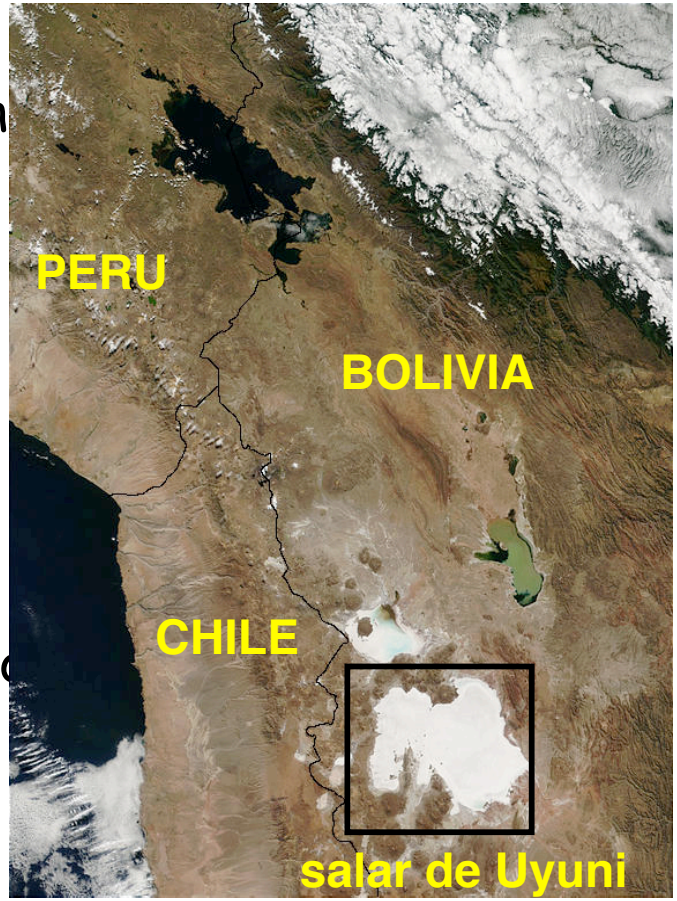
Range correction for saturated returns

- Test of Xiaoli correction for Uyuni Playa

# Uyuni Site characteristics

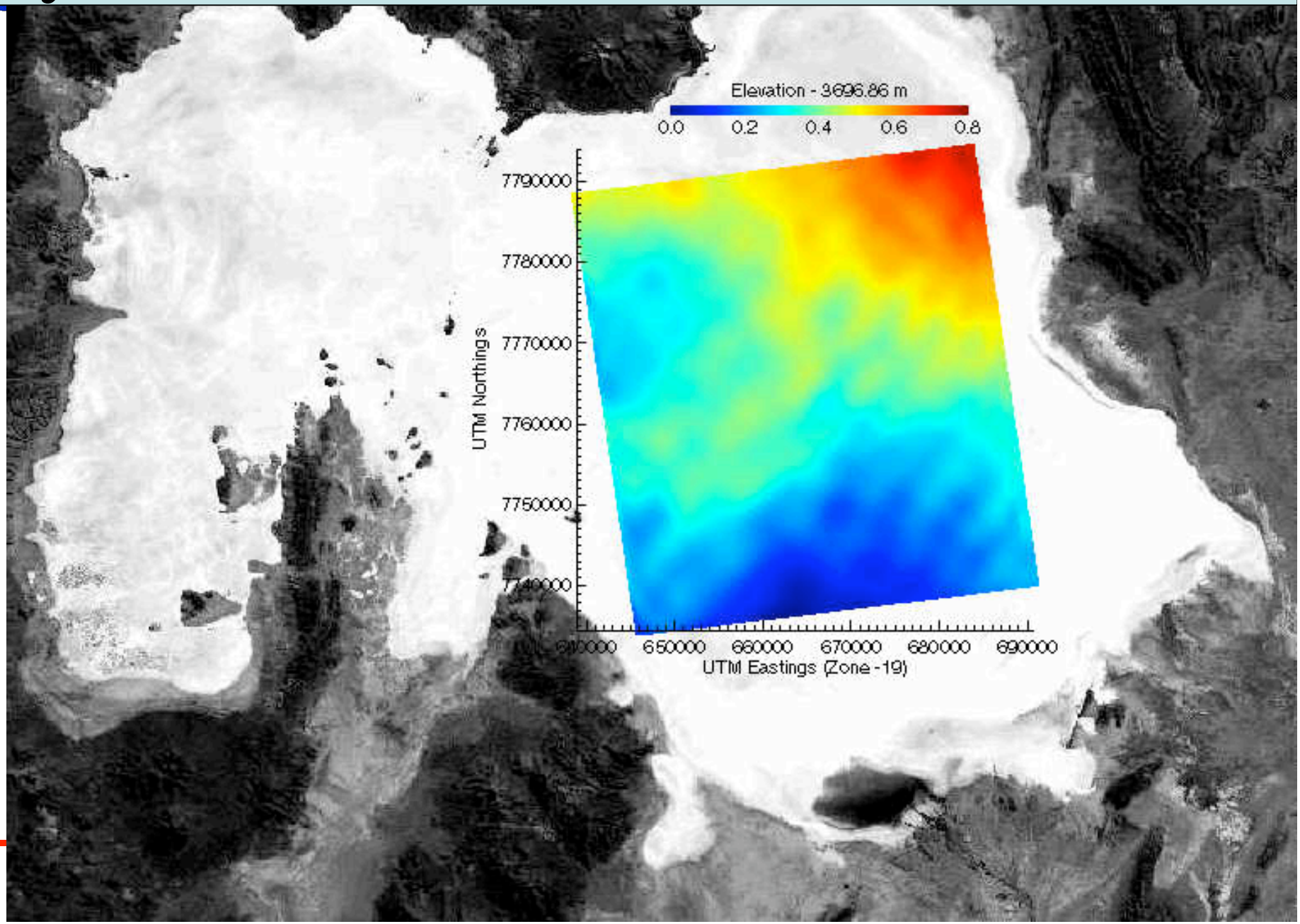
.Salar de Uyuni, a 9,600 km$^2$ salt lake in the Bolivian Altiplano, is the largest dry salt lake in the world

- 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

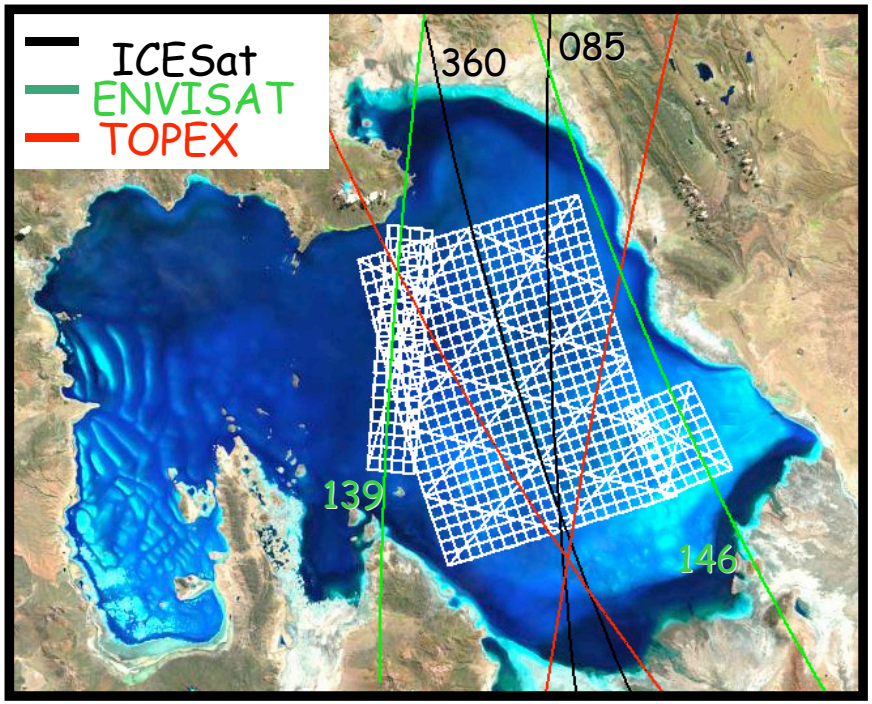


Landsat images showing flooded conditions vs. dry conditions; photo to right shows surface water

# Uyuni Gridded GLAS Cal/Val surface



# Survey area and grid design



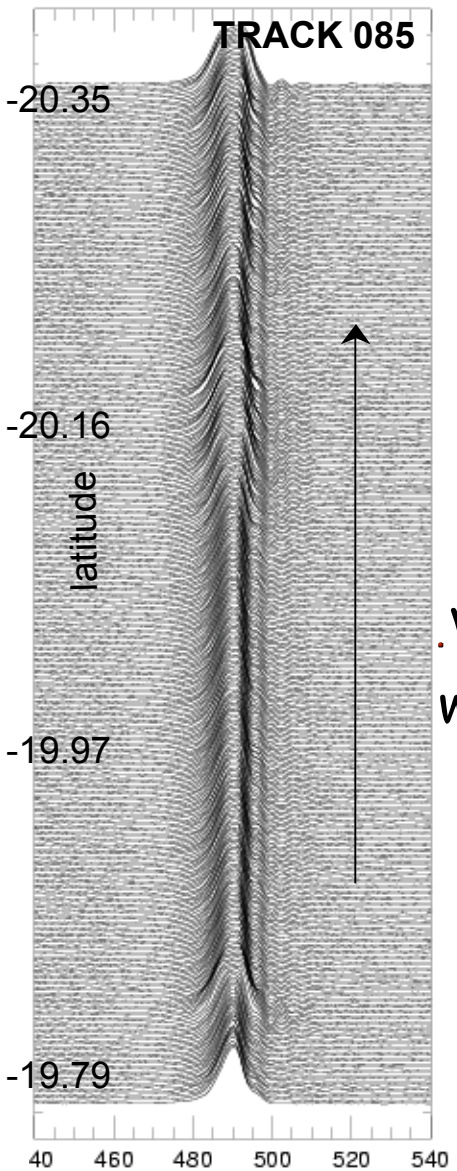

.Eastern part of salar is larger and flatter than the western part, and was obvious choice for our survey

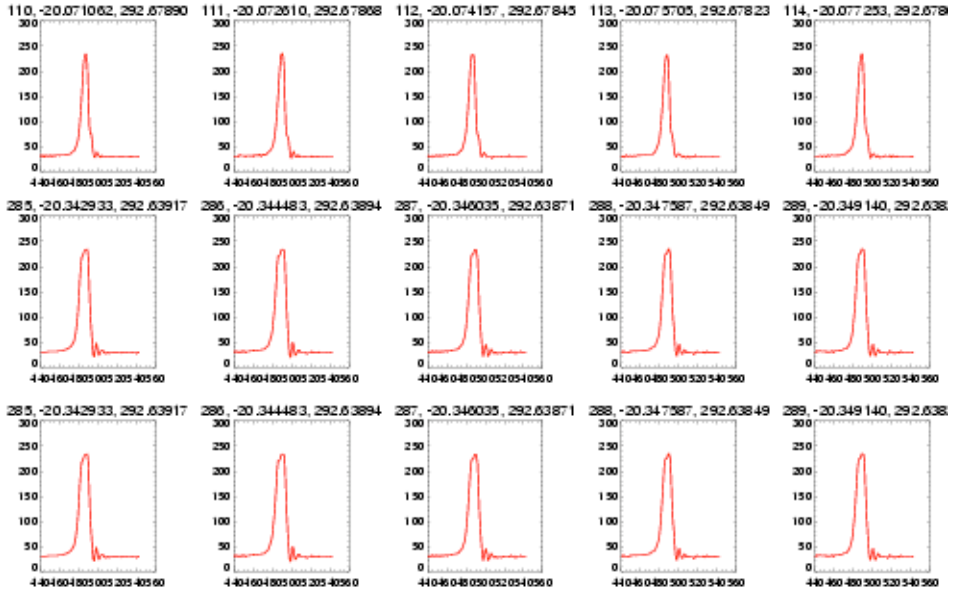
- Survey bounds further determined by surface suitability (by reconnaissance), our desire to keep the survey area rectangular, and time

.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

# GLAS waveforms and retracking



**Non-saturated waveforms**

**Partially-saturated waveforms**

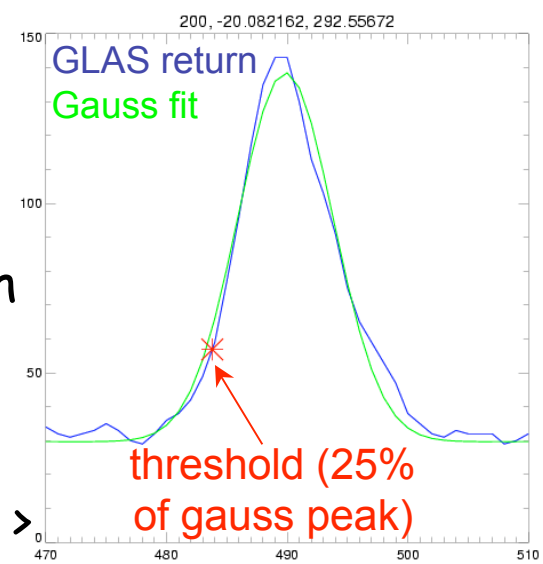
**Fully-saturated waveforms**

.We retracked GLAS return waveforms in three ways:

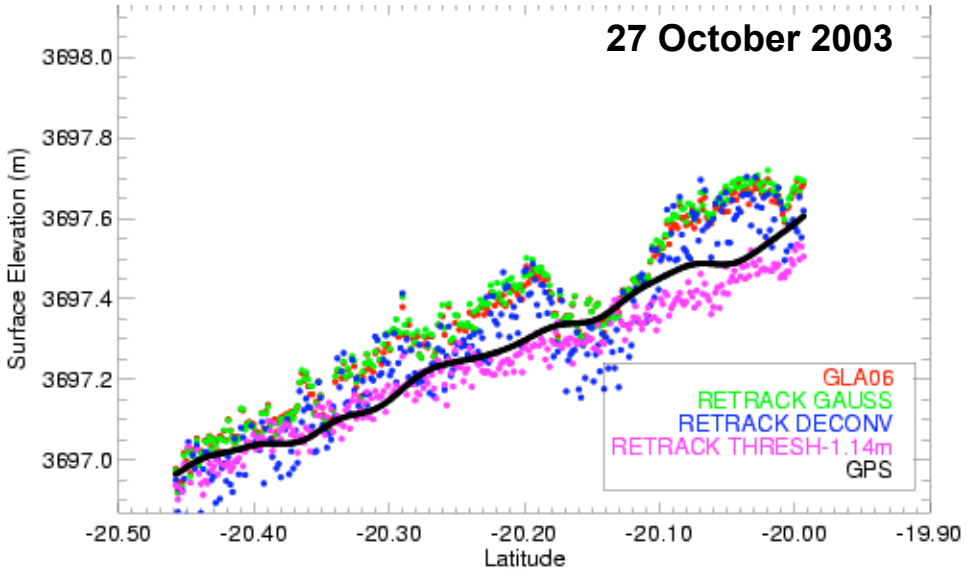
i) centroid of a single Gauss fit

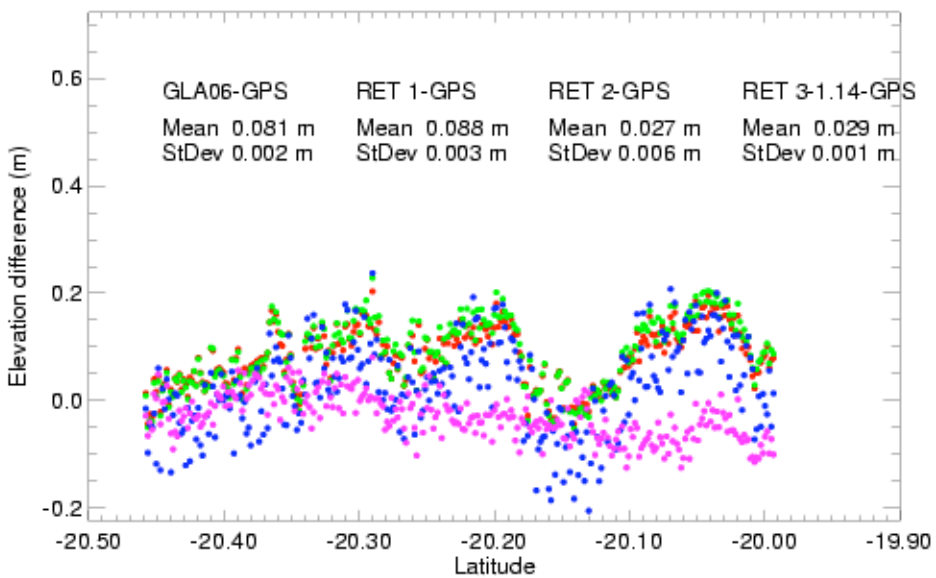
ii) deconvolution algorithm which locates the ground return

iii) threshold retracker which finds 1st bin in the return pulse > 25% of Gauss peak



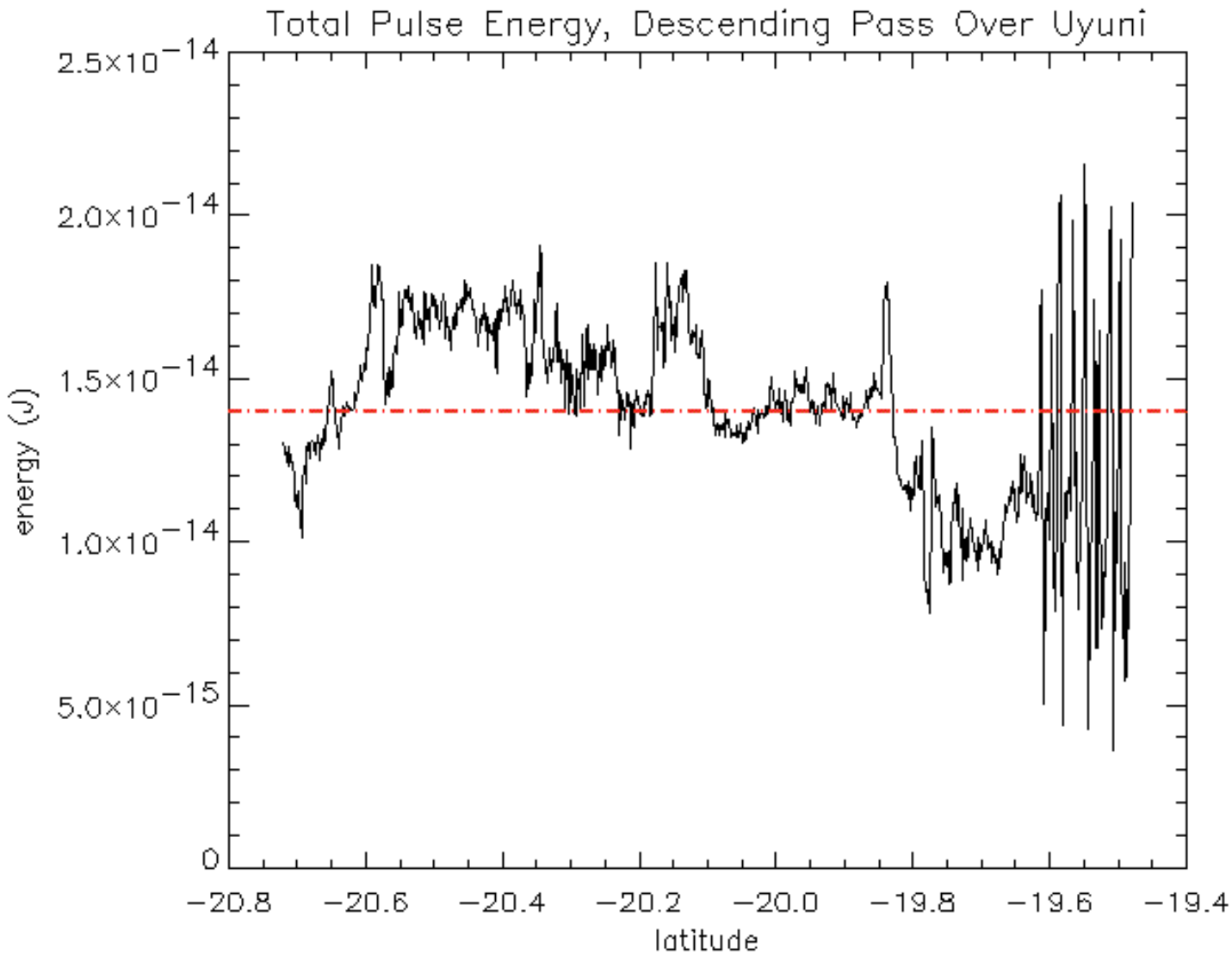
# GLAS track 085 comparison (rel 12)



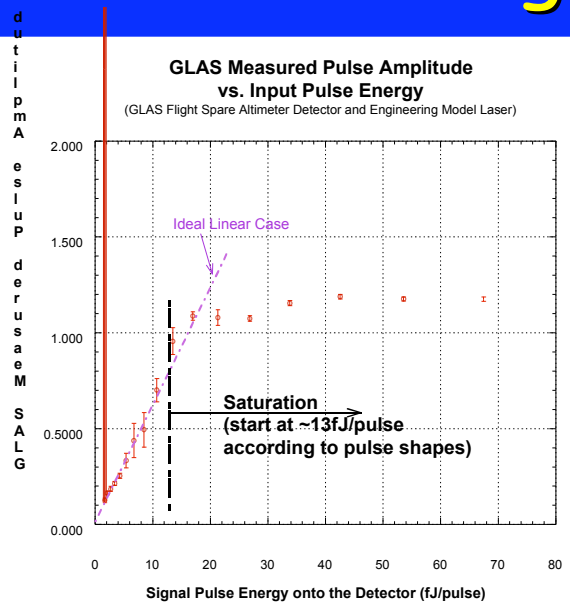



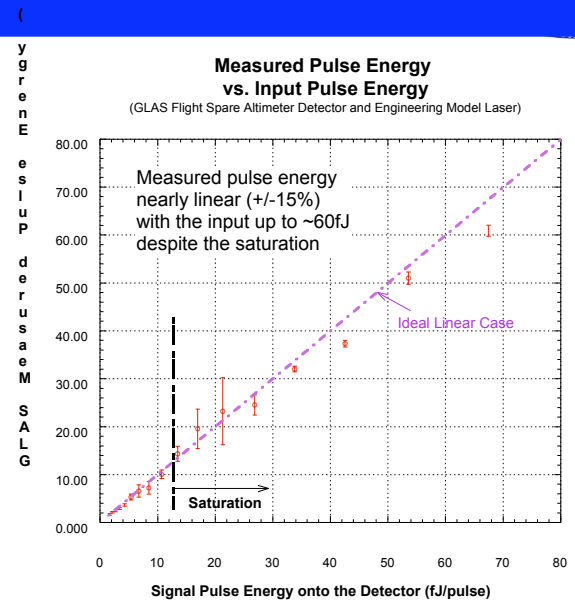

- Figure shows results from Release 12 GLA06 (also uses a Gauss fit), our retrackers, and GPS interpolated points
- Both Gauss retrackers & deconvolution enhance "dip" at -20.15, coinciding with the most saturated waveforms
- Threshold follows surface but has 1.14 m bias (it picks an earlier point on the waveform)
- GLAS instrument team is currently building a saturation correction which will be applied in later data releases

# UYUNI PULSE ENERGIES, SATURATION

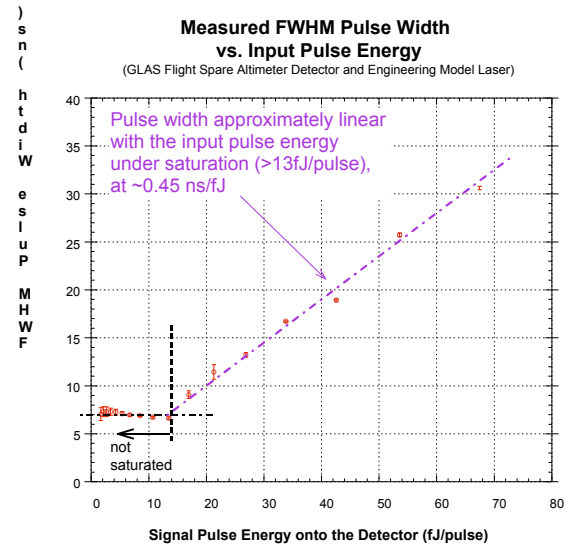


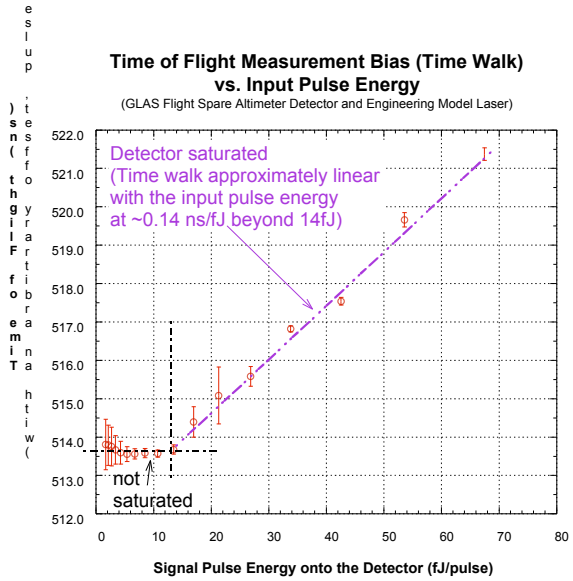
# GLAS "range walk" saturation correction



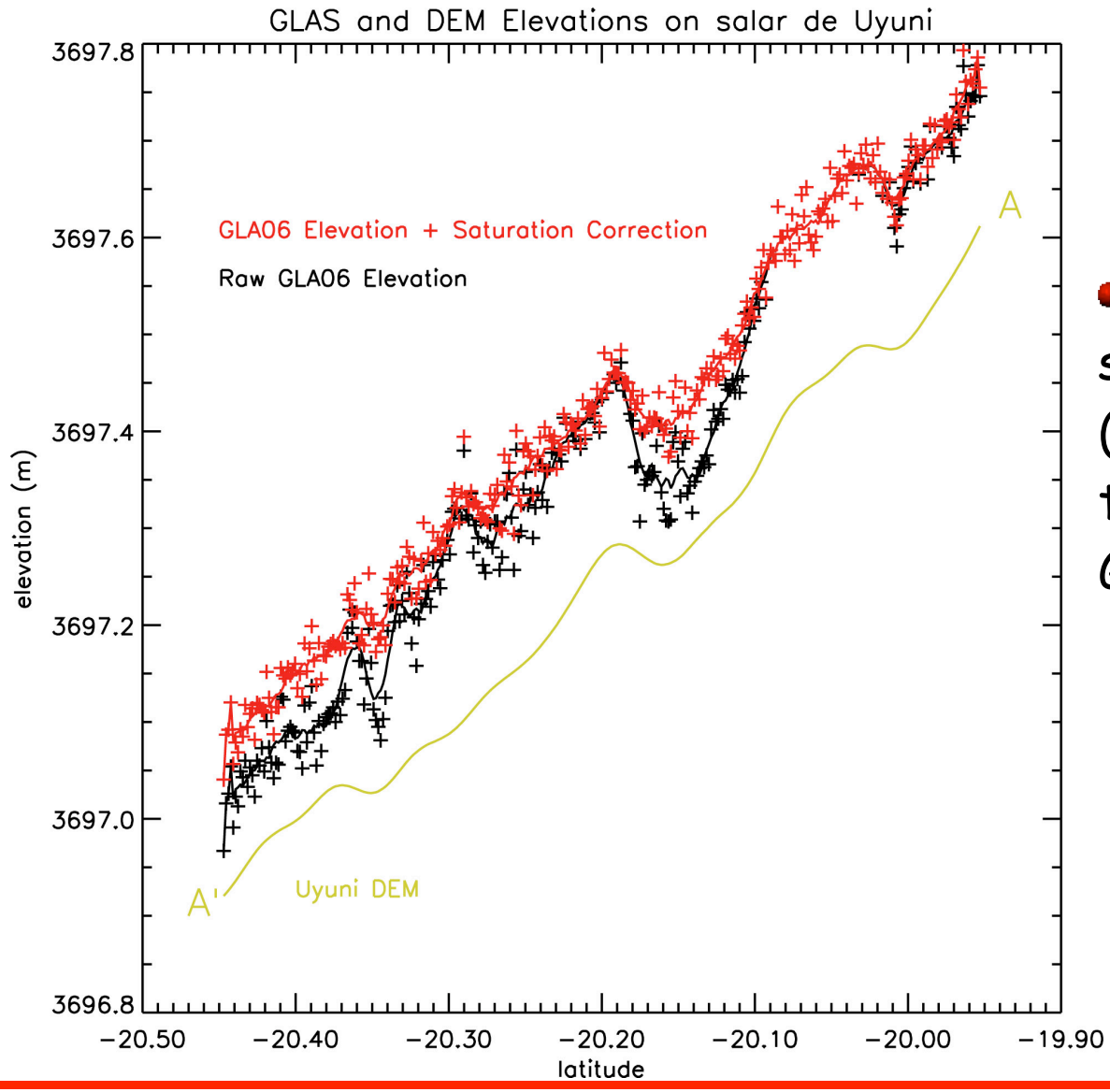




- Empirical saturation correction ("time walk" or "range walk") measured by Xiaoli Sun. (Fall AGU 2003)
- 0.14ns/fJ for echo pulse energy in excess of 14fJ,



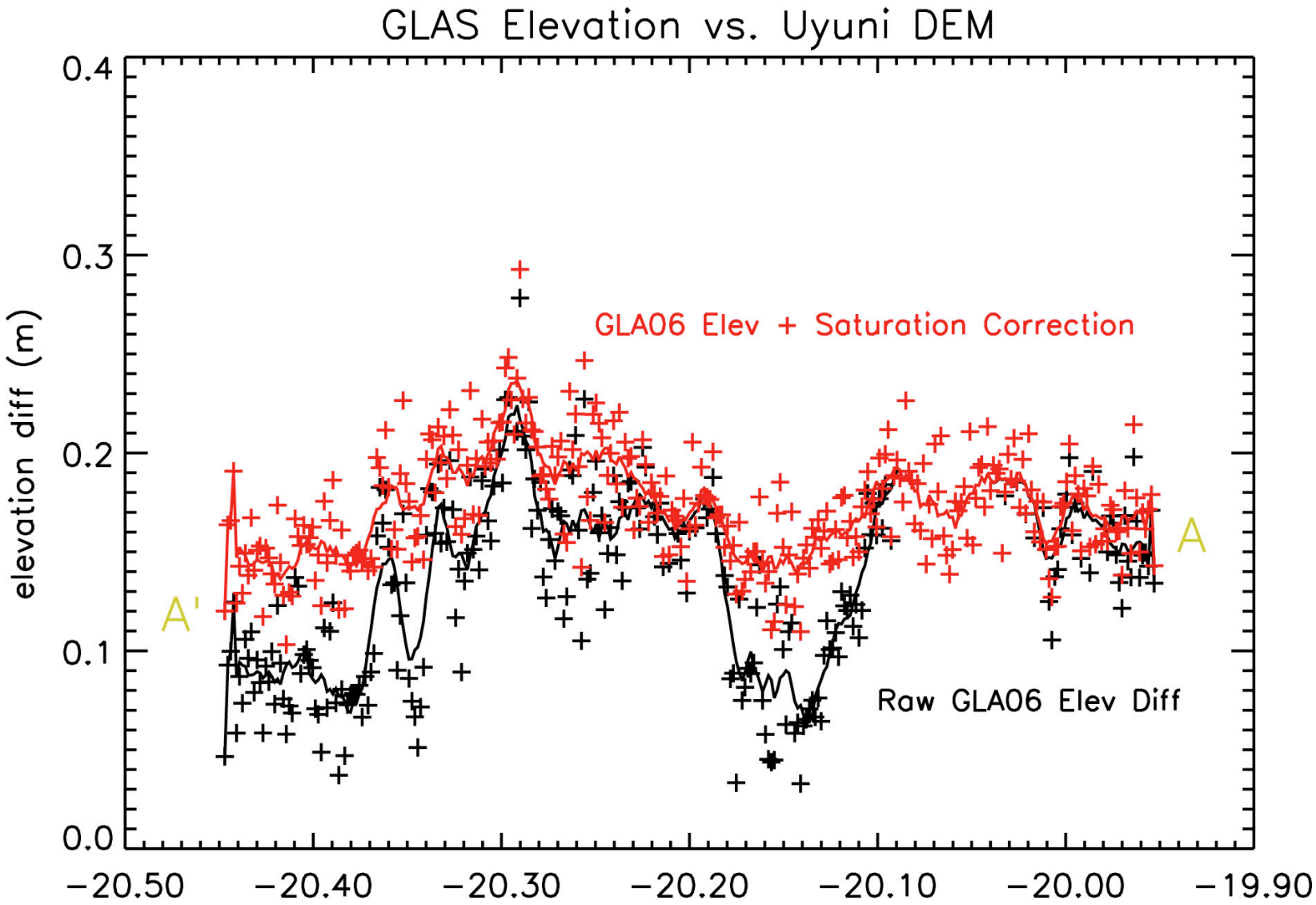



# UYUNI PROFILE, Corrected for Saturation

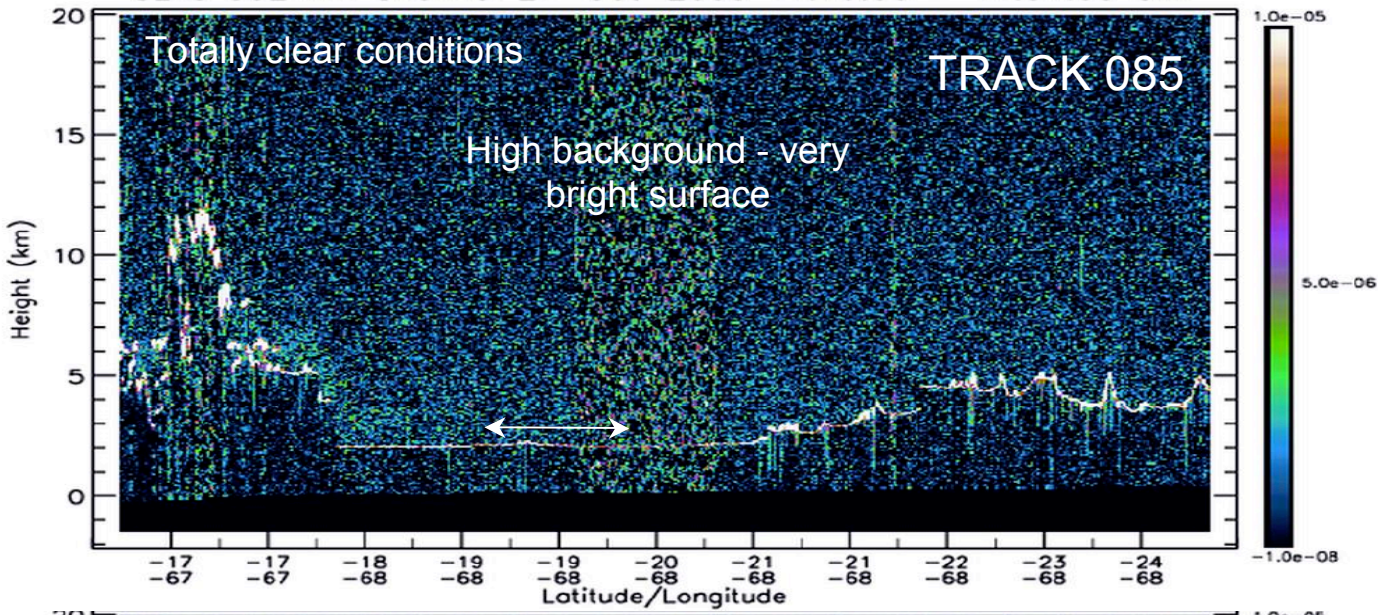


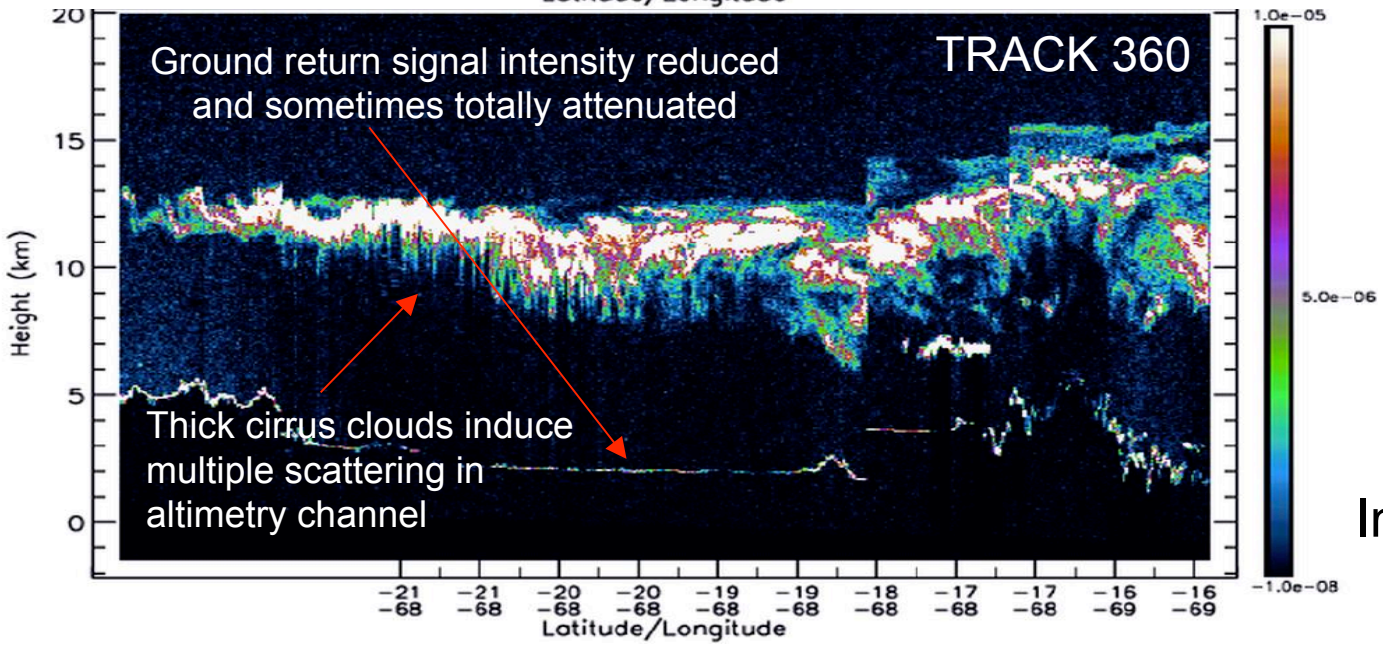

- Xiaoli's empirical saturation correction (range walk) improves the comparison with GPS DEM.

# GLAS Track 085, saturation correction



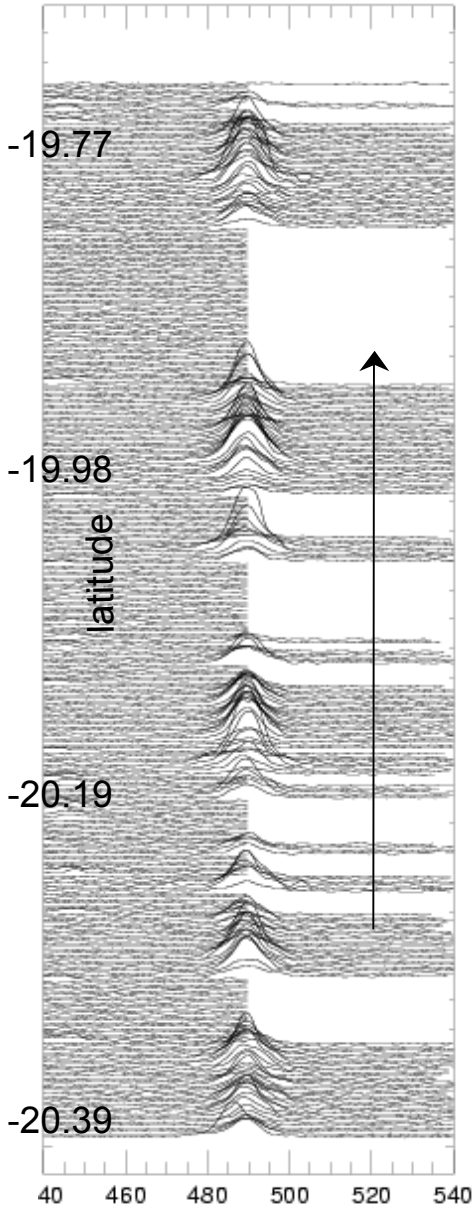
# GLAS 532nm channel profiles

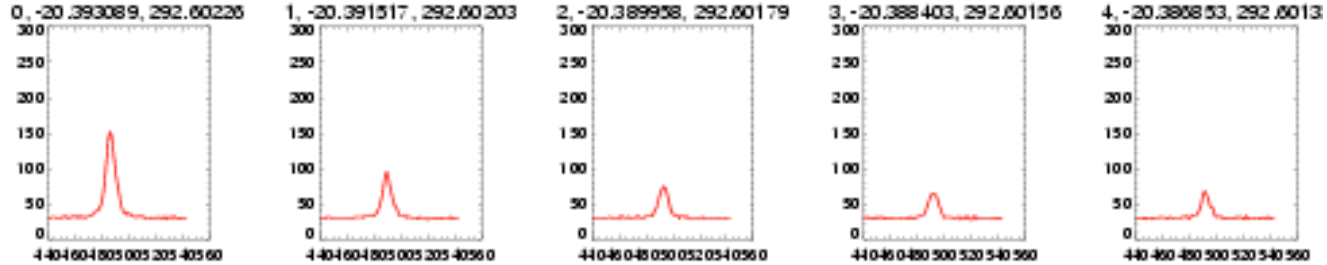


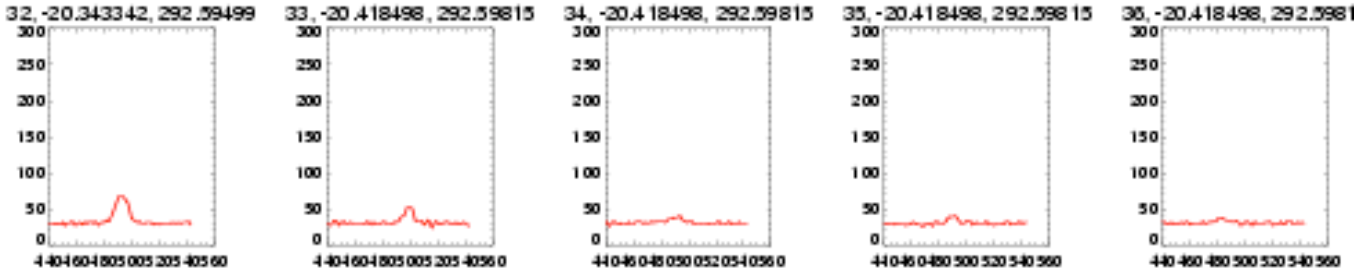

Images courtesy of Steve Palm

# GLAS waveforms track 360

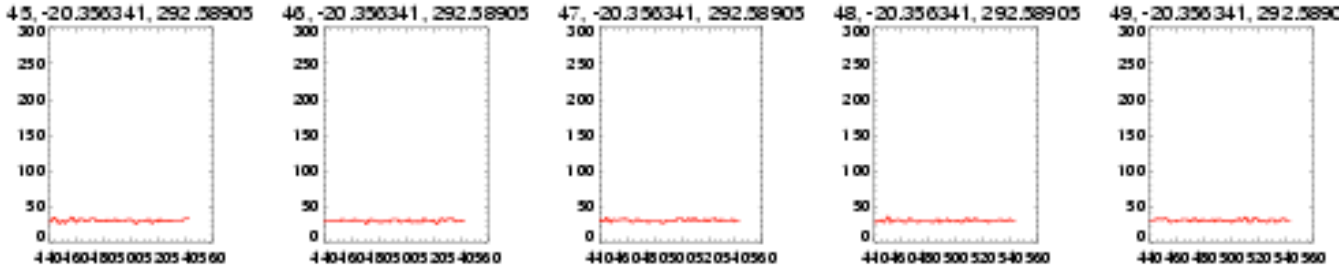



**These example waveforms manage to penetrate the cloud cover**

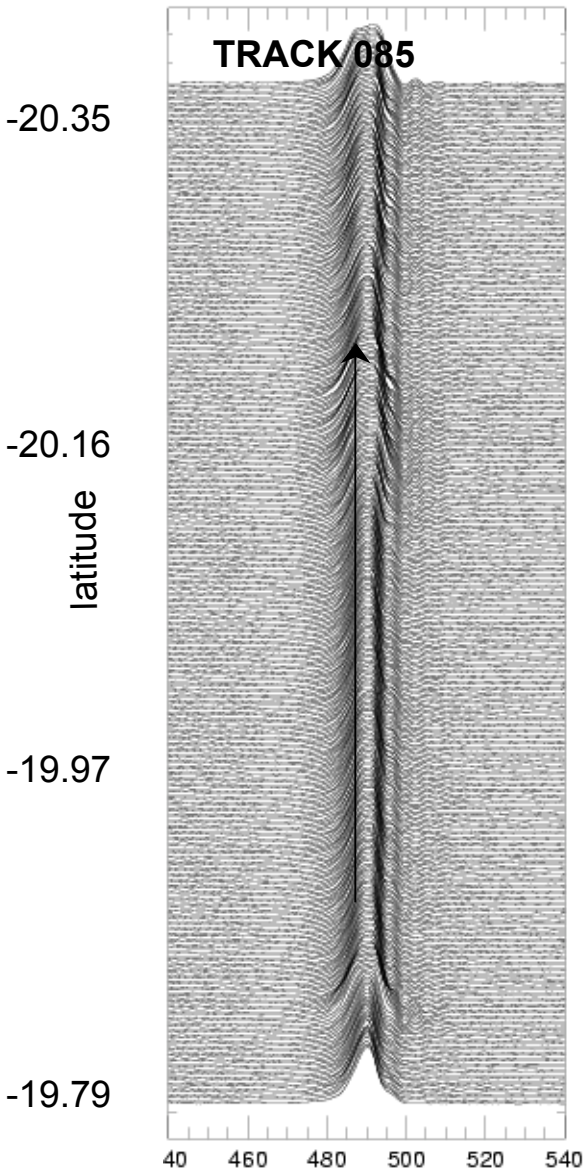



**These example waveforms partially penetrate the cloud cover**



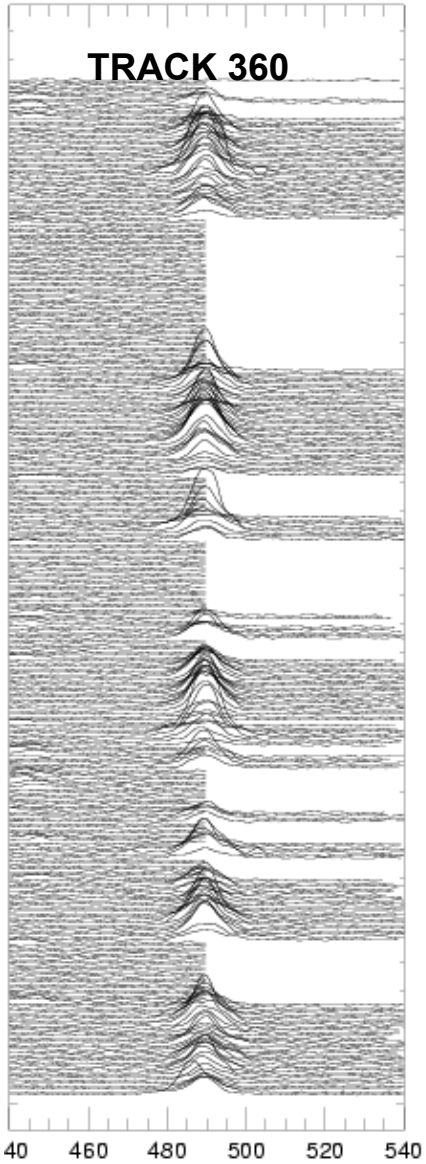

**These example waveforms do not penetrate the cloud cover**

# GLAS waveforms over Uyuni

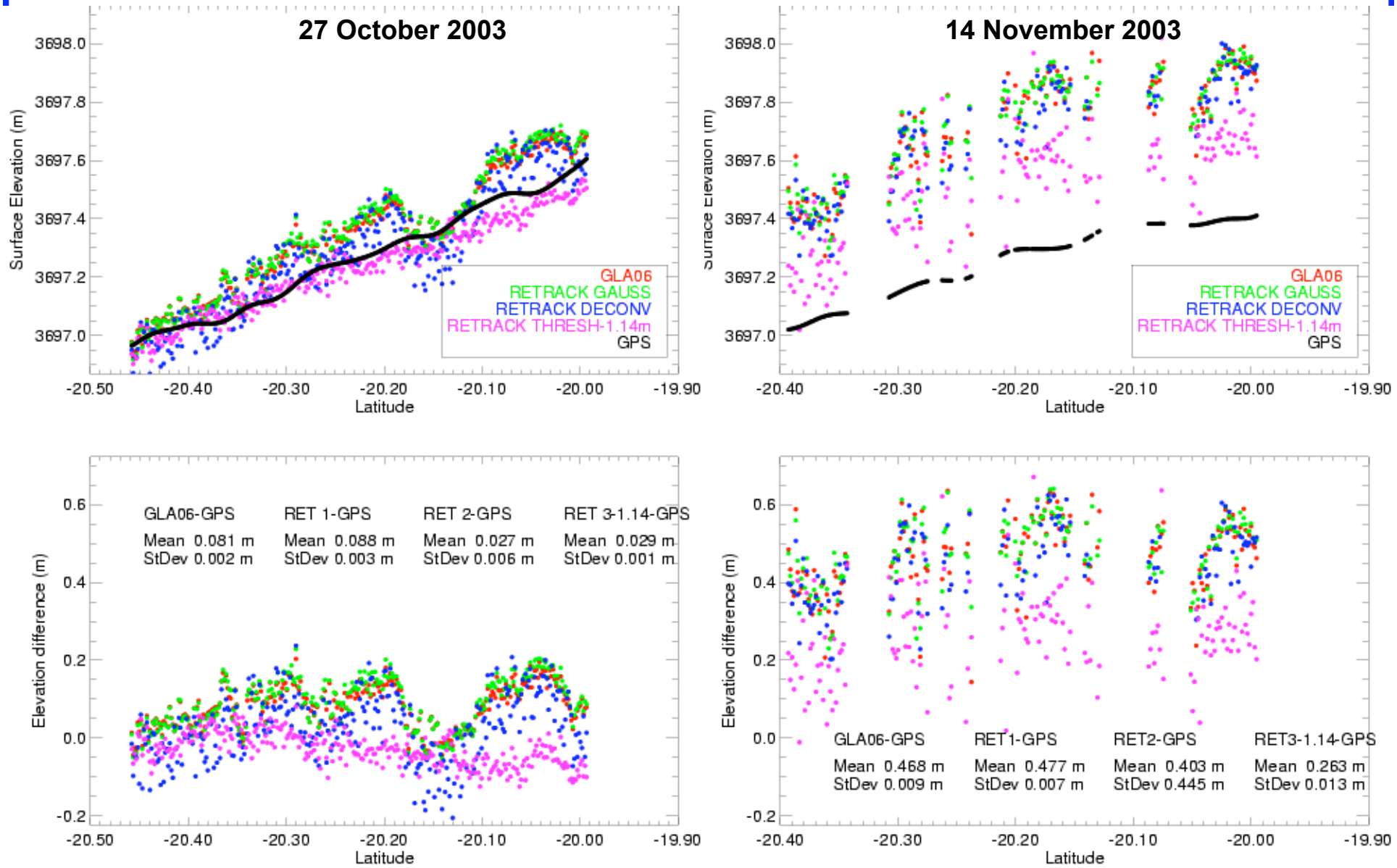



Clear atmosphere
Descending track 085

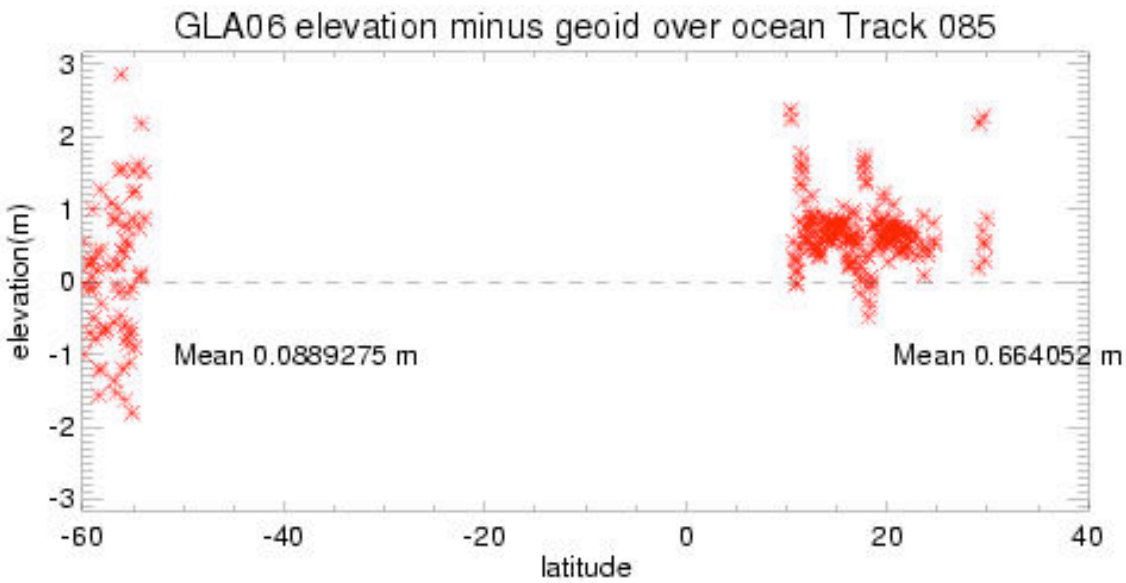
Cloudy
Ascending track 360

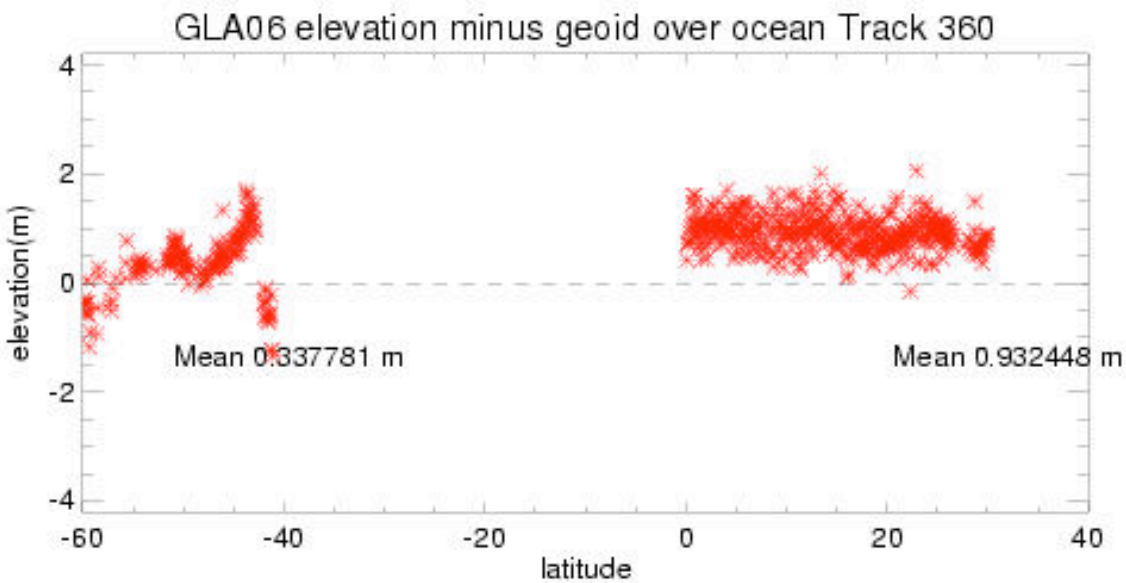


# GLAS track 360 comparison



# GLAS Ocean Elevations, (rel. 12)

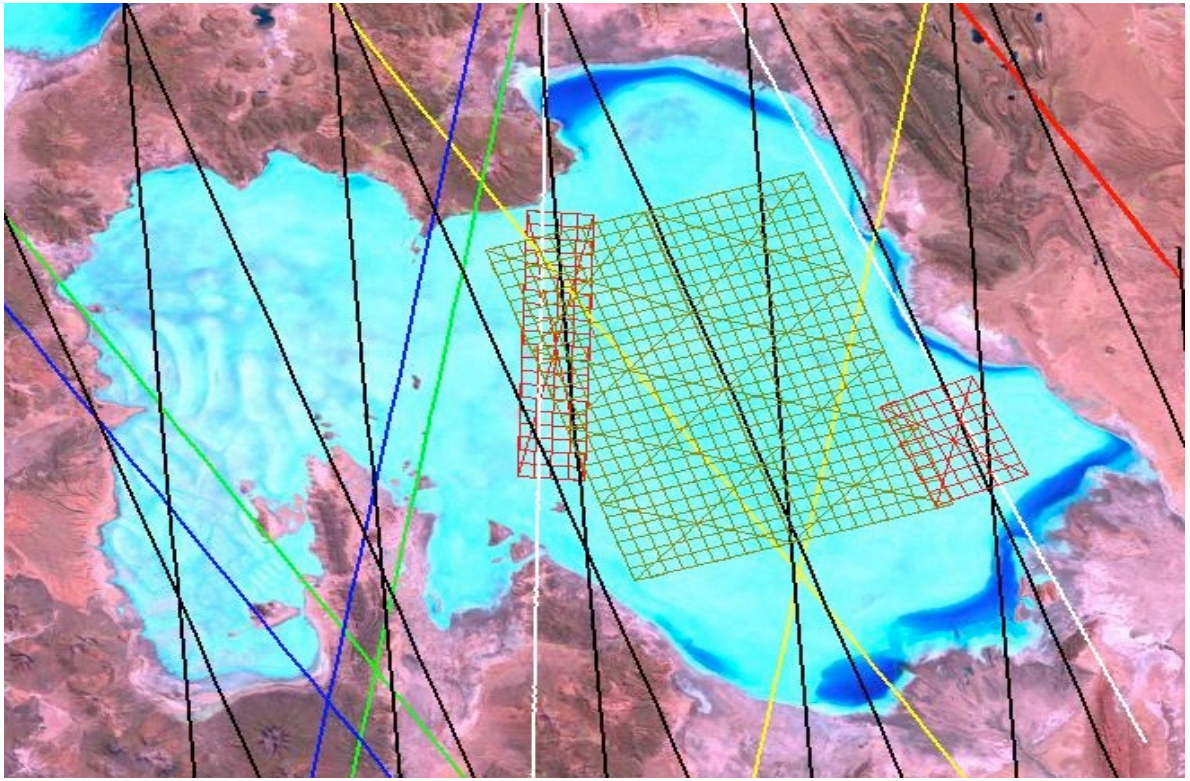



- Ocean elevations along tracks 085 and 360, both south and north of Uyuni, appear to show a relative elevation bias similar to what is seen at Uyuni.

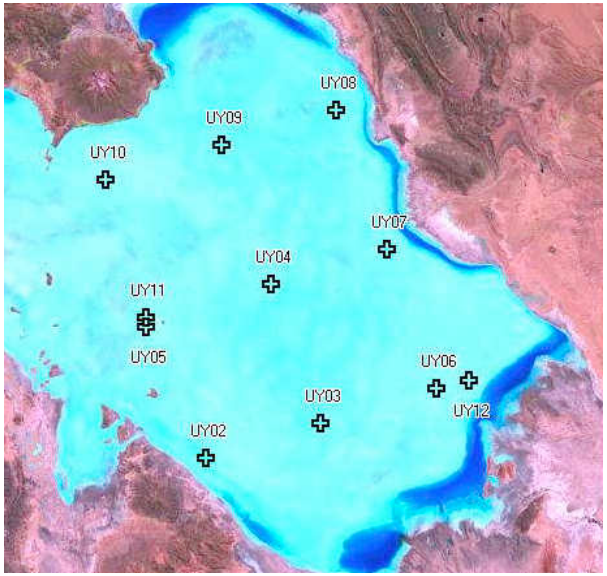
- Track 360 is biased by about +30cm, relative to track 085.

# 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

# GPS ground control and multipath




.Eleven sites were established as ground control points (GCP)

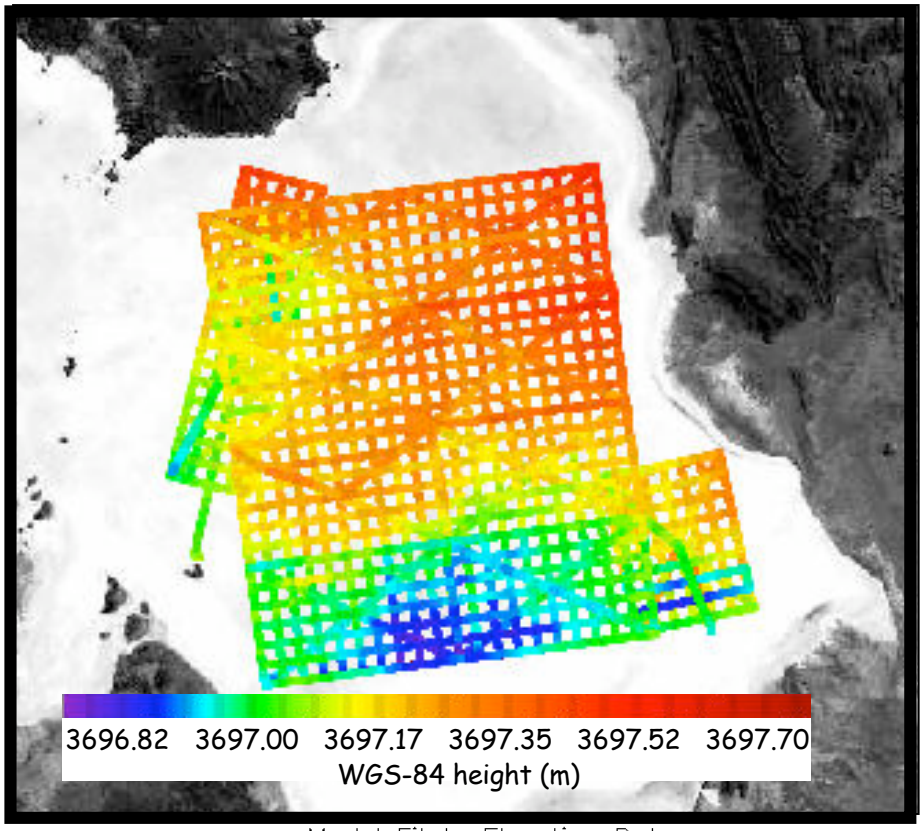
- Central GCP (UY04) occupied at 30s for entire survey to tie into ITRF2000
- Surrounding GCPs set up as base stations for kinematic surveys: occupied for at least 24 hours – each grid had 4

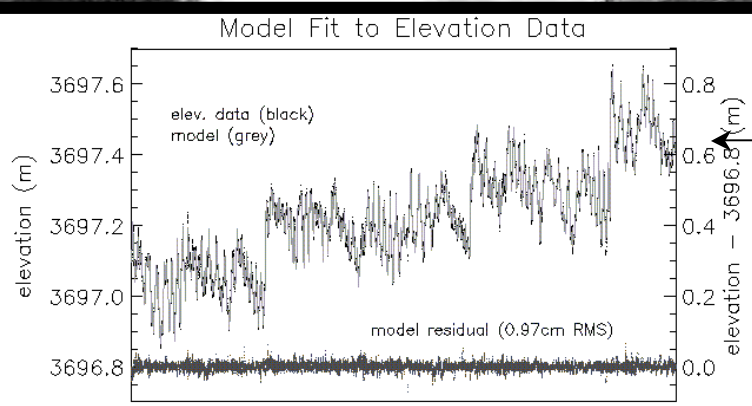
GCPs: UY04 plus 3 others running at same rate as rover (3s)

· 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

# Elevation over survey region



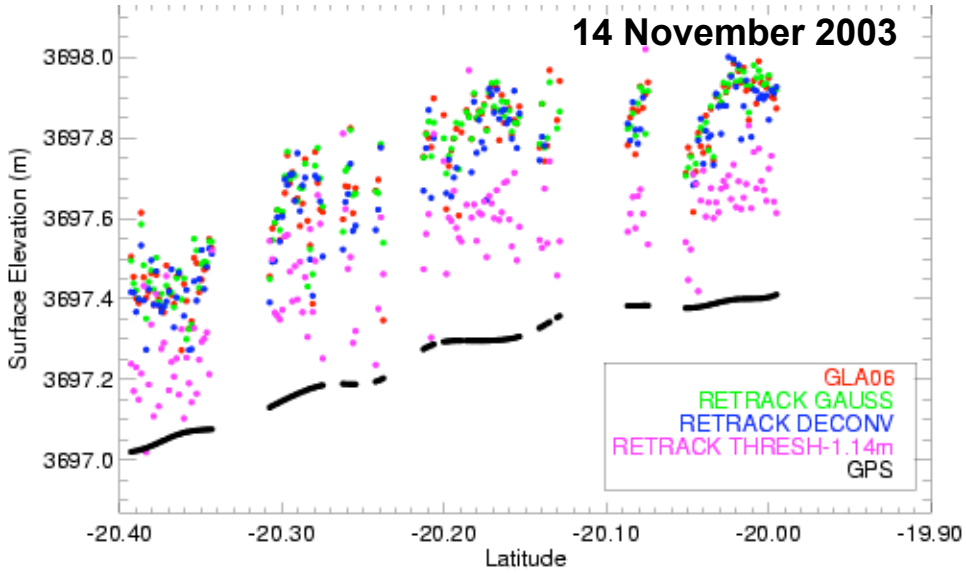

.Survey took six days (4 to 9 Sept 2002) with two cars

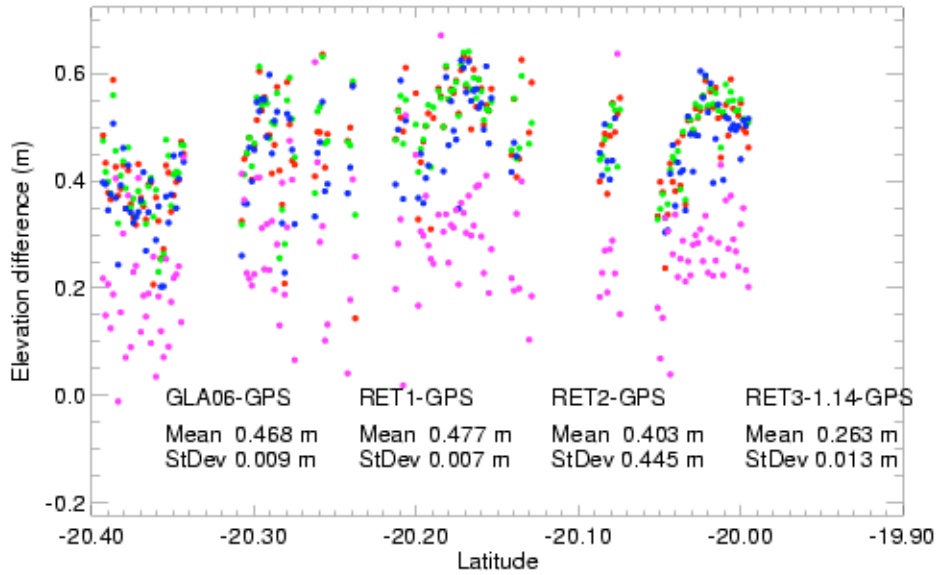
- Kinematic GPS data processed using TRACK (GAMIT); LC solutions
- Crossover analysis showed that internal consistency of grid heights was ~3 cm
- Heights consistent from car to car and from day to day
- Two surface DEMs made:

  i) Fourier fit (6 km wavelength; 500-m grid cells) for GLAS

  ii) Gauss-smoothed (2-km cells) for RA-2/ERS-2 comparison

# GLAS track 360 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