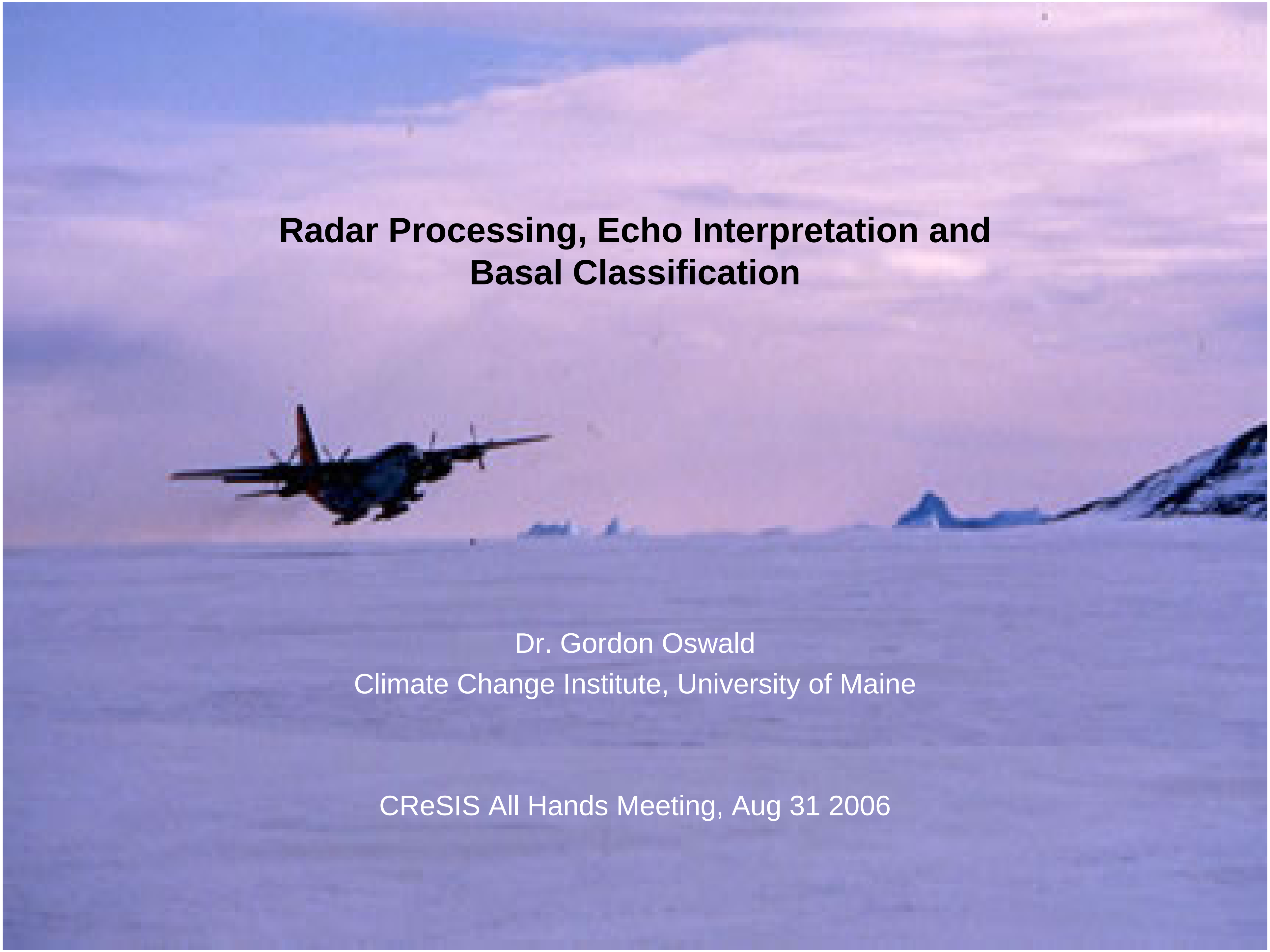
Radar Processing, Echo Interpretation and Basal Classification



Dr. Gordon Oswald
Climate Change Institute, University of Maine

CReSIS All Hands Meeting, Aug 31 2006

Radar Processing, Echo Interpretation and Basal Classification

Orientation

Technology & tools

Melt discrimination

Mapping basal melt in Greenland

CReSIS objective

To predict sea level rise as a result of ice sheet changes requires improved understanding of the behavior of ice sheets – and in particular of their stability.

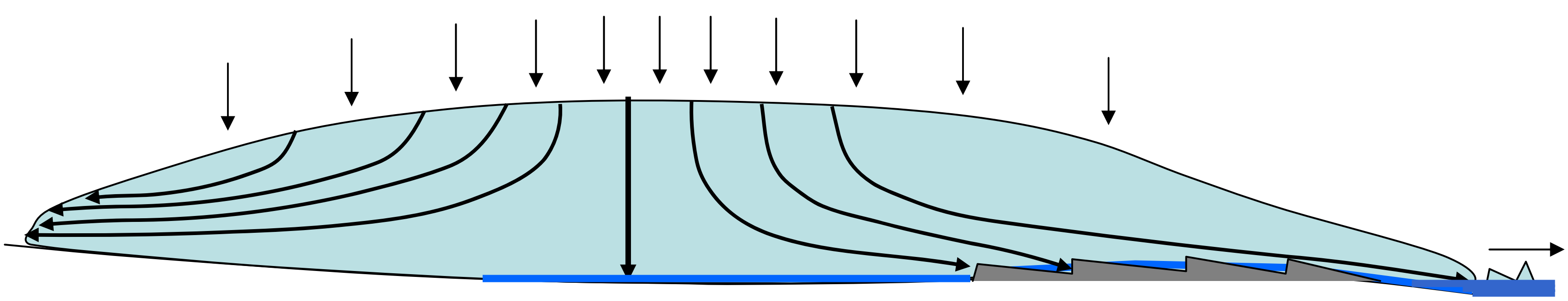
Stability is affected by:

- internal characteristics of ice
- temperature and stress distribution
- changes in driving stresses
- changes in the restraining forces

Friction at the base is the force that keeps ice sheets in place.

- As Bob Thomas put it:

'An Ice Sheet wants to be an Ice Shelf'



The role of remote sensing

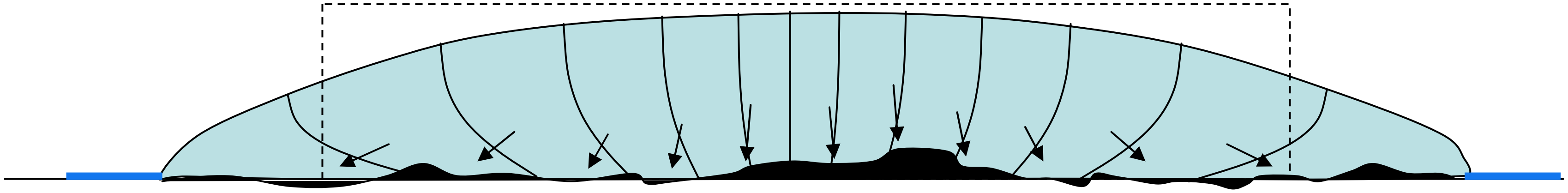
Remote sensing is used in many ways to observe ice sheets.

The most remote of all is to observe the subglacial interface.

<< This is where the friction happens >>

- The depth of the interface has been the measurement requirement from radar sensors.
- Investigators are now focusing on the nature and condition of the interface.

- The first priority is to determine whether and where water affects the friction between ice and bedrock
- Earlier studies have suffered from signal variability and the lack of absolute calibration of the radar

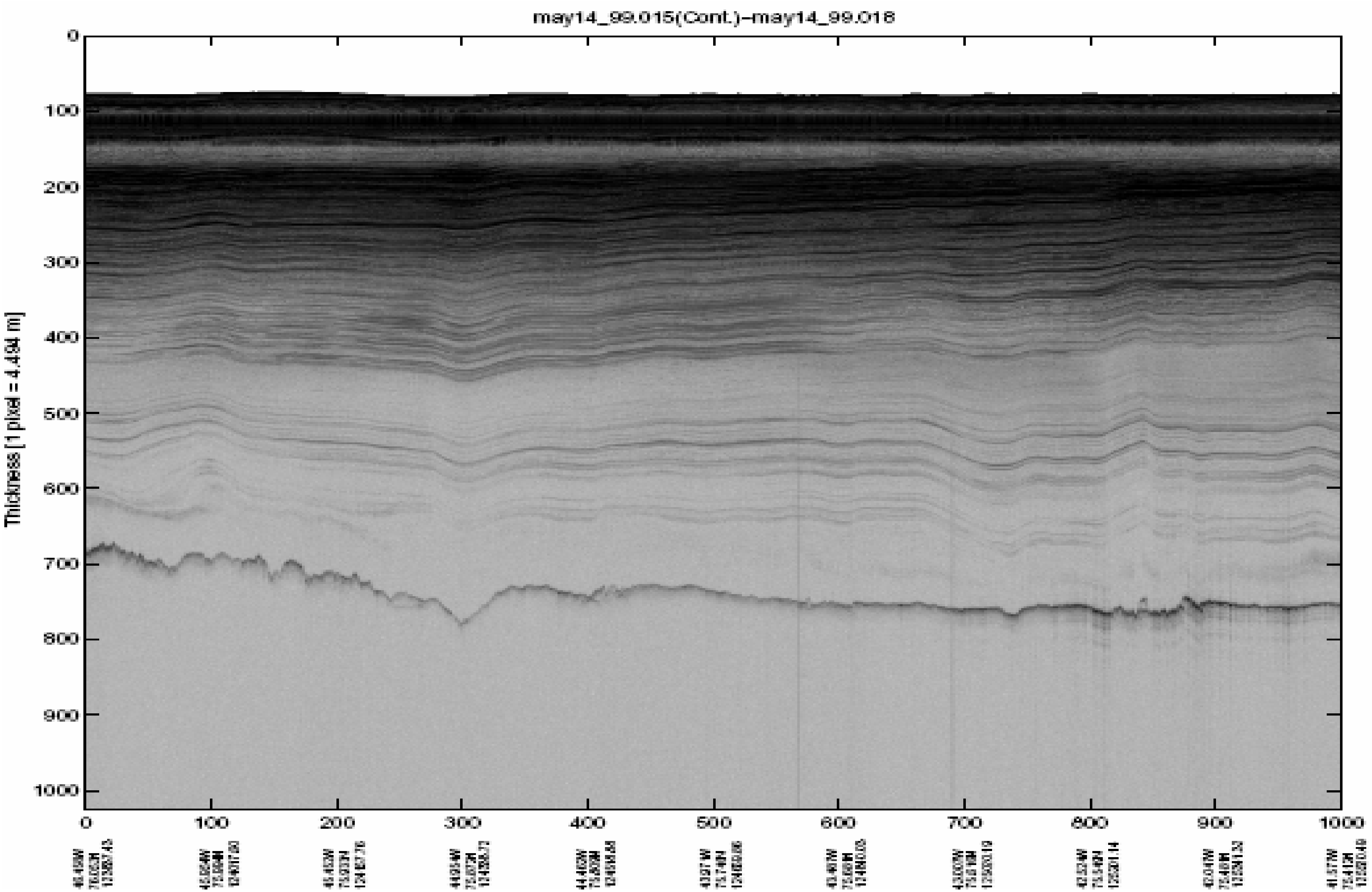


Echo characteristics - orientation

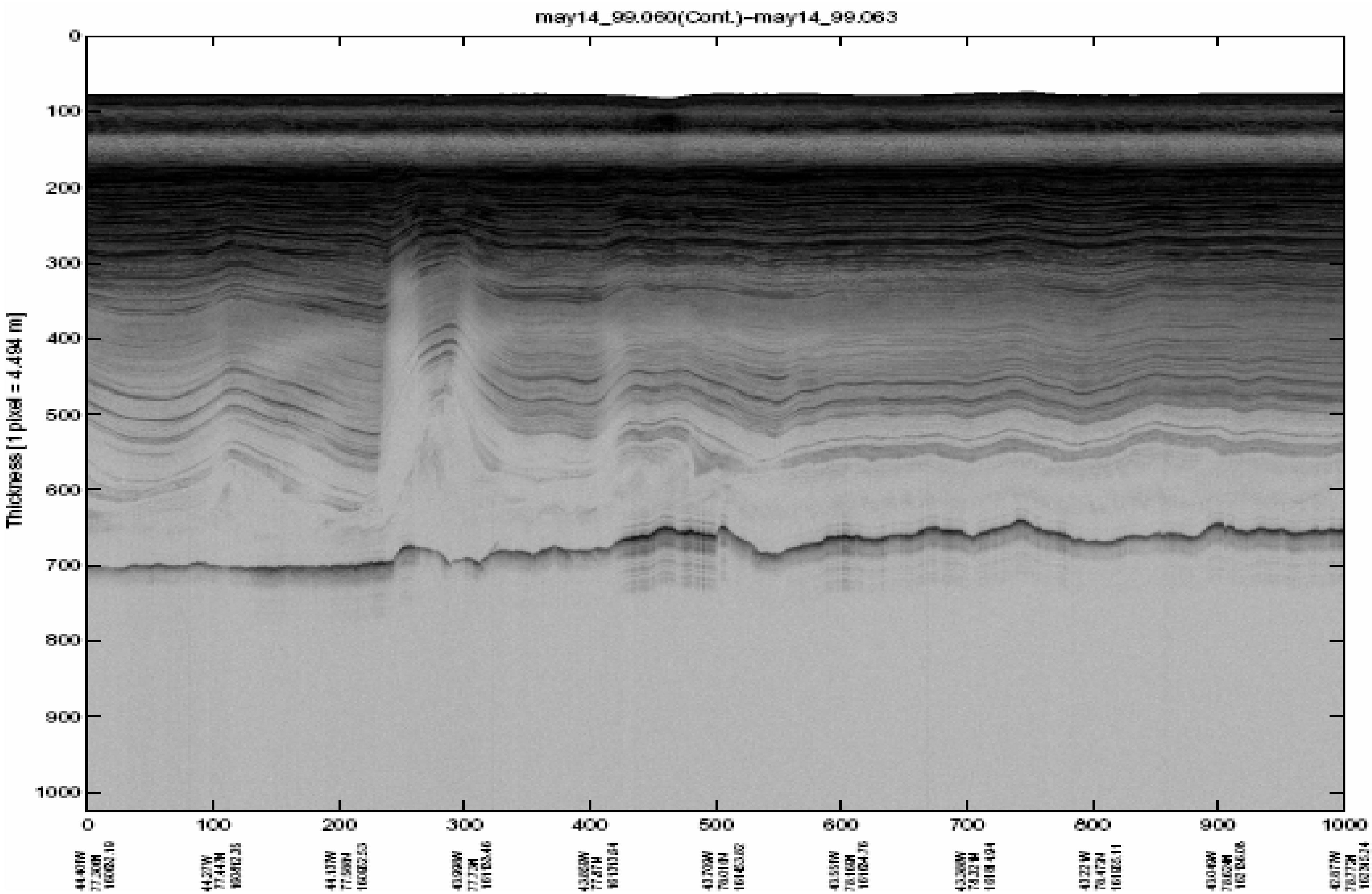
Greenland ice is itself variable in its appearance under radar investigation

The following slides illustrate a range of features that may be significant for ice sheet stability

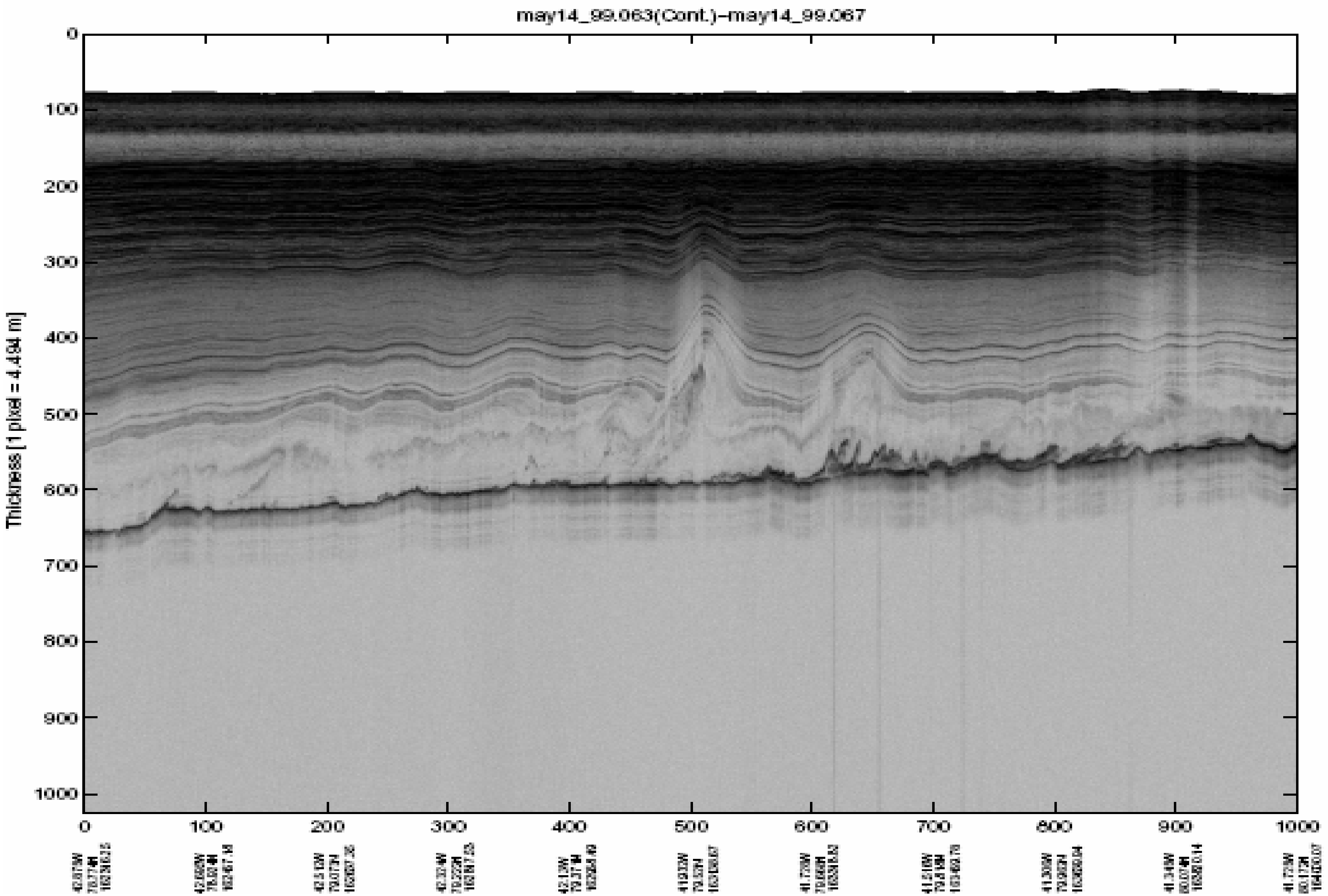
Radar data – examples of basal and internal signal returns



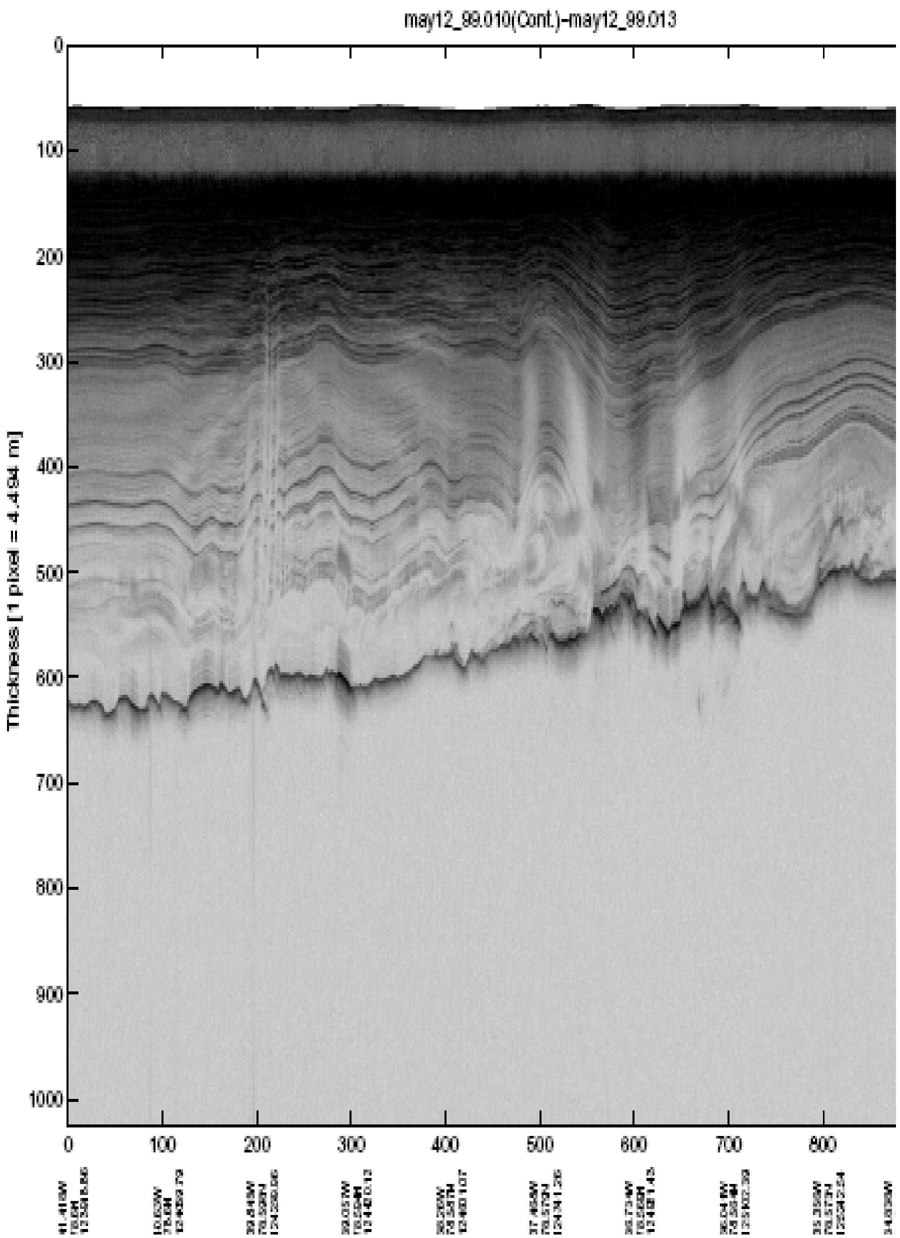
Radar data – folding and ice loss

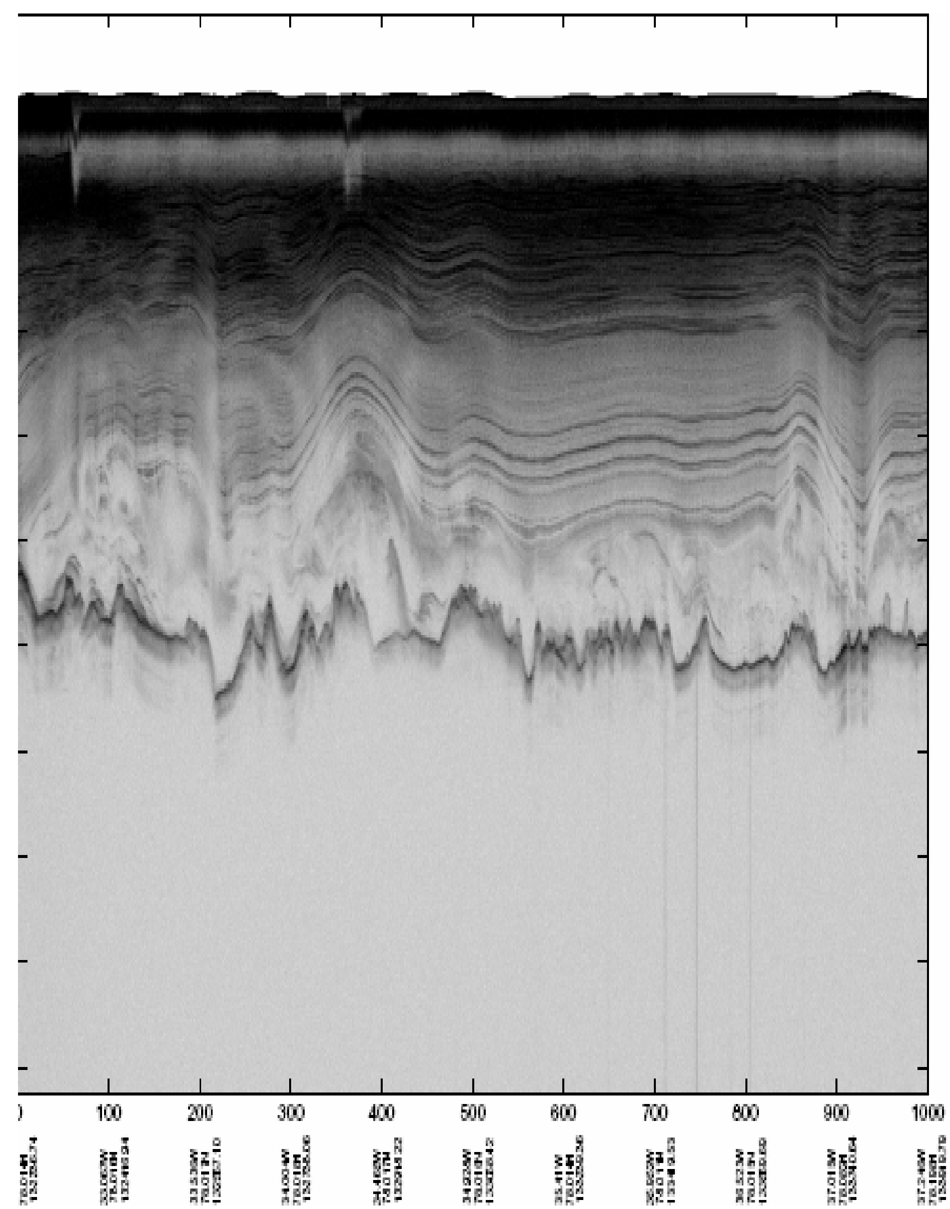


Radar data – basal strain

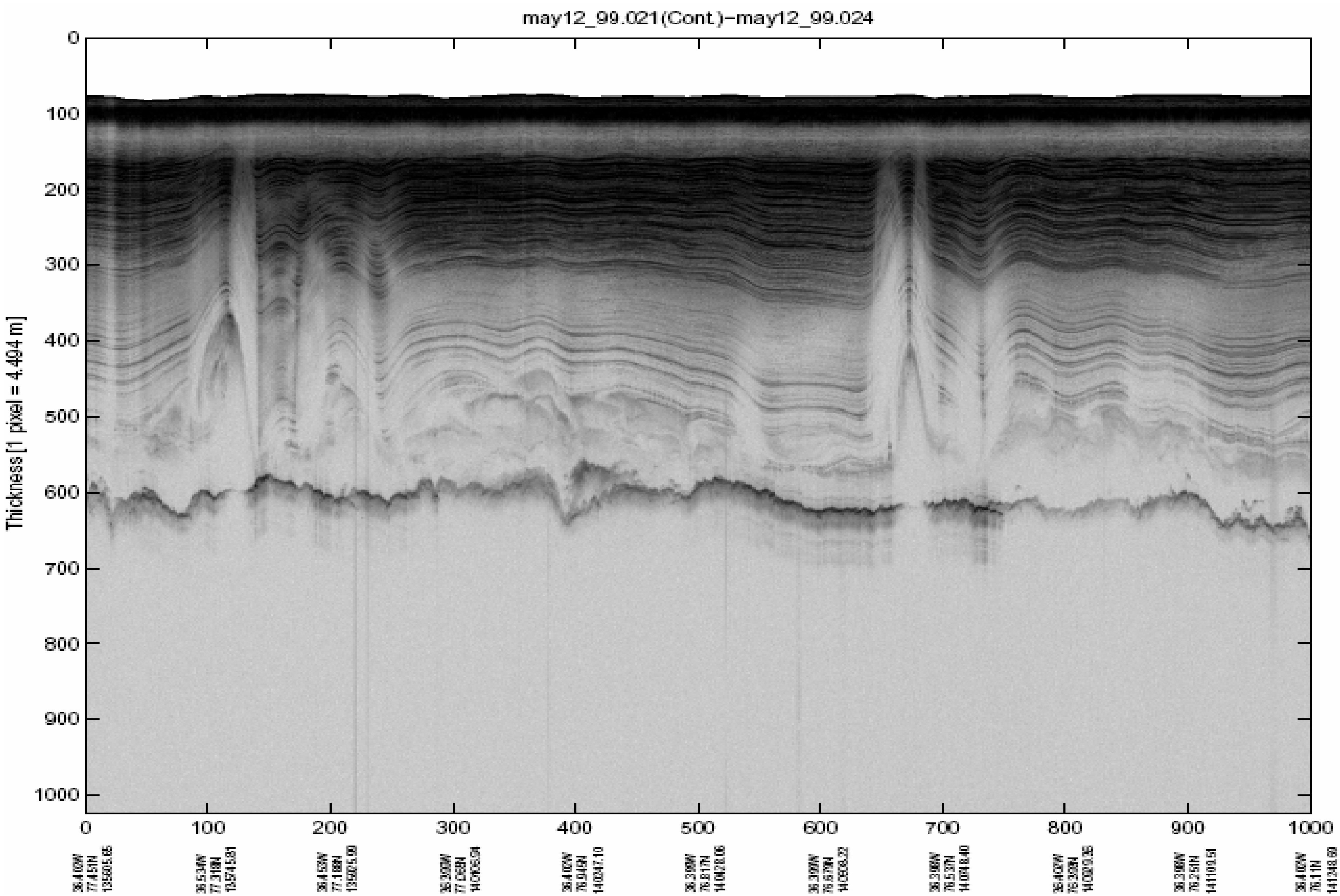


Radar data – layer distortion and ice loss





Folding and basal turbulence



Technology & tools

Radar signals are the result of generation, propagation and processing

- RF:
  - Chirp (SAW) & PA
  - Antennas/feed and beamforming network
  - Spherical (Fraunhofer) forward propagation; dielectric loss & int. reflections
  - Rough surface reflection and diffraction
  - Spherical return propagation;
  - LNA
  - Pulse compression (conjugate SAW)
  - Bandpass filter & downconversion > complex IF
- AF:
  - Bandpass filter
  - Time-varying gain
  - A/D conversion
- Digital pre-process:
  - Coherent integration
  - Incoherent integration
  - NOT – absolute calibration, recording of attenuator settings etc.
- Record

Echo post-processing and interpretation

Primary task has been echo detection and depth profiling

- Conditioning
  - Further incoherent integration and filtering for optimum SNR
  - Image filtering for clutter removal
- Peak detect, track and filter for upper surface and bed
  - Import Nav data
  - Output composite image product, profiles, tracks etc.

- Depth measurements have provided comprehensive topographical maps of Antarctica and Greenland

Echo interpretation

- Interface characteristics have been obscured by signal statistics and lack of absolute calibration
- In this study we have selected basal melting for investigation as a test case for further signal conditioning and interpretation

What else can be learned?

- Signals return from all parts of the ice volume
- Internal layering, folding and ‘turbulence’, internal debris
- Condition of the base, especially melting.

What additional tools do we have?

- Further signal analysis
  - Pulse envelope qualification; angular spectrum; interface smoothness
  - Signal energy aggregation & averaging
  - Relation of fading to intensity
  - Pulse coherence measurement; surface & interface gradient
- Prior knowledge about ice, rocks, till and water
  - Interpretation of signal intensity range
  - Normalisation of minimum mean intensity
- For the future:
  - Relate materials to ice flow patterns, coastal geology, hydrology
  - Internal interfaces: coherence, curvature, reflection vs. depth
  - Cross-point analysis
  - Cross-track resolution

Melt discrimination

Melt discrimination

This study focuses on basal melt as the highest measurement priority

Subglacial melt has been identified in particular cases

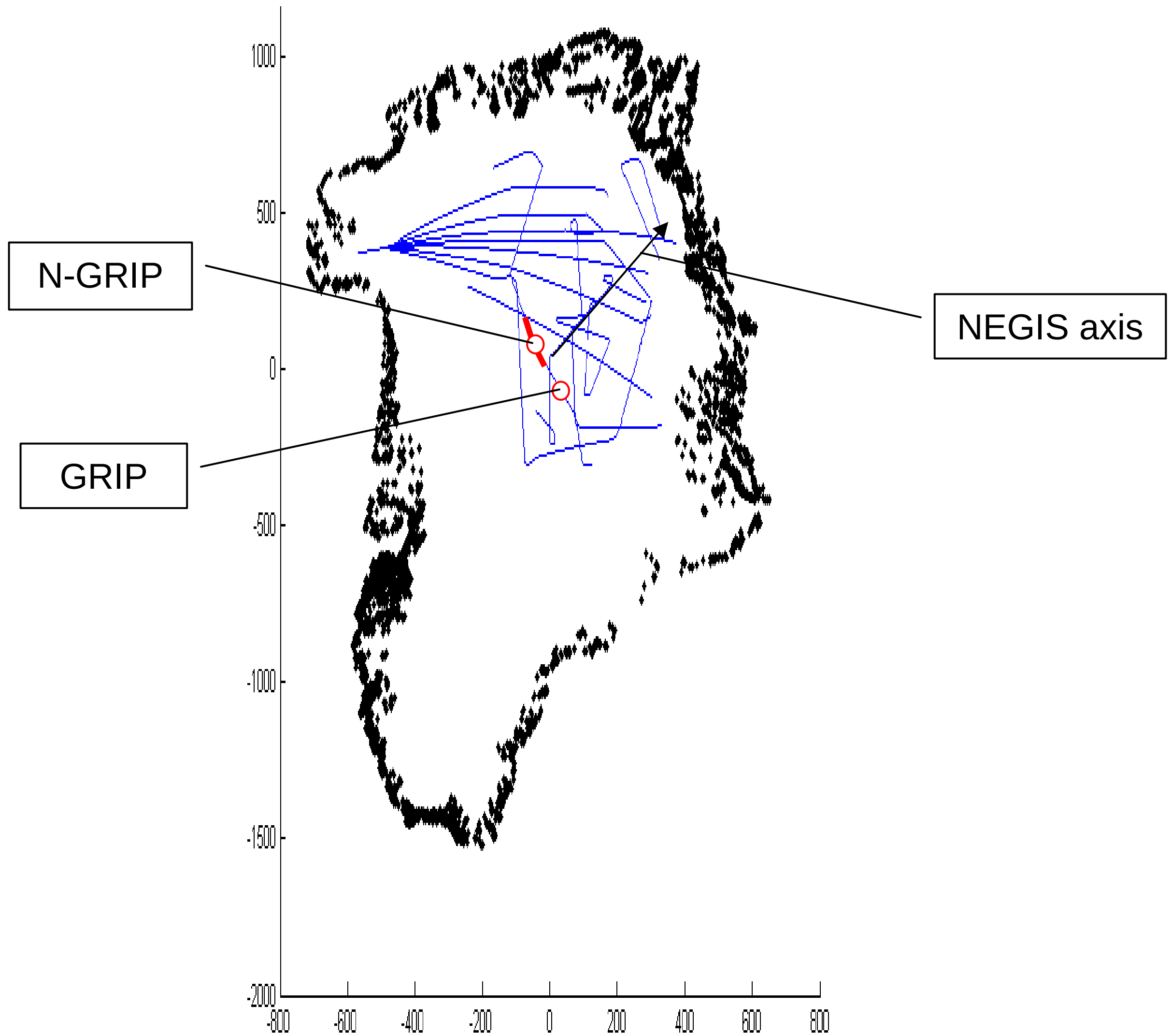
- Antarctic lakes
- Volcanic ice caps
- Ice stream tributaries (WAIS)
- Temperate glaciers

Melt extent has not been extracted globally with ice depth over continent-wide surveys. It has been mapped as an output of models

Our opportunity is to extract melt locations and extent, then use the results as input boundary conditions for the modellers

Subglacial water test set

These flights include the NEG Ice Stream, GRIP, North-GRIP, glaciers, steep relief, etc.



Scale is in km based on a center at 75N, 40W, local projection

Challenges

Echo variability

- Wave divergence with depth
- Propagation and reflection loss
- Interference and diffraction
- Reflection coefficient

System variability

- Uncalibrated attenuation

Rock variability

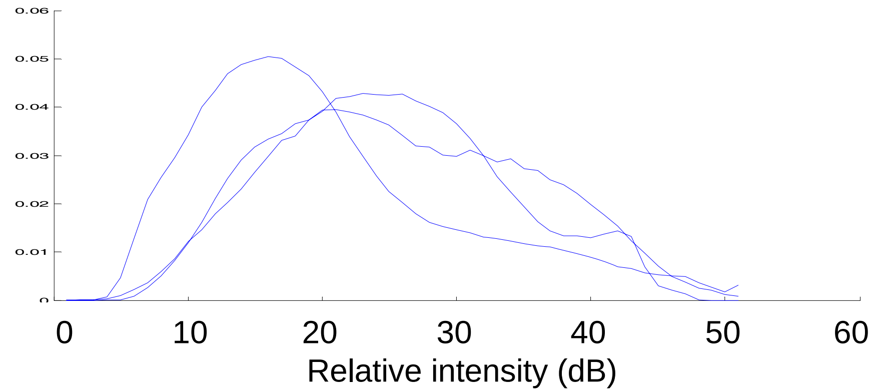
- Permittivity typically 5-10
- Reflection -19 > -11dB

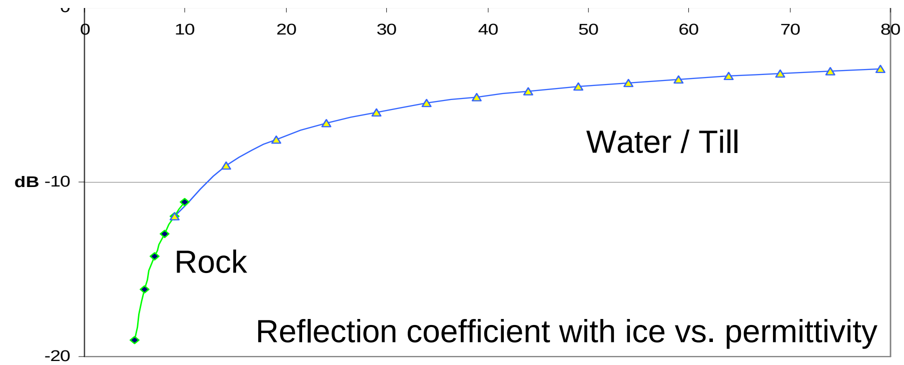
Water / till fraction / thin layers

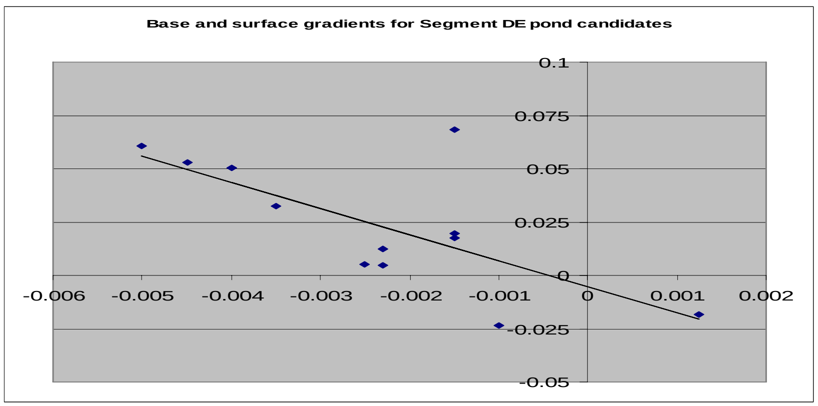
- Effective permittivity typically 10-80
- Reflection -12 > -3dB

Verification

- Drill core findings
- Model expectations
- Population inference
- Density inference



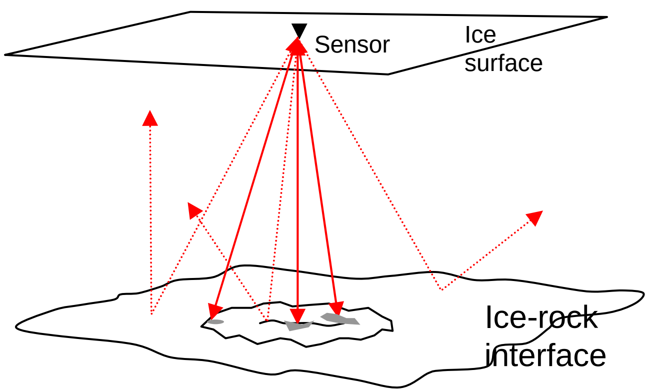




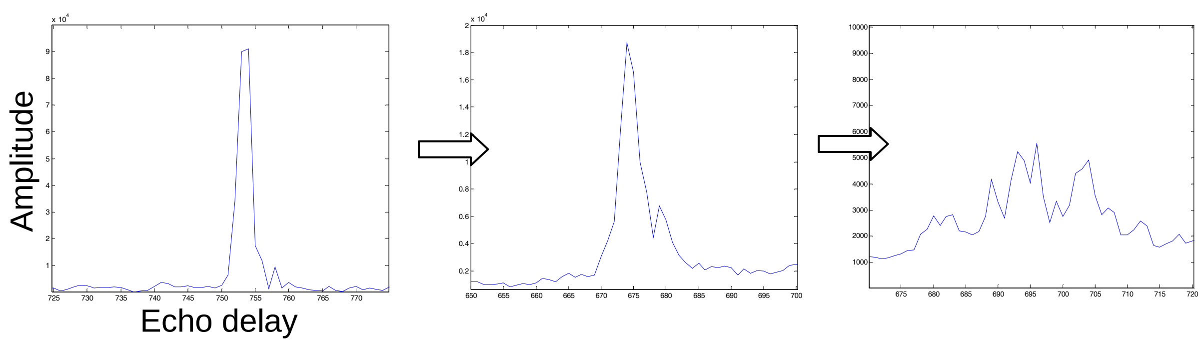
Further processing and inference

Echo intensity statistics have previously focused on the ‘first return’

- that is, the power reflected from the nadir point.
- In practice the base return is extended by off-nadir reflections, but for small angles these do not affect the overall ‘gain’ of the interface
- Facet reflections interfere, causing increases and decreases in power
- By aggregating the extended signal and averaging along track, the full reflecting power can be retrieved, provided the scattering/reflecting angles are within the beam
- This gives less variability and greater accuracy than first-return alone



(ignoring refraction)



Pulse envelopes for increasing roughness

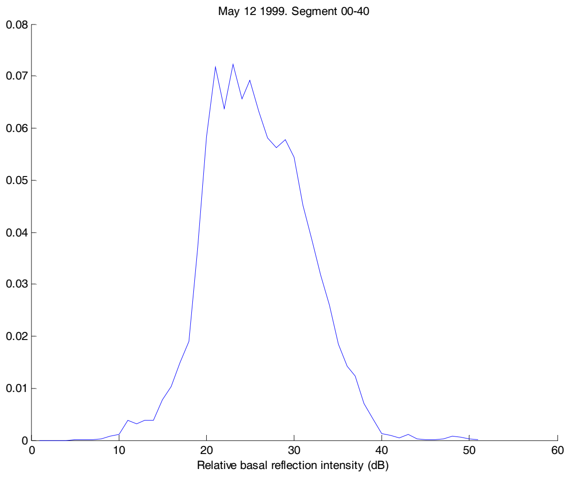
In this study a top-down / bottom-up approach is used to resolve the uncertainties

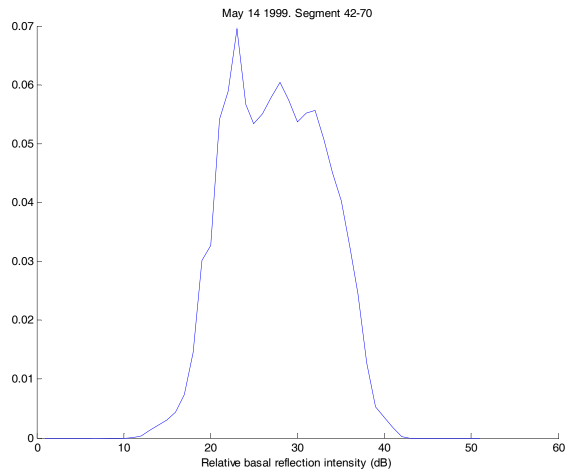
Signal intensities have been corrected by:

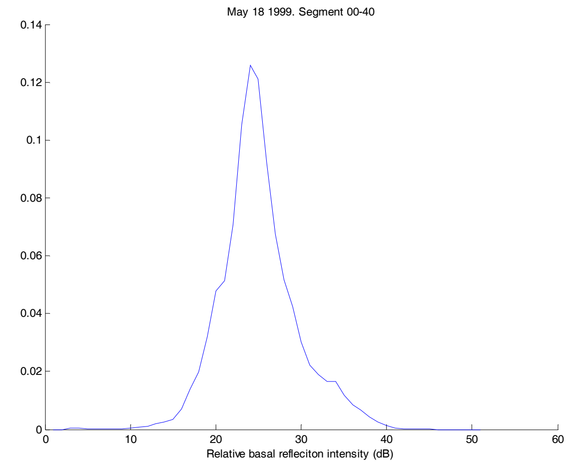
- Filtering out the effects of signal fading due to interference
- Compensating for echo divergence and diffraction (pulse envelope analysis)
- Compensating for dielectric losses and their variation with temperature, plus internal reflective losses (best global fit with the data)

Distributions are normalised to a minimum level for large survey populations, related to observed fine intensity resolution

- Adjustments of -5 to +2dB have been sufficient to give precise correspondence for distribution minima over 500-1200km flight segment lengths
- Typical segment distributions are:







Discrimination of subsegment populations

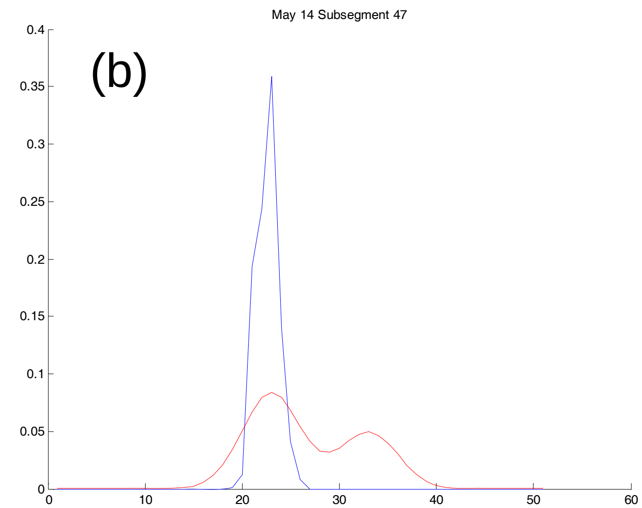
Subsegments provide distinct, narrow distributions:

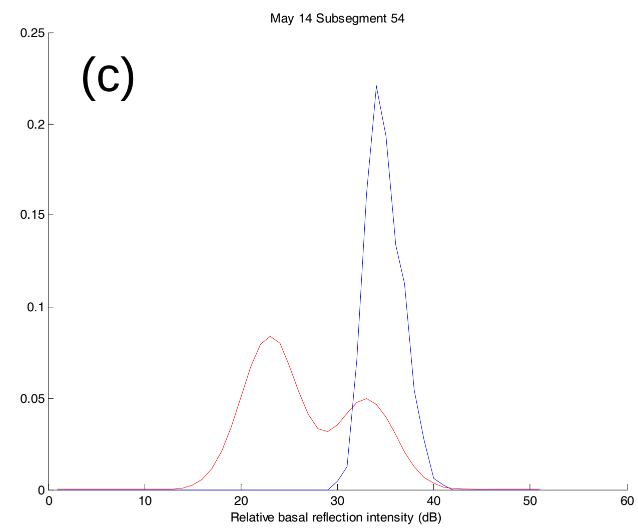
(a) May 25 44-54

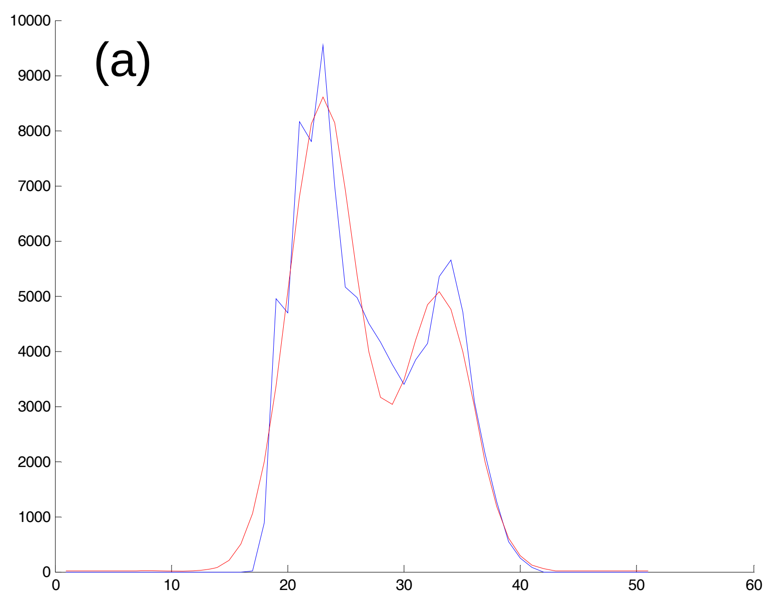
(b) GRIP @ 45 (drilled frozen)

(c) N-GRIP @ 54 (drilled wet)

(North-GRIP, redrilled, returned frozen after pressure release)





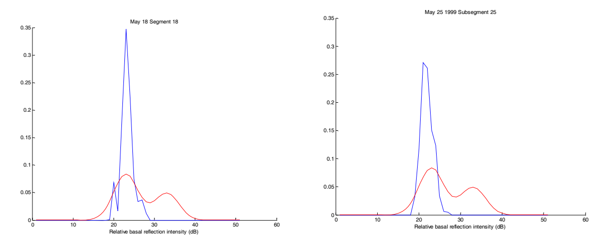


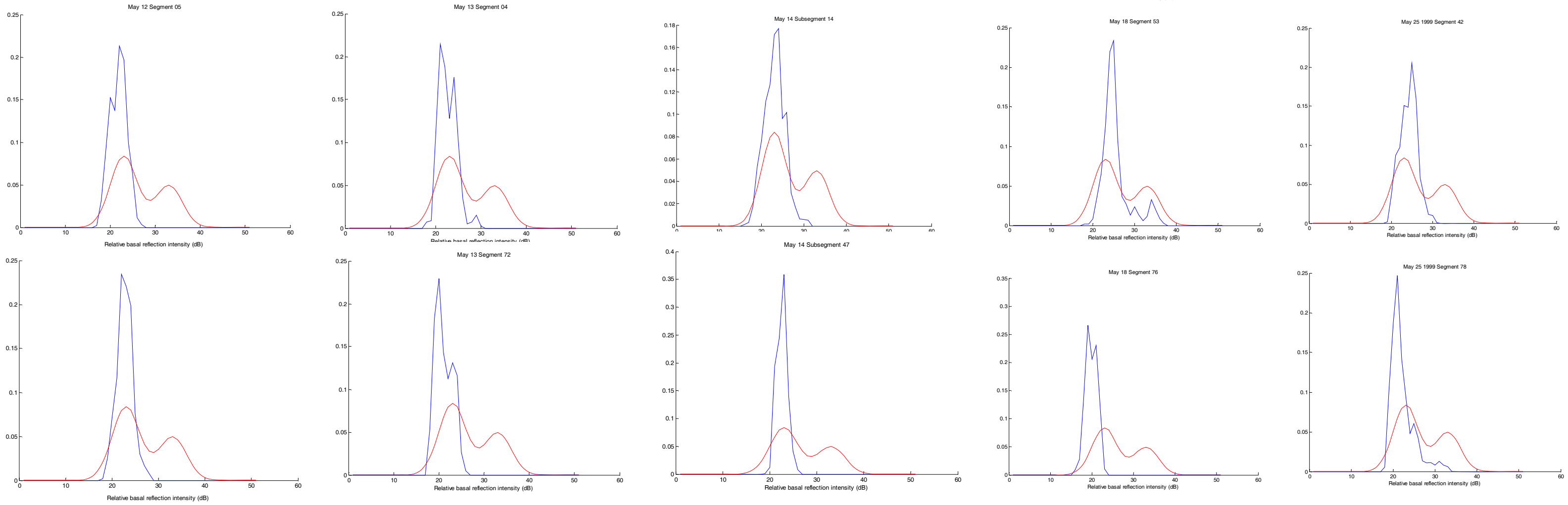
Melt discrimination

All test set flights conform to this pattern

- An abrupt lower edge to the distribution
- Few extensions above low maximum + 15dB
- Separable into rock subsegments, water subsegments and mixed
- Variation of upper branch within that expected for water/till mix

Rock segments provide excellent alignment

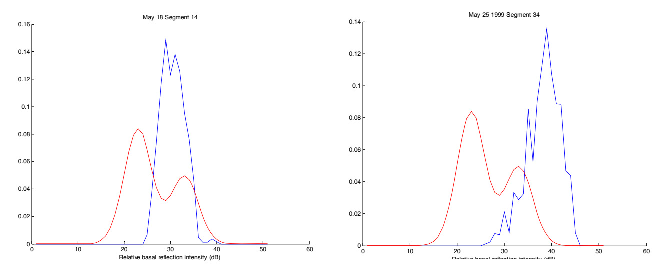


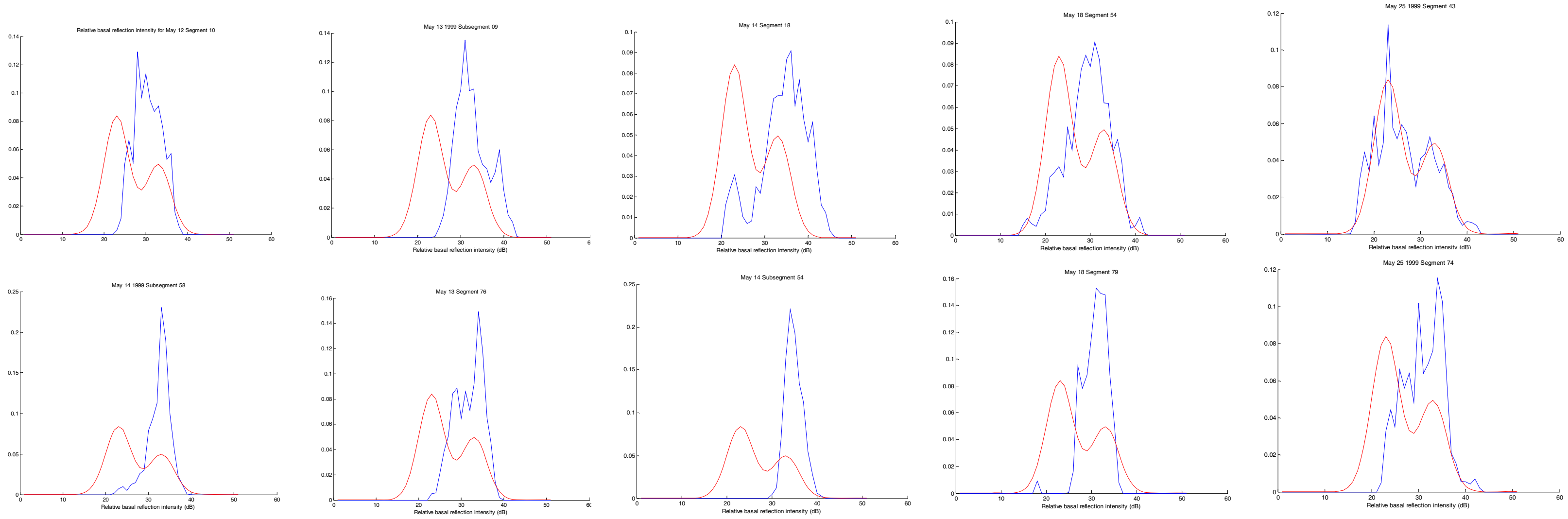


Water segments also provide clear alignment

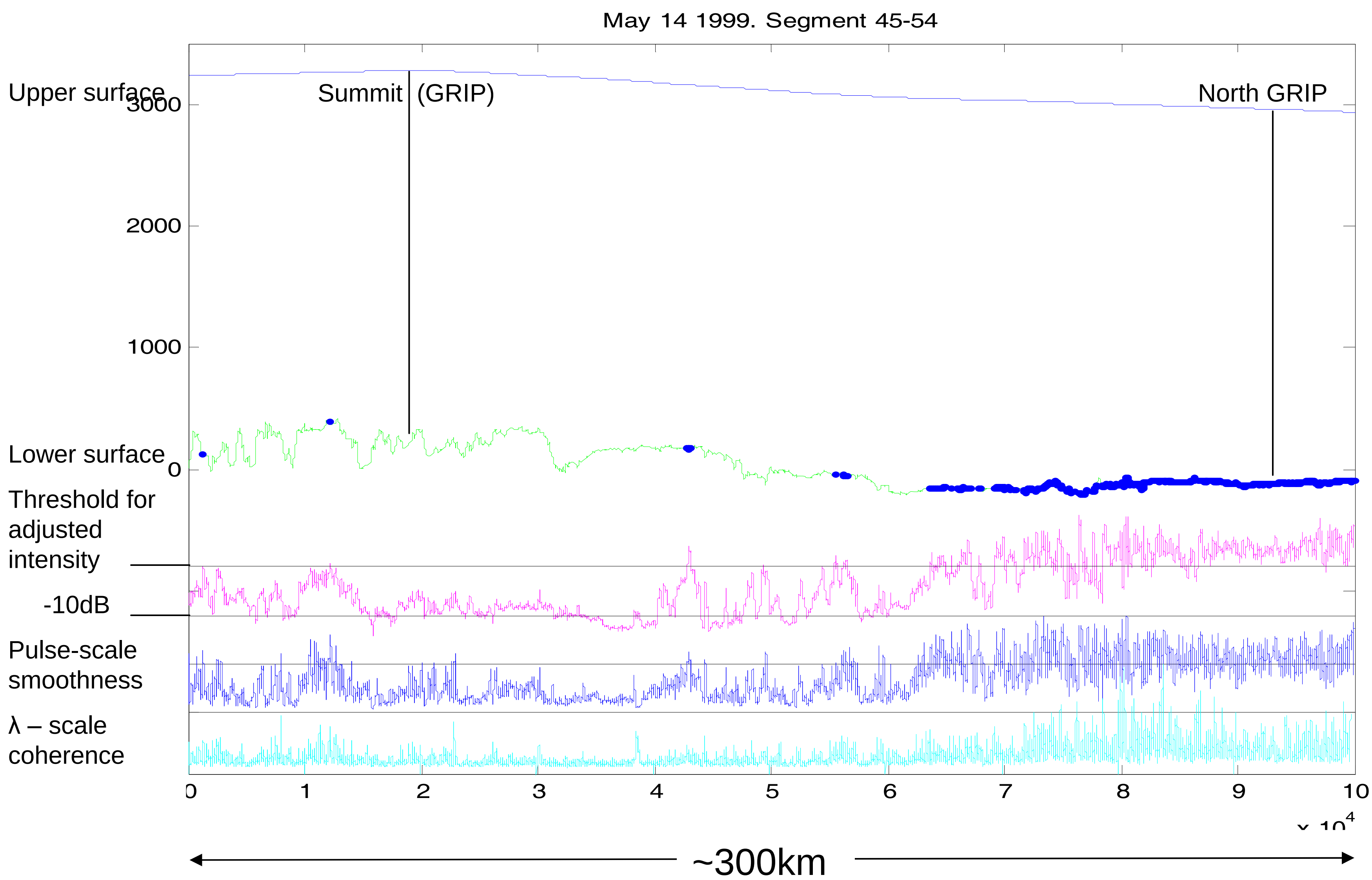
- Greater variability due to till
- 21% of base is discriminated as wet
- Some segments have only mixed rock / water base
- Water is discriminated by:
  - Exceeds threshold at |Rk| + 8dB
  - Exceeds smoothness criterion

    (I_{abr} > 0.25)

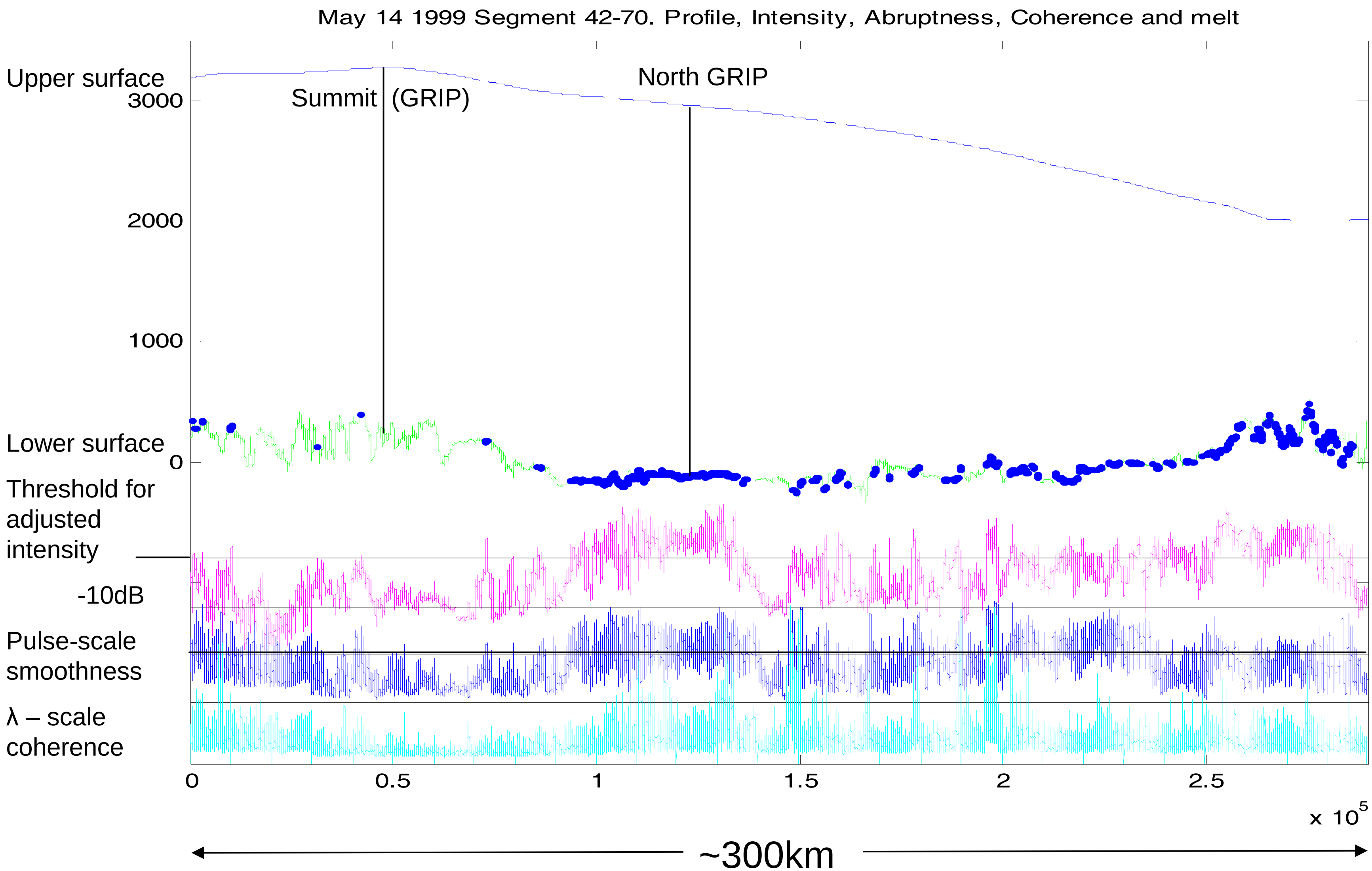




Key parameters and locations of water reflectors for Summit / N-GRIP segment



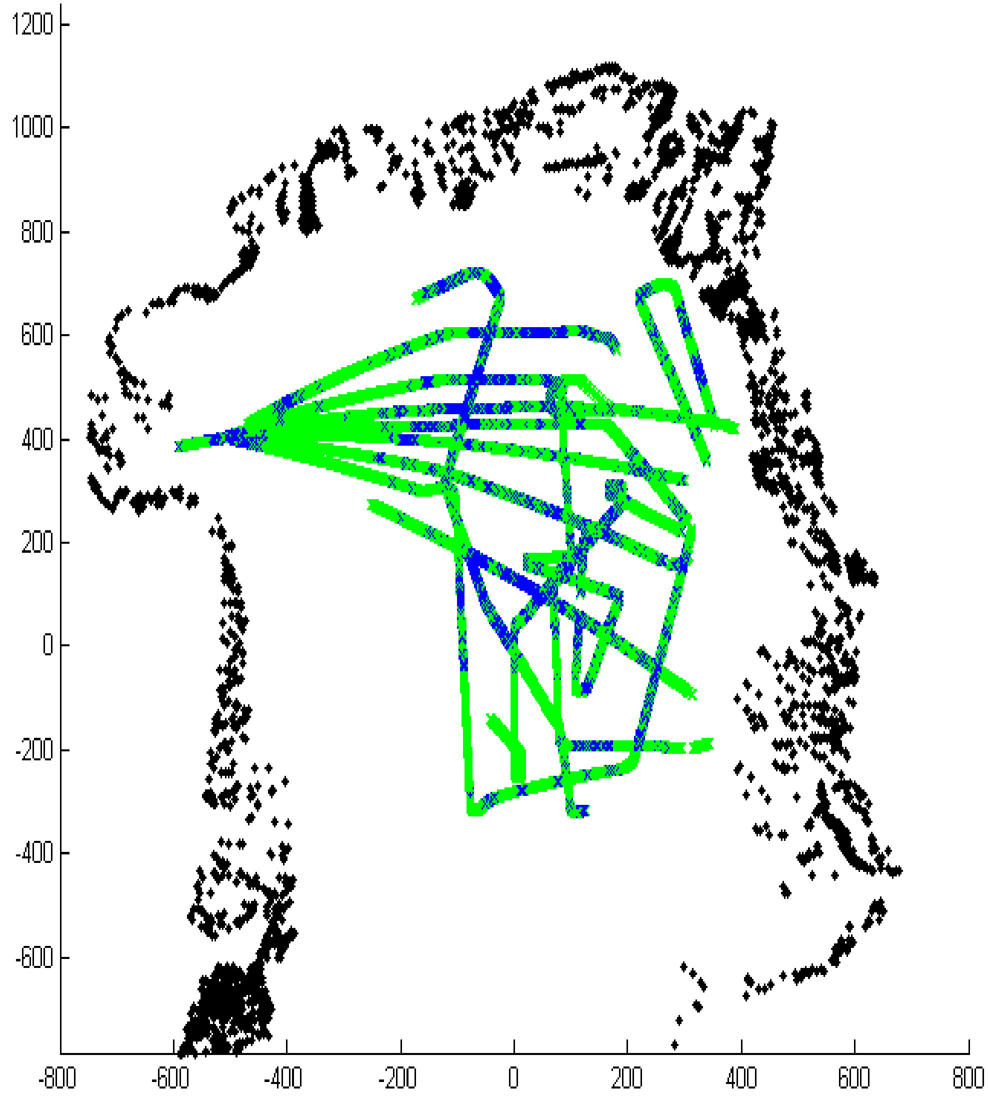
Key parameters and locations of water reflectors for Summit / N-GRIP segment



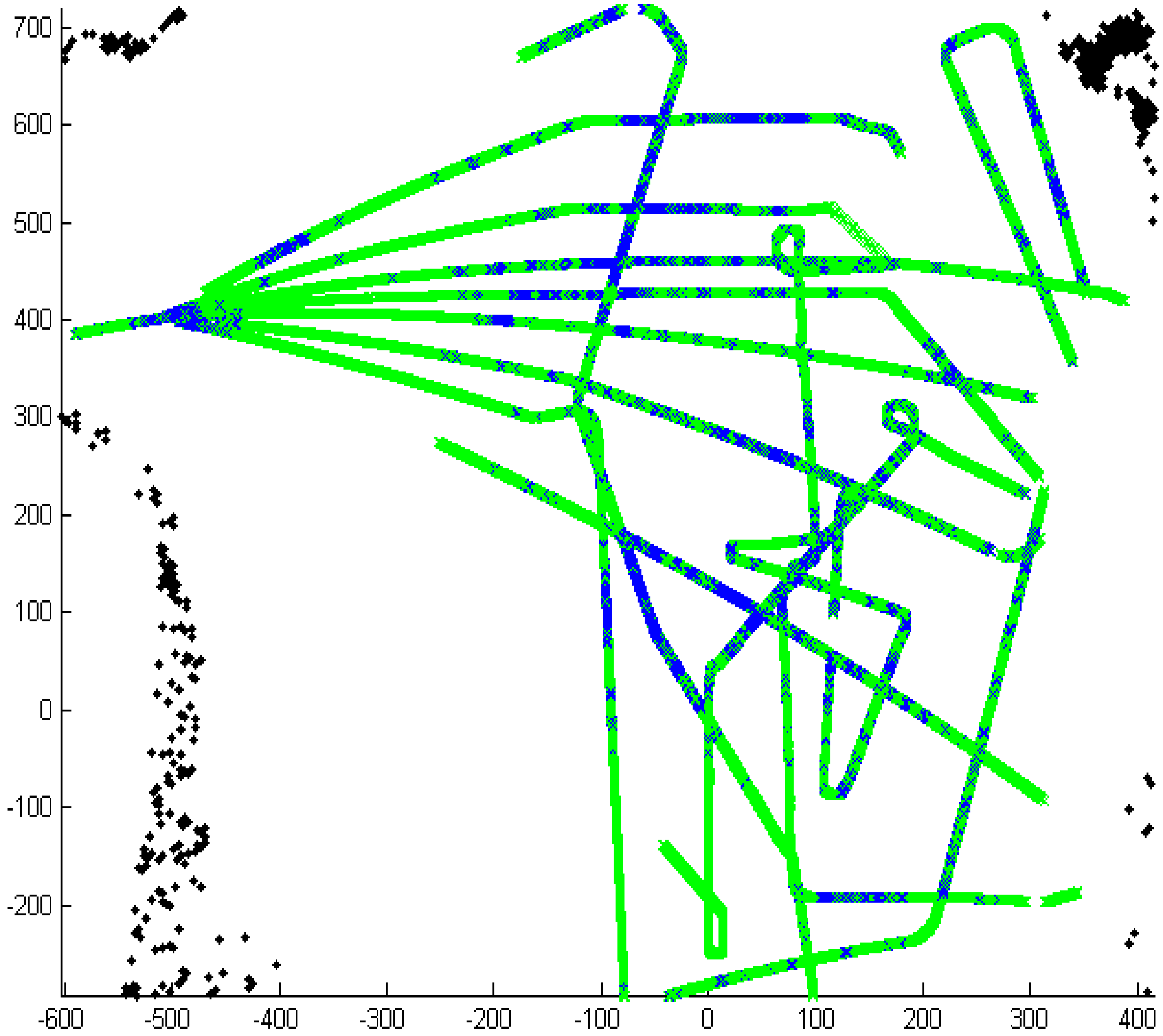
Mapping melt locations

Subglacial water determinations in Northern Greenland

21% of these flight kilometres yield water or saturated till returns

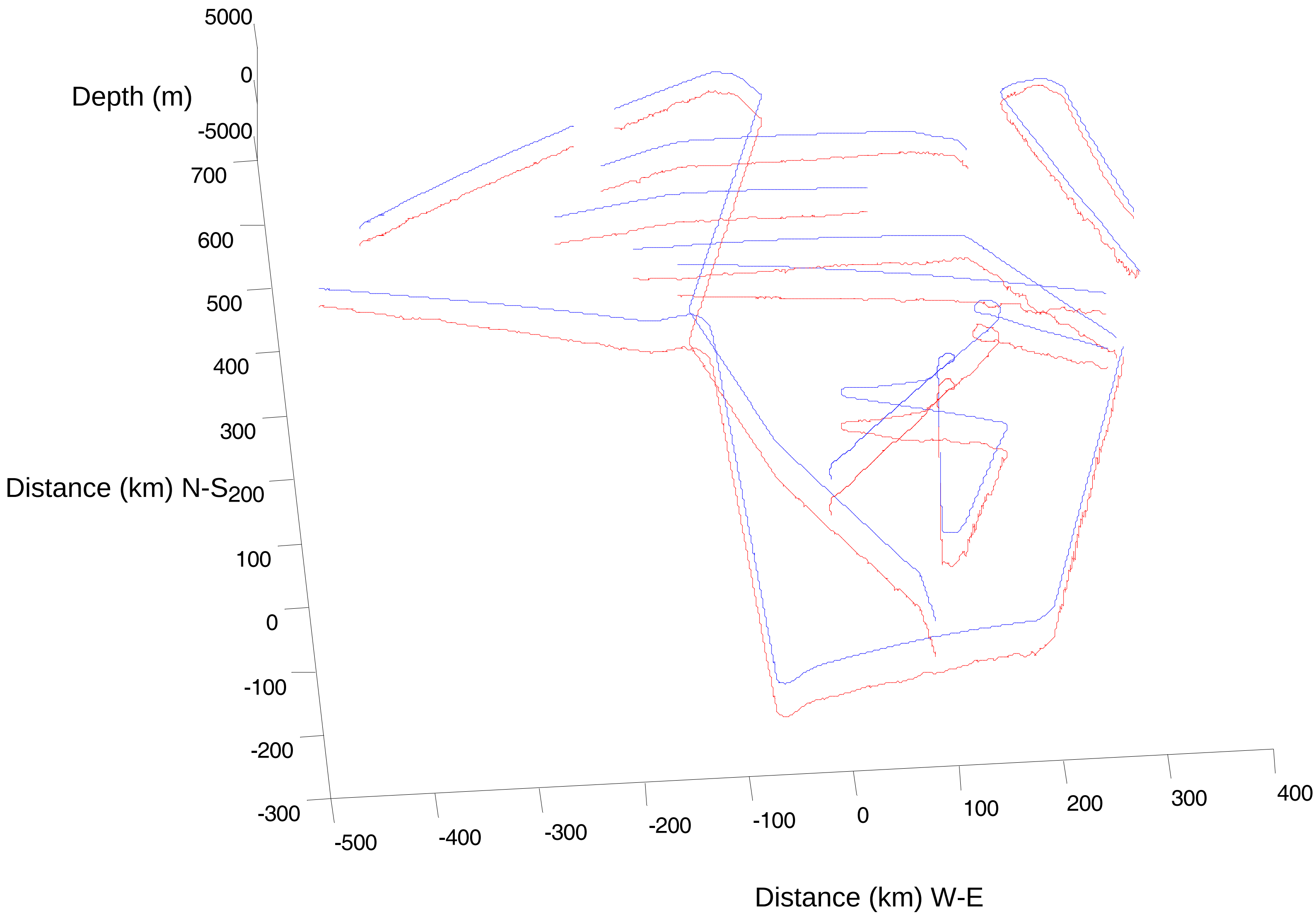


With closer focus



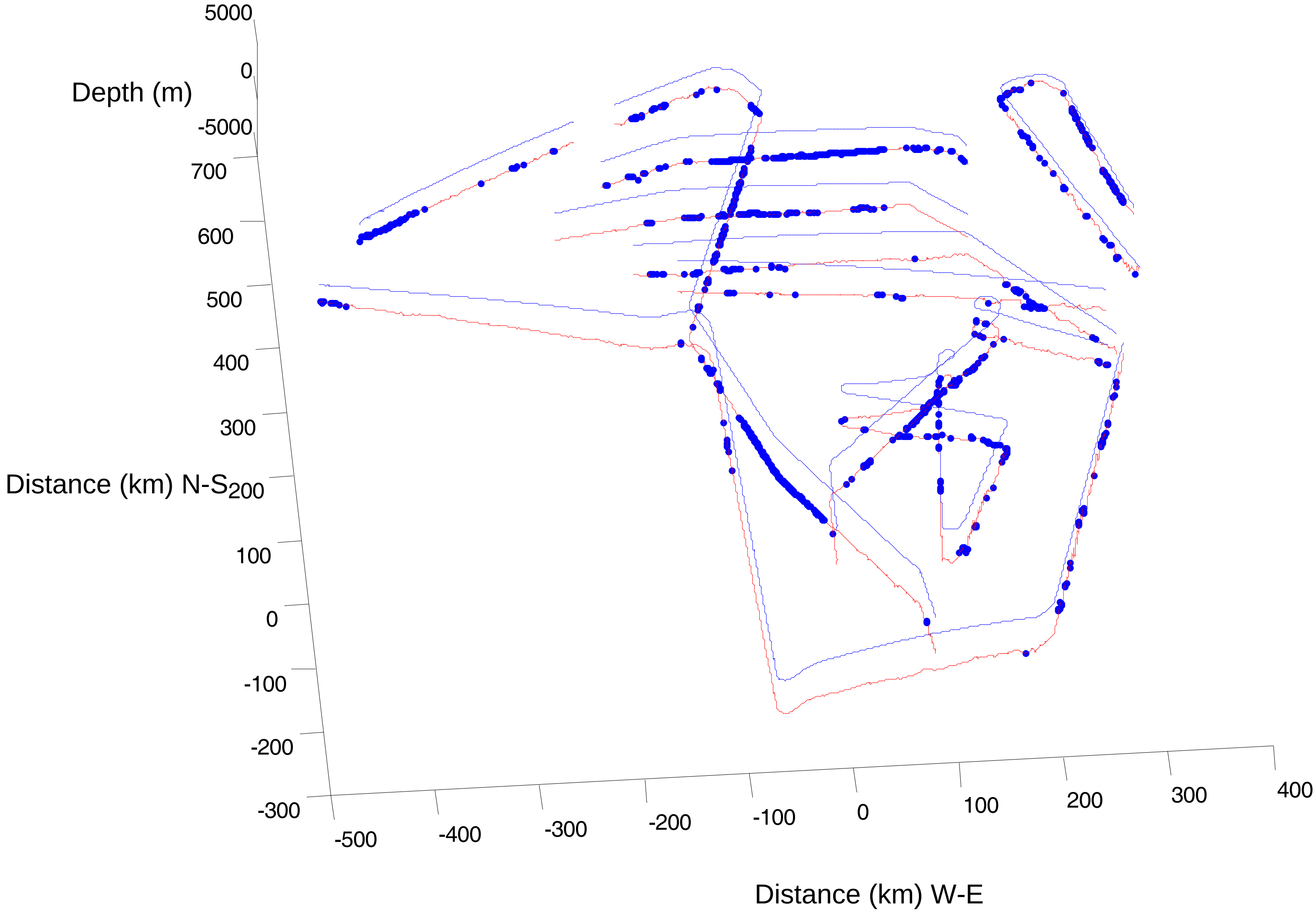
Subset of flight lines with upper surface and lower interface topography

KU RSL Flight segments from May 12, 14, 18 and 25, 1999 (vertical exaggeration 10:1)

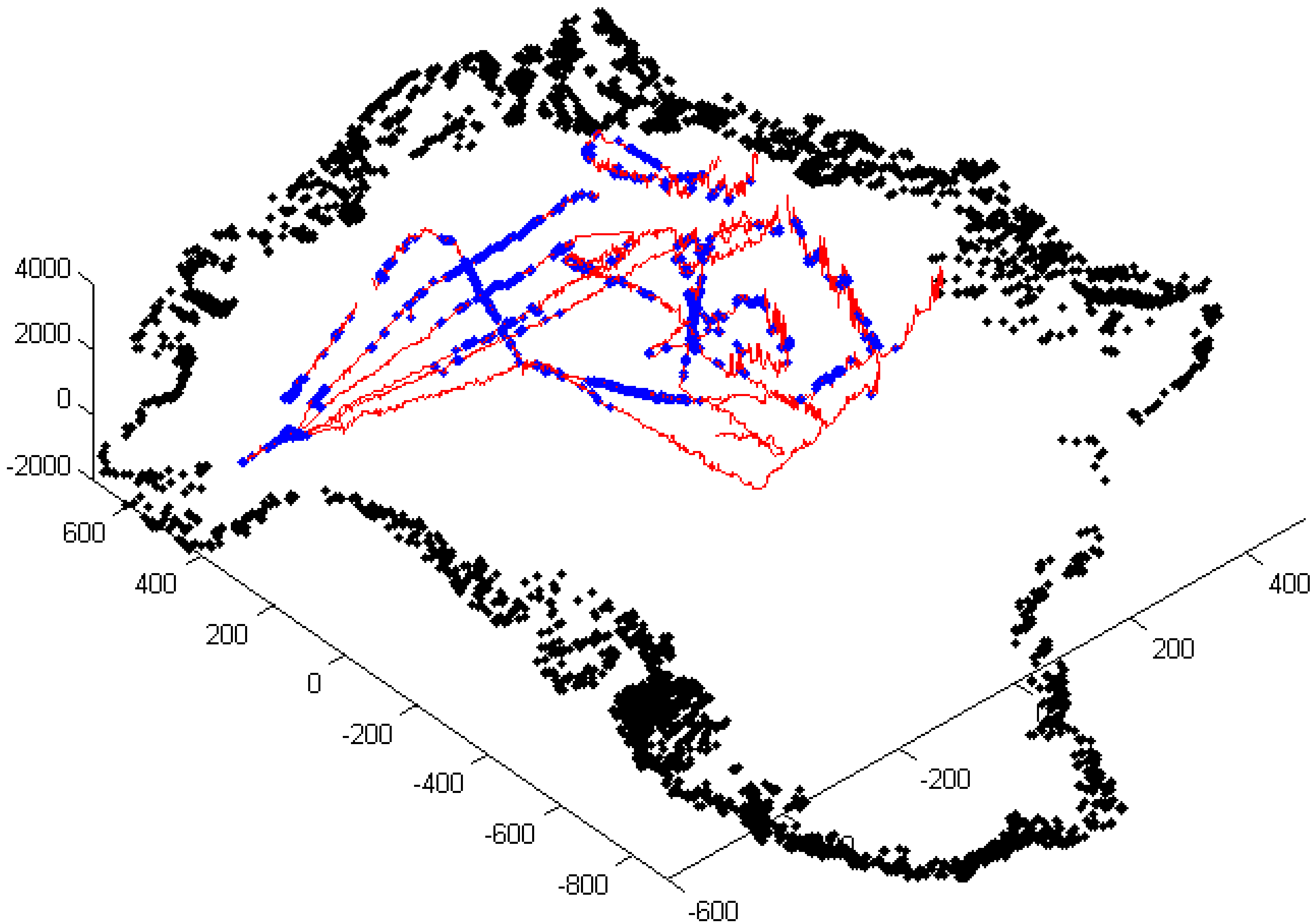


Subset of flight lines and basal water locations

Water locations based on smoothness-qualified, adjusted reflection intensity. Water extent is 21% of entire sample. Some subsegments exceed 80%.

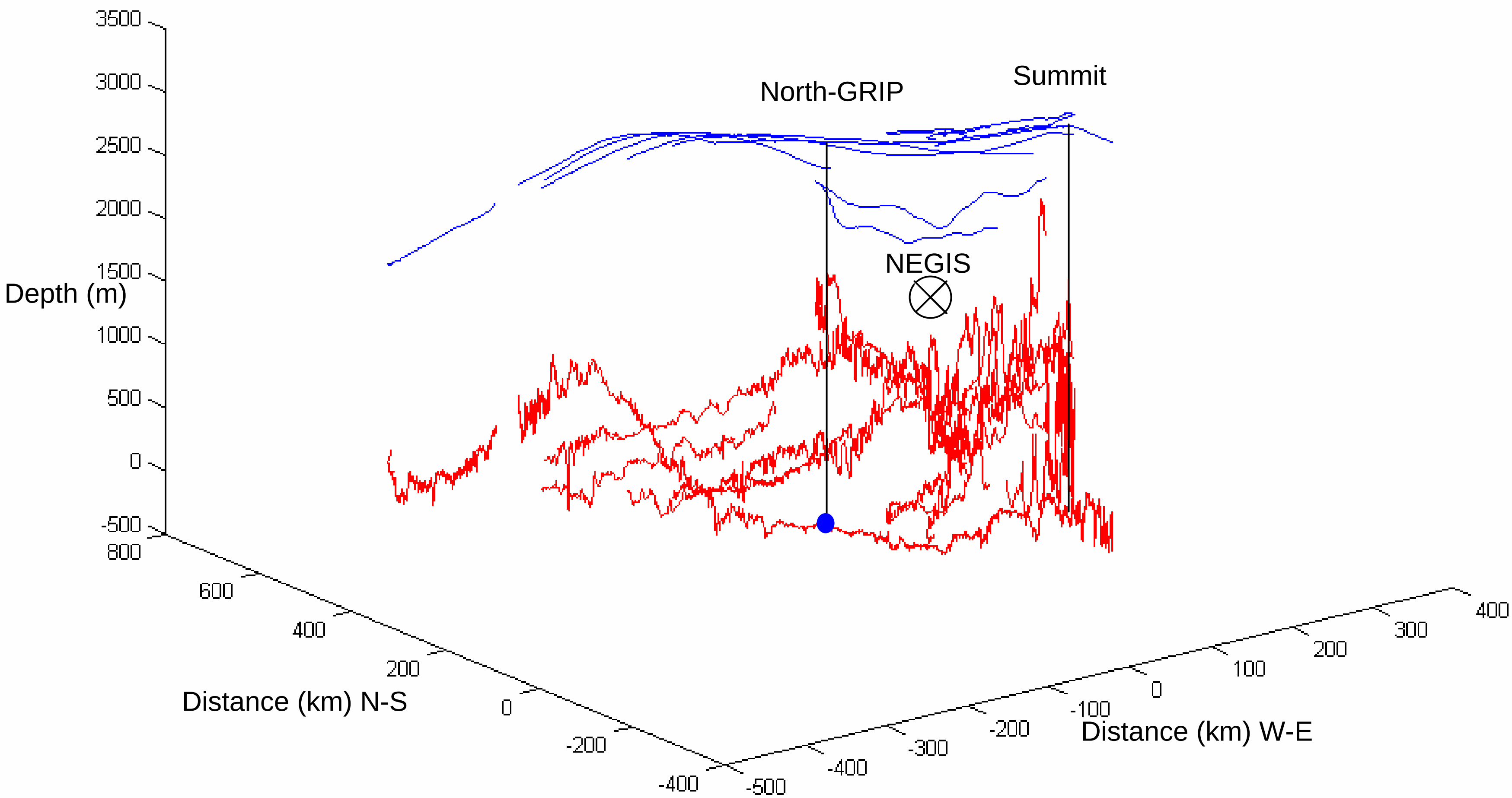


Perspective view with topography



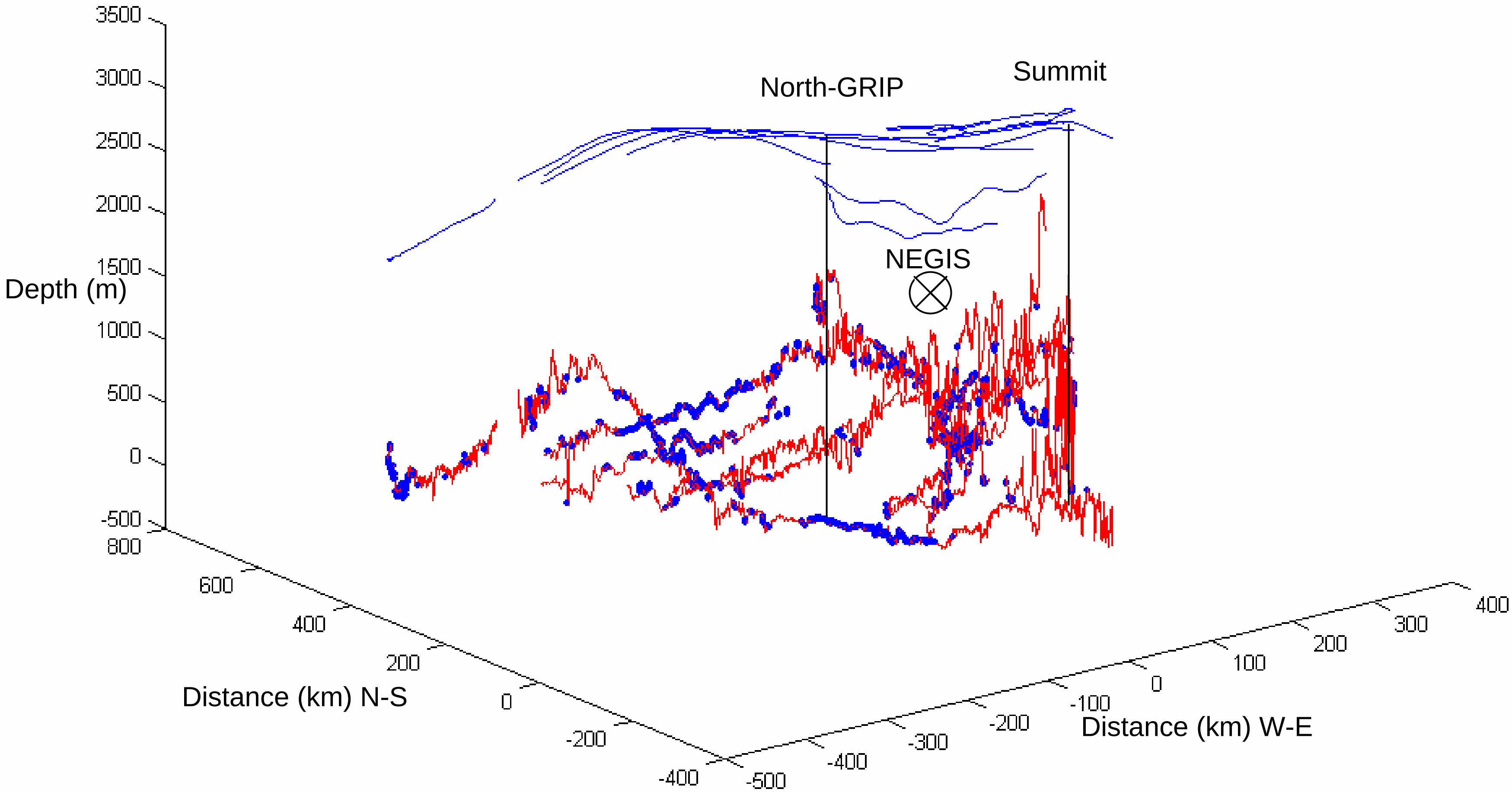
Perspective view of upper and lower surfaces for the series of survey flights

The view is through the ice, with the ice surface indicated by the blue flight lines and the basal interface by the red lines. The line of sight (⊗) is along the North East Greenland Ice Stream, with Summit and North-GRIP borehole sites



Locations of basal melt: perspective view

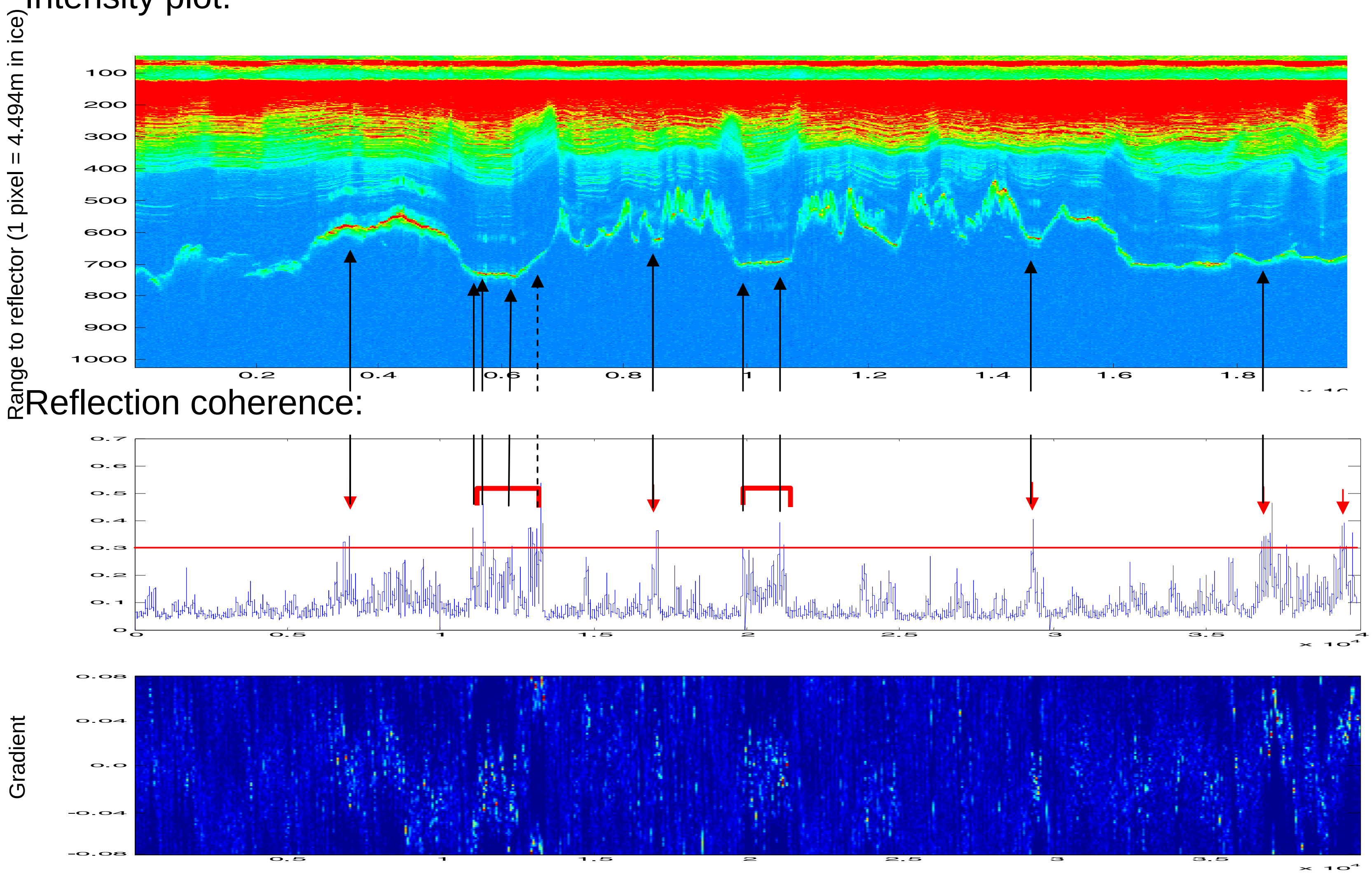
The view is through the ice, with the ice surface indicated by the blue flight lines and the basal interface by the red lines. The line of sight (⊗) is along the North East Greenland Ice Stream, with Summit and North-GRIP borehole sites



Additional verification: association of coherence, intensity and gradients

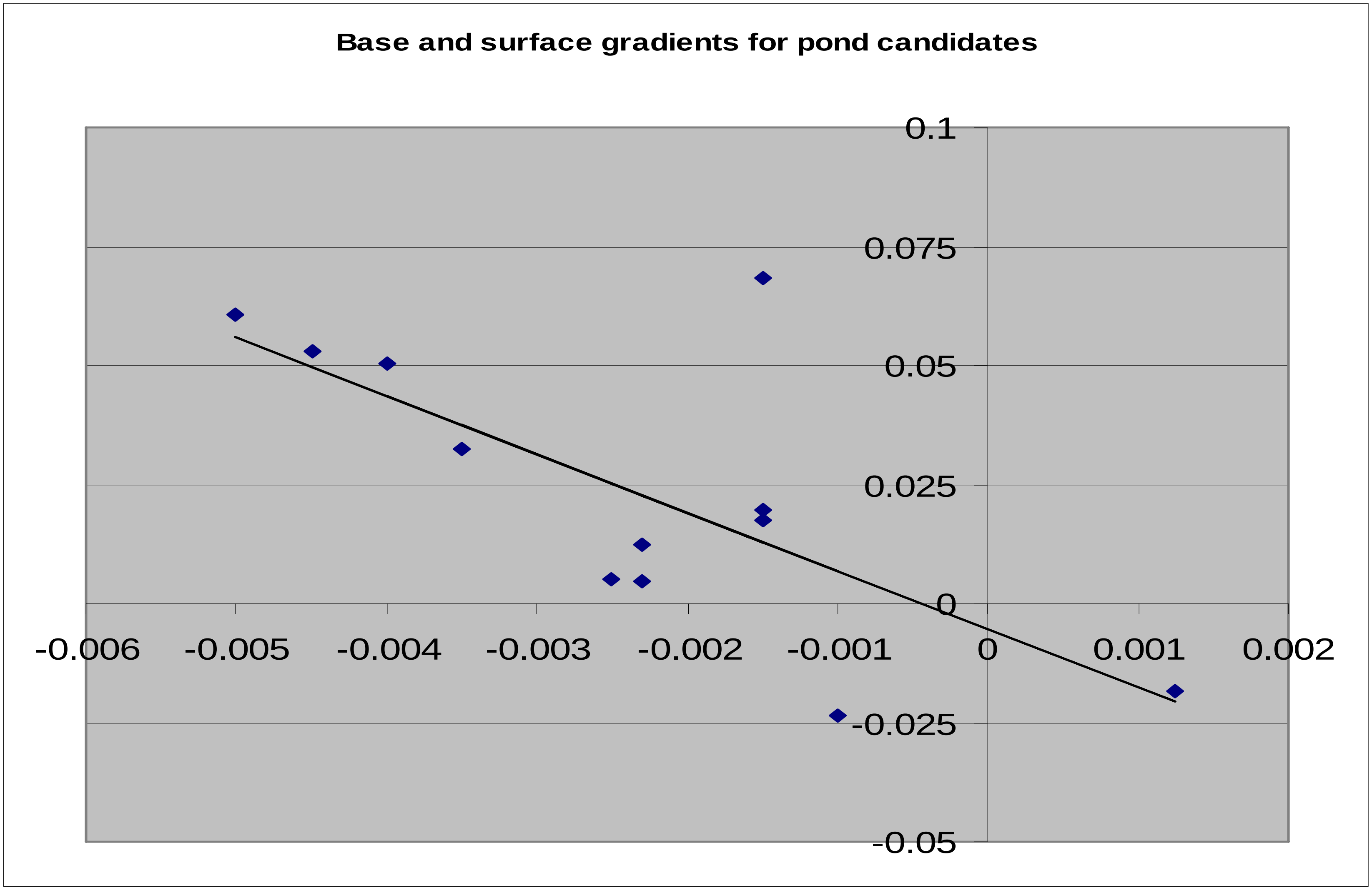
Coherent, intense returns can be associated with steep relief

Intensity plot:



Comparing smooth basal interface gradients with surface gradient

In equilibrium, for $\rho_i = 0.92$, $\rho_w = 1$, the interface gradient should be correlated with the surface gradient. The regression fits density 0.99.



Next steps

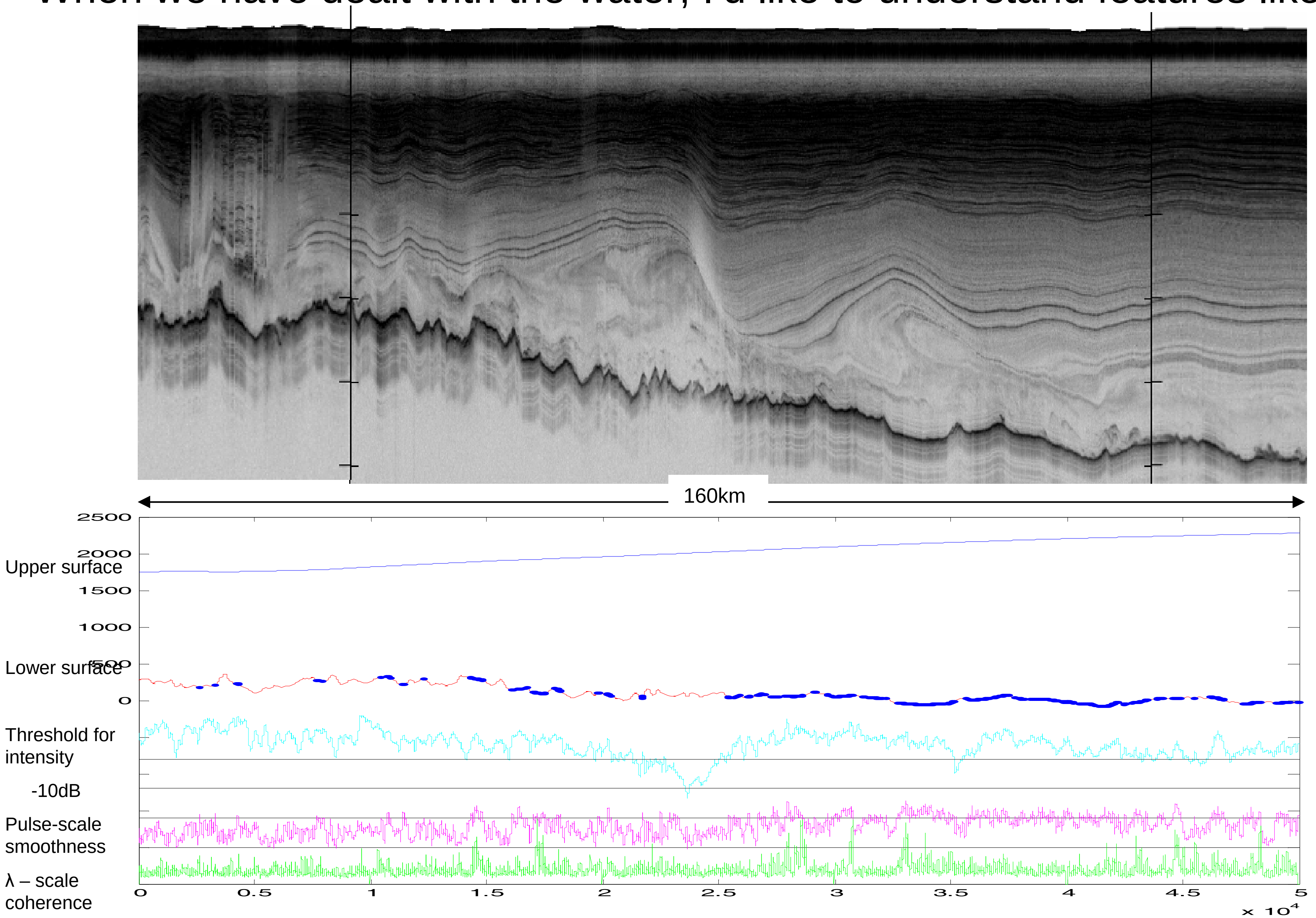
These results offer a direct mapping of subglacial water.

Next, we wish to:

- Extend analysis to other flights and years
- Relate water locations to melt predictions from internal layer trends
- Derive a survey mesh suitable for model input
- Introduce basal water distribution mesh explicitly as an input to ice sheet models, to incorporate the effects on:
  - heat flow
  - ice advection
  - basal friction
  - ice stability
- Analyse further features of the ice sheet…

Next steps

When we have dealt with the water, I'd like to understand features like:



Acknowledgements

All of the work reported in this presentation has been based on data kindly provided by Dr S. P. Gogineni and Dr P. Kanagaratnam from the PARCA/CReSIS database

This visit is supported by the University of Kansas

Facilities have also been provided by CReSIS and by the Climate Change Institute, University of Maine