Radar Depth Sounder Processing And Digital Thickness Map of Outlet Glaciers

Harish N.Ramamoorthy

May 17, 2004

Committee

Dr. Pannirselvam Kanagaratnam (Chair)

Dr.Prasad Gogineni

Dr. David Braaten

Information and Telecommunication Technology Center

University of Kansas

Outline

- Motivation
- Radar Depth Sounder System
- Signal Processing
- Data Interpolation
- Implementation on Glacier Data
- Conclusion and Future Work

Motivation

- Monitor mass balance of ice sheet in Greenland and Antarctica
- Quantify the effects of global warming on polar ice sheets
- Understand glacier dynamics by understanding bed topography
  - Develop digital thickness map of bedrock using measured ice thickness
  - Create 3D perspective of bedrock to reveal its nature and other artifacts

Outline

- Motivation
- Radar Depth Sounder System Description
- Signal Processing
- Data Interpolation
- Implementation on Glacier Data
- Conclusion and Future Work

Radar Depth Sounder Systems

- Type – Pulse Compression Radar
  - Long detection range
  - Fine resolution
- Operating Frequency Range – 140-160 MHz
- Range Resolution – 4.494m
- Peak transmit power – 200W
- ICARDS – First Airborne Antarctic field experiment
  - Pulse width – 1.6μs
  - Sampling frequency – 18.76 MHz
  - Receiver Dynamic Range – 93 dB
- ACORDS – Airborne Greenland field experiment
  - Pulse width – 200ns to 10μs
  - Sampling frequency – 55 MHz
  - Receiver Dynamic Range – 110 dB

Outline

- Motivation
- Radar Depth Sounder System Description
- Signal Processing
- Data Interpolation
- Implementation on Glacier Data
- Conclusion and Future Work

Signal Processing

- Aim – Enable accurate thickness measurement by reducing random noise and other undesired signals from the collected data
- Pulse Integration – Improves spatial resolution by synthesizing longer antenna
  - Coherent Integration
    - Return pulses added before detecting the envelope
    - Phase information is preserved
    - SNR gain – N for N coherent integrations
  - Incoherent Integration
    - Return pulses added after detecting the envelope
    - Phase information is lost
    - SNR gain - $\sqrt{N}$ for N incoherent integrations
- D.C.Offset Removal – RF Power leakage during T_X off period

  Mean level of noise floor subtracted from return from ice layer

Signal Processing (Contd.)

- Gain Compensation
  - Normalizing gain in the return signal to remove sudden increase in noise level
  - Signal in each A-Scope is normalized by a factor that depends on the ratio of its noise floor level to the maximum noise floor level in the data

$nP = \text{No. of pulses received in 1 second}$

$nS = \text{No. of samples in noise floor}$

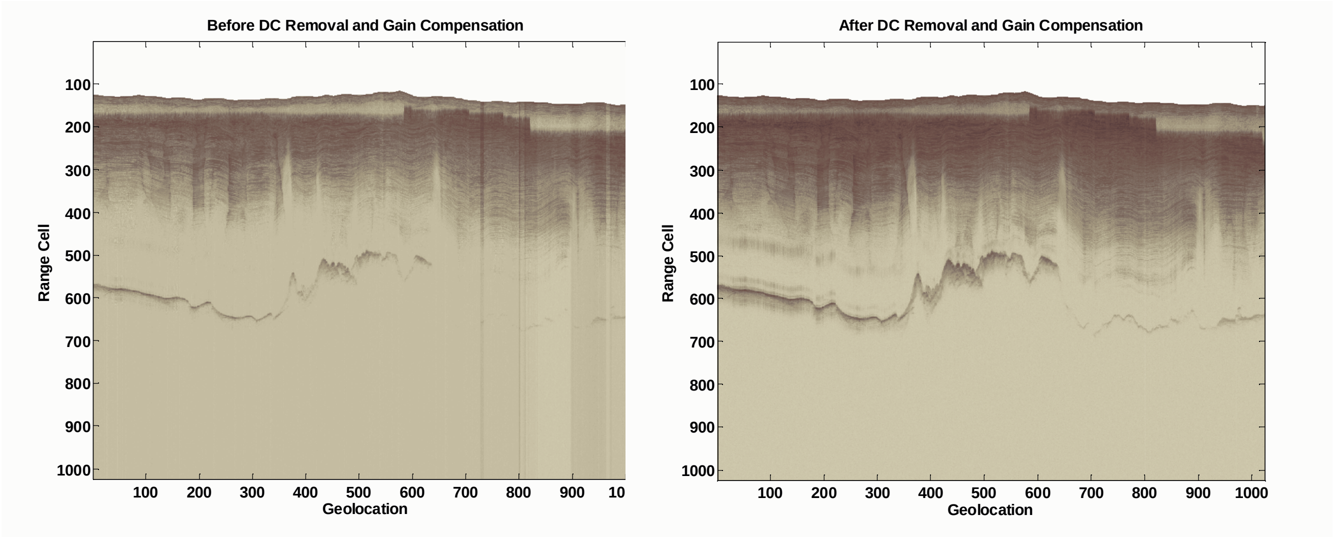
$$P_{N-Ave} = \frac{1}{nP}\sum_{1}^{nP}\left[\frac{\sum_{1}^{nS} P_N}{nS}\right]$$

$$P_{N-Max} = \max((P_{N-Ave})_{1\ldots K}$$

$$k = {}^{n}\mathrm{R}/_{nP}$$

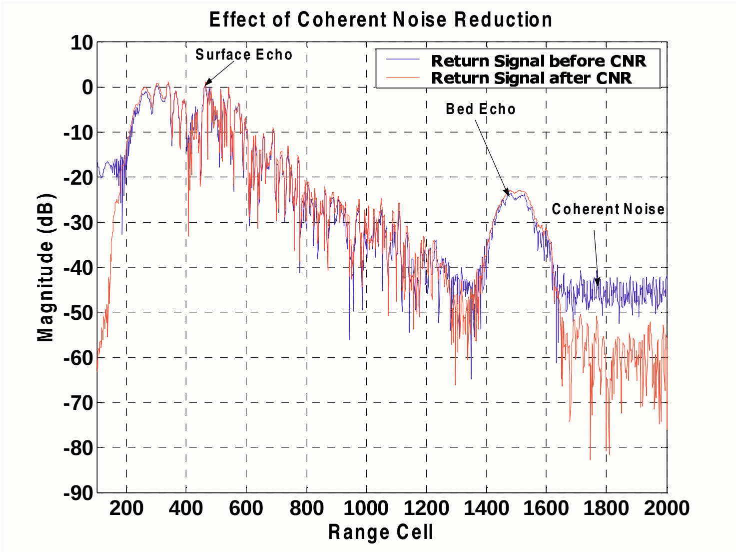
$$\rho_{1\ldots k} = \sqrt{(P_{N-Max}/P(_{N-Ave})_{1\ldots k})}$$

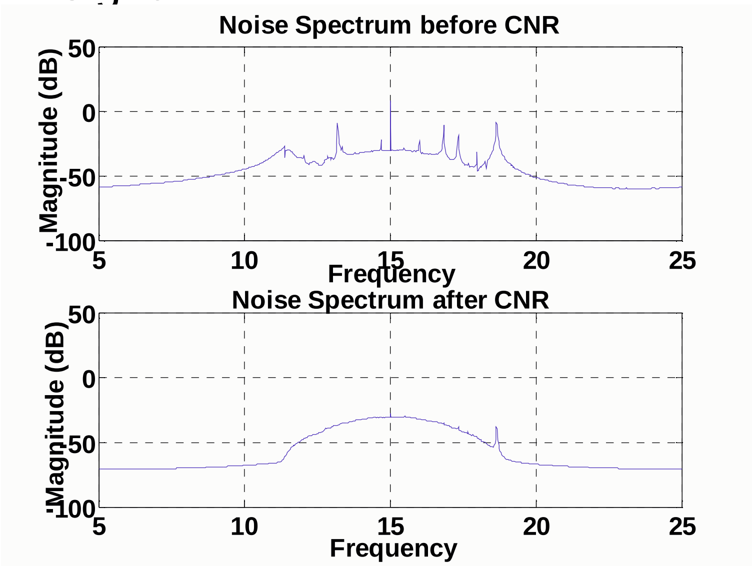
$$\tilde{S} = S_{1\ldots k} \times \rho_{1\ldots k}$$



Signal Processing (Contd.)

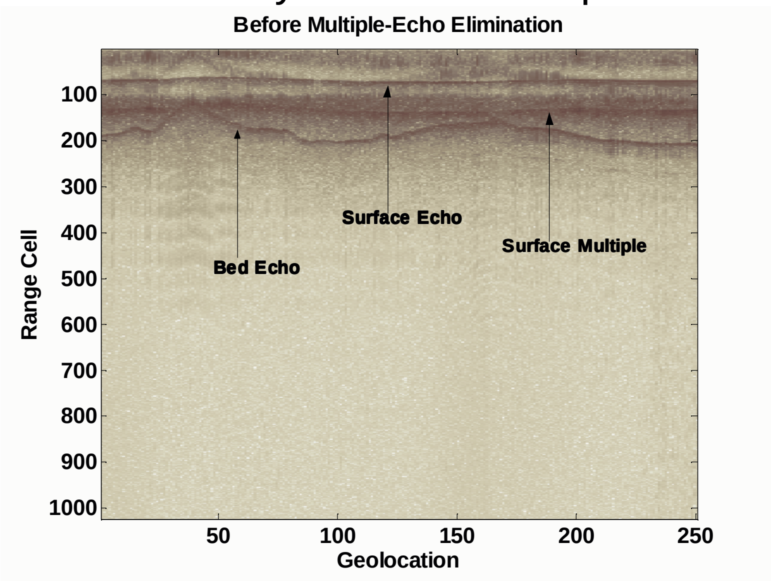
- Coherent Noise Reduction
  - Coherent Noise …
    - Leakage signals from antenna, RF section (systematic sources)
    - Vary temporally and spatially
    - Continuous in phase with backscattered signals
  - Backscattered echoes from ice received over long duration are coherently averaged to decorrelate return signals from distributed targets – Gives an estimate of coherent noise present
  - Coherent noise estimate is subtracted from return signal

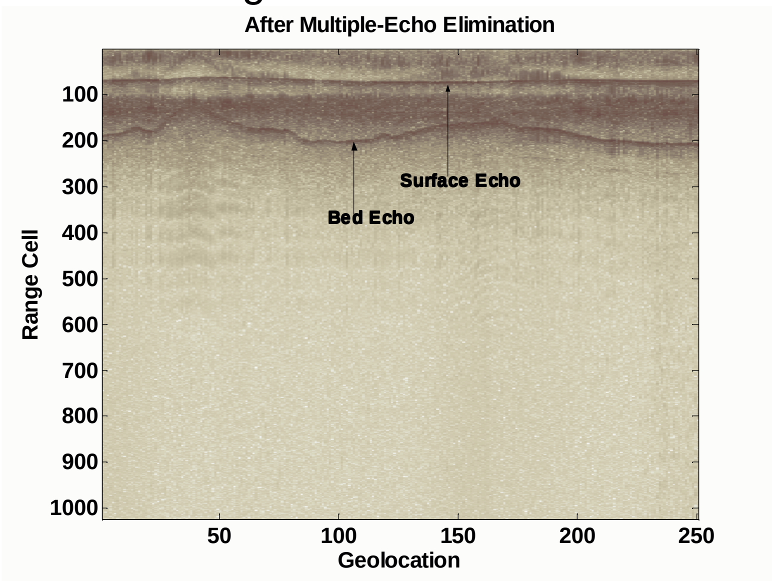




Signal Processing (Contd.)

- Multiple – Echo Cancellation
  - Multipath involving ice-surface return and chassis of the aircraft
  - Critical when depth of ice sheet is same as aircraft height – Multiple masks the return from the bedrock
  - To eliminate multiple echo –
    - Phase and amplitude of the multiple echo is determined
    - Multiple echo is synthesized by injecting the phase and amplitude from above to the return from the surface
    - Synthesized multiple is subtracted from actual return signal



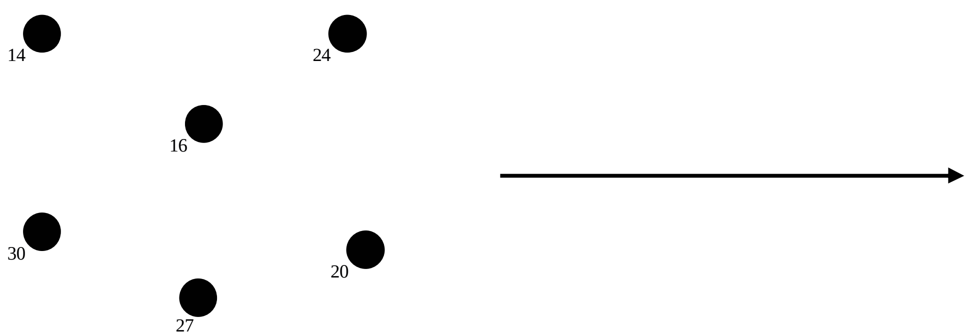


Outline

- Motivation
- Radar Depth Sounder System Description
- Signal Processing
- Data Interpolation
- Implementation on Glacier Data
- Conclusion and Future Work

Data Interpolation

- Purpose
  - Practical limitations on the experiment set up to sample every location in the study area
  - Dispersed sample points have to be generated into surfaces of continuous data before they can be visualized
- Solution
  - Interpolation – Prediction of unknown values using the measured values
  - Creates a raster of the attribute that is being modeled from limited number of samples



14	17	20	23
13	16	19	24
30	23	18	20
28	27	25	19

Data Interpolation (contd.)

- Interpolation
  - Assumes spatial correlation between input points
  - Predicted value is estimated as weighted mean of input values
  - Types
    - Deterministic – Input points weighted depending upon their distance from prediction location
    - Geostatistical – Input points weighted depending upon their distance from prediction location and statistical relationship between input and prediction location
  - Thickness measure of outlet glaciers exhibit spatial relationship
  - Thickness data modeled using a geostatistical interpolation technique – Kriging

Kriging

- Kriging Interpolator

$$\hat{Z}(s_0) = \sum_{i=1}^{N} \lambda_i Z(s_i)$$

where $Z(s_i)$ is measured value at the i^{th} location

λ_i is the unknown weight for the measured value

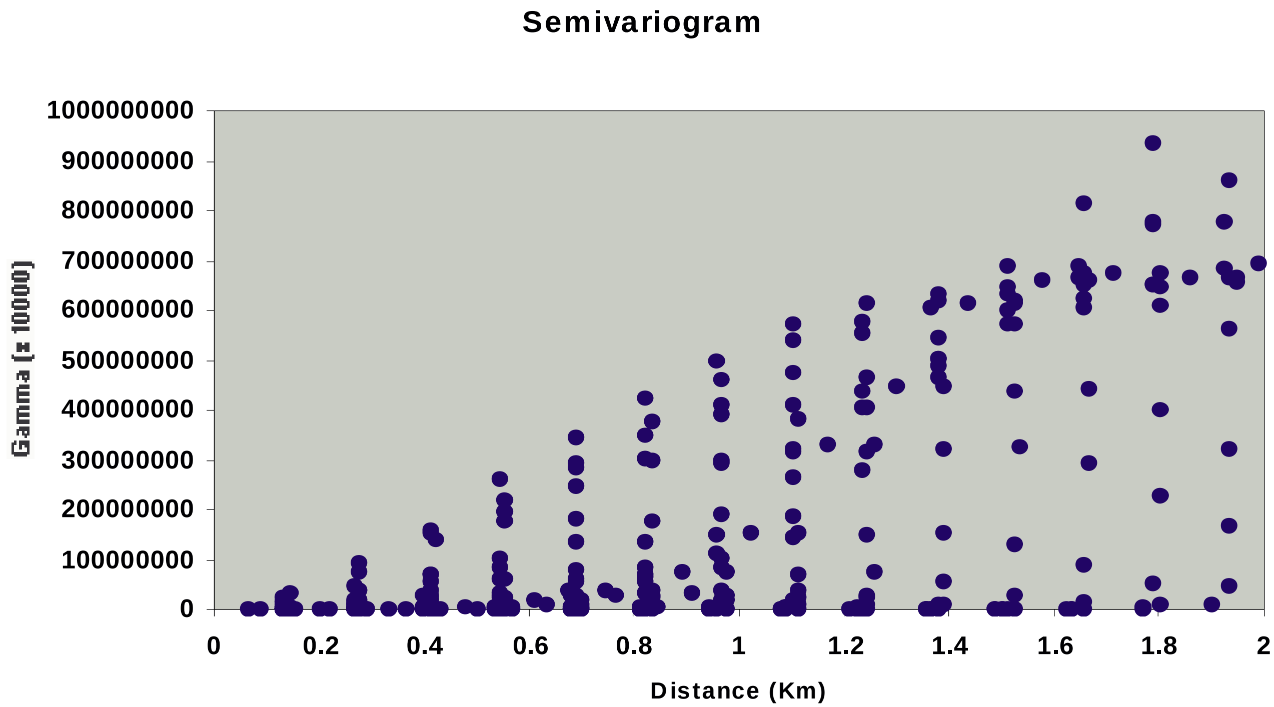
s_0 is the prediction location

N is the number of measured values

- Weight λ_i depends on a model fitted to the measured samples, distance of the prediction location from the measured points and spatial relationships among the measured values surrounding the prediction location

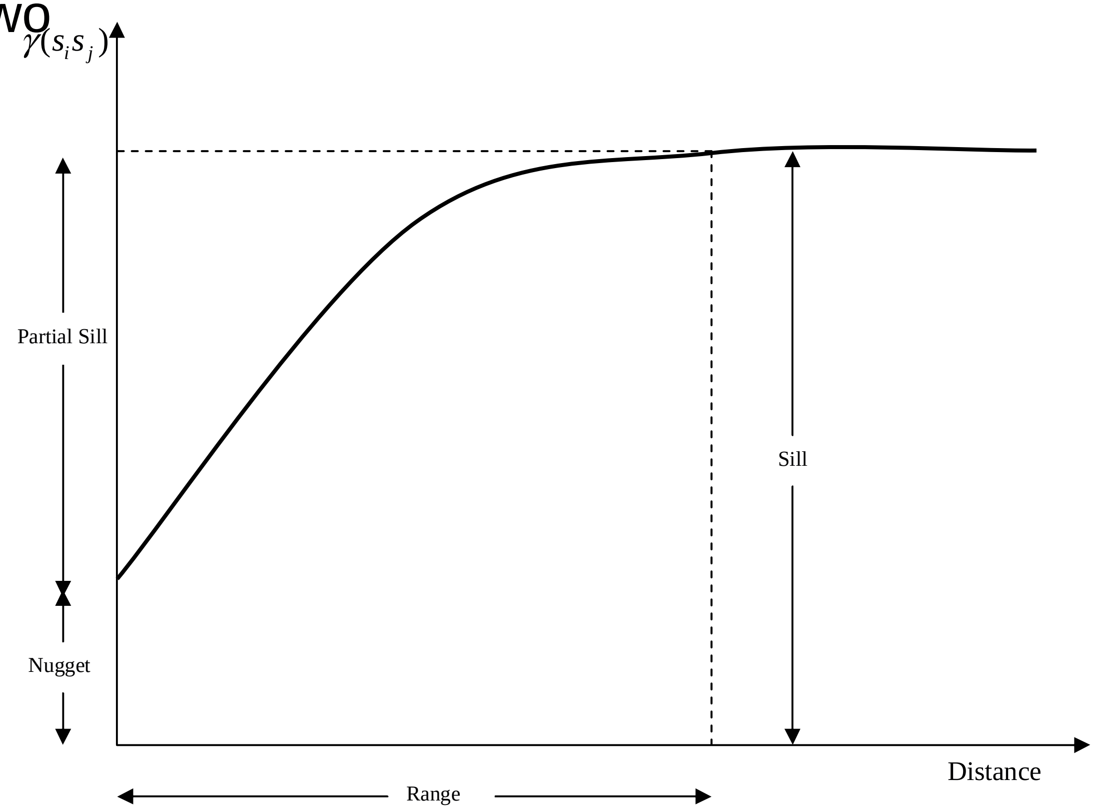
Kriging – Procedure

- Empirical Semivariogram
  - Tool to quantify spatial correlation among the measured values
  - Plot of half the squared difference in thickness between all pairs of sample points (semivariance) against the distance that separates these points



Kriging Procedure (Contd.)

- Fitting a Model to Empirical Semivariogram
  - The points in the empirical Semivariogram are fitted with a least squares fit
  - Range – Distance between two measured samples beyond which they have no spatial relationship
  - Sill – Semivariance at which range is attained
  - Nugget – Semivariance at zero distance of separation
    - Should ideally be zero
    - Error due to spatial variation at distances less than sampling interval



Kriging Procedure (Contd.)

- Validation of the Selected Interpolation Model
  - Creation of Validation Model
    - A "measured" location is "predicted" using the neighboring thickness values on the basis of the designed interpolation model
    - Validation model is created on the basis of these comparisons
  - Quality Metrics for the Interpolation Model
    - Bias – Estimated by Mean Prediction Error (Mean difference between predicted and measured values)
    - Precision – Variability of prediction from true values – Estimated by inverse of standardized root mean square error (standard deviation of prediction)
    - Accuracy – Unbias + Precision
  - The "Ideal" Model …
    - Unbiased – Zero mean prediction error
    - Precise – Standardized root mean square error of unity
    - Accurate – Unbiased and precise

Kriging Procedure (Contd.)

- Creating Weight Matrices
  - Neighboring thickness data points are weighted
  - Number of data points to be included in prediction depends on range of the semivariogram
- Making the Prediction
  - Unknown value is predicted from the weighted known values

Tool Used

- arcGIS – An integrated GIS package
- Interpolated data are "geo-referenced" before display
- arcScene – Interpolated thickness values in raster displayed in a 3D perspective
- 3D view helps in visualization of real-world features of glaciers, actual depth of the bedrock and other artifacts

Outline

- Motivation
- Radar Depth Sounder System Description
- Signal Processing
- Data Interpolation
- Implementation on Glacier Data
- Conclusion and Future Work

Implementation on Outlet Glaciers Data

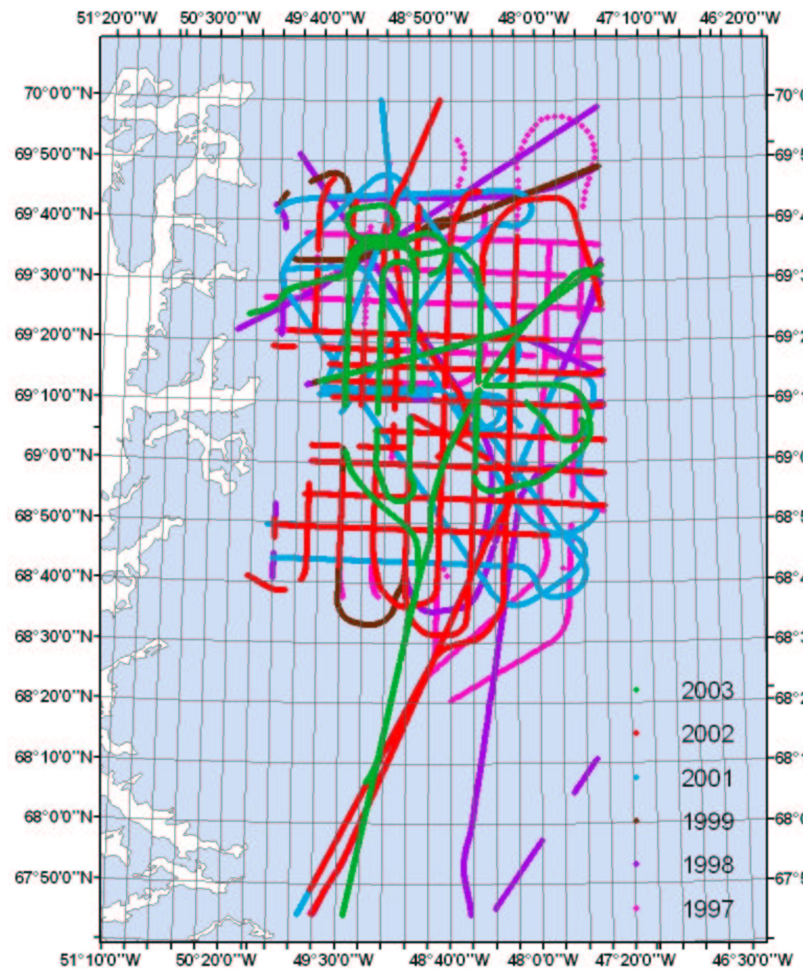
- Radar Depth Sounder Data
  - Thickness data collected over Jakobshavns Isbrae, Petermann and Kangerlussnaq modeled into raster
  - Data collected over six years – includes data from the most recent 2003 field experiment in Greenland using Advanced COherent Radar Depth Sounder
  - Data Filtering
    - Data collected during flight turns – to avoid measurement errors due to aircraft banking

Implementation on Outlet Glaciers Data (contd.)

- Interpolation to Raster Elevation Data
  - Two step process
    - Quantization of spatial correlation in thickness and design of interpolation model based on the estimated statistical dependence
    - Implementation of the designed interpolation model on the measured data after validation
  - Semivariogram of thickness data observed to follow exponential or spherical fit
    - Exponential Fit – Exponential decrease of spatial autocorrelation with distance of separation
    - Spherical Fit – Progressive decrease of spatial autocorrelation with distance of separation
  - Binning the empirical Semivariogram
    - Huge volume of data – Calculation of semivariance becomes complex
    - Data points grouped based on the distance between them – “bin”
    - Semivariance determined for each point in the bin and averaged to obtain semivariance per bin – used to quantify the spatial dependence

Jakobshavns Isbrae

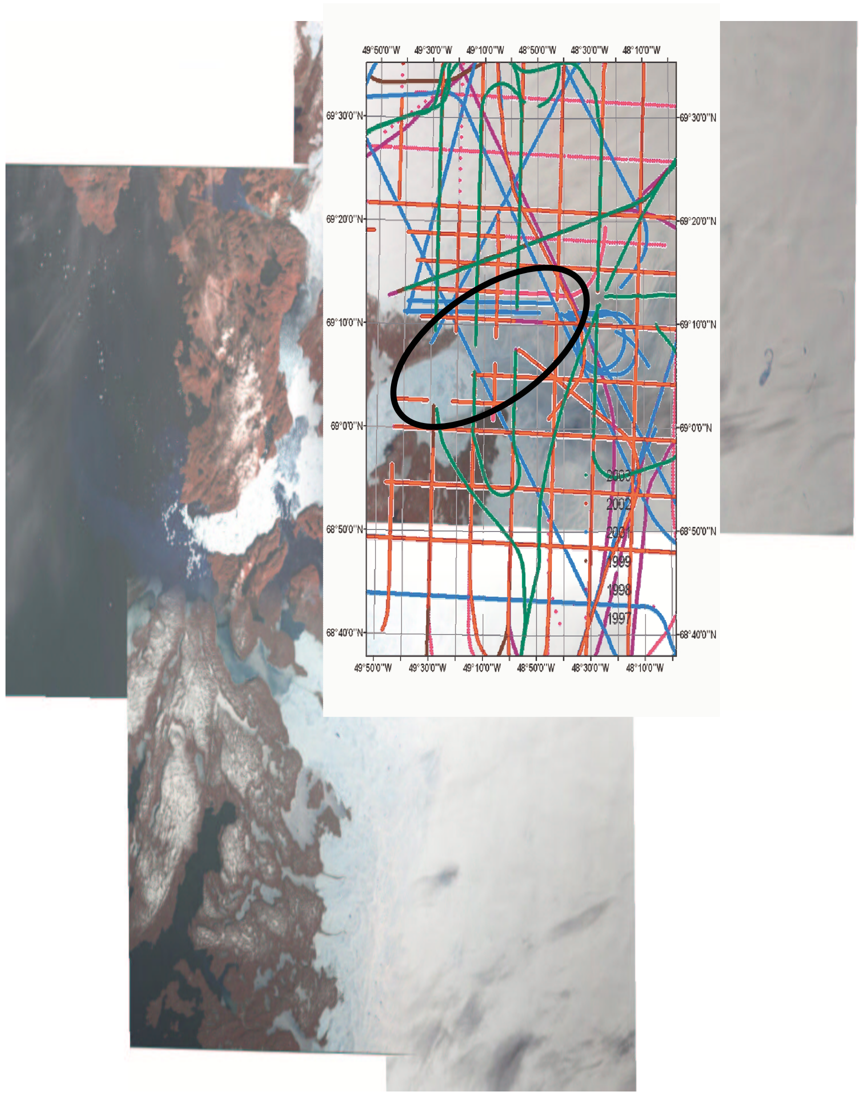
- Largest, fastest moving outlet glacier
- Drains about 6.5% of Greenland Ice sheet
- Attempt to understand the dynamics of the glacier by studying the topography of the bedrock
- Depth Sounder Data from 1997 to 2003
- Gridded Data – 1 km grid
- Average spacing – 130m



Jakobshavn Channel

- Missing basal return at center – strong surface scatter

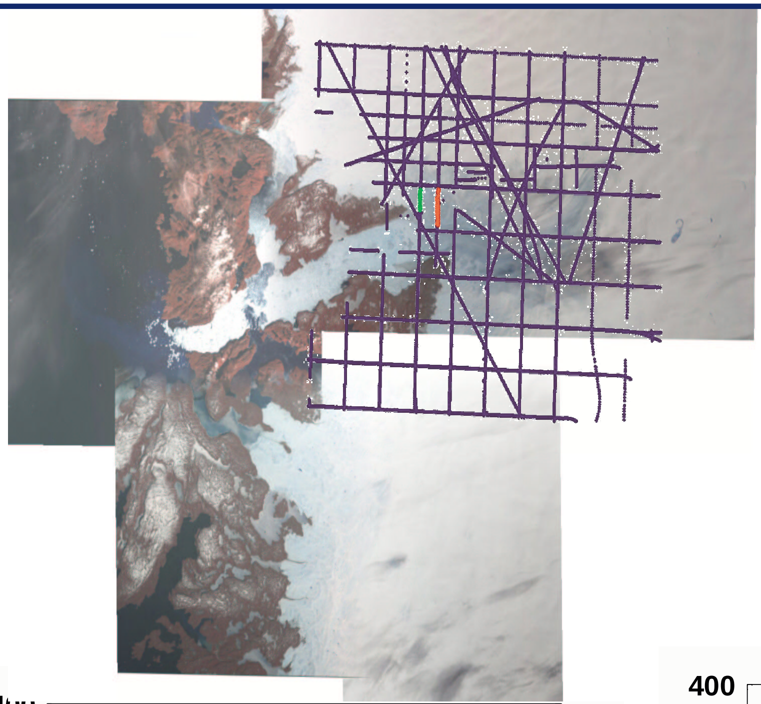
- Evidence from seismic reflections – Depth varies from 2600m to 700m near the calving front.

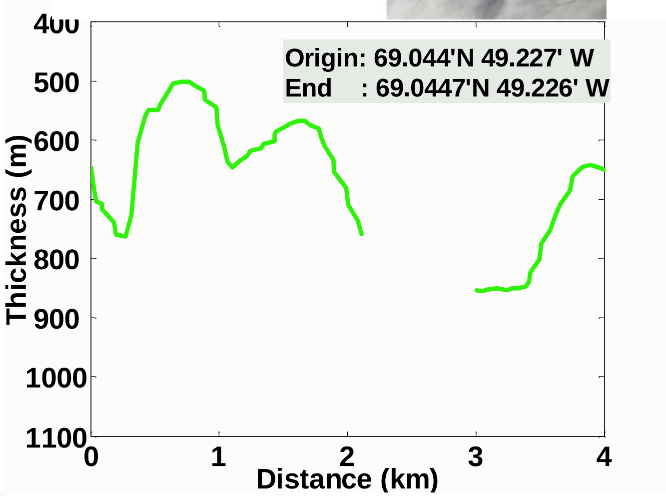


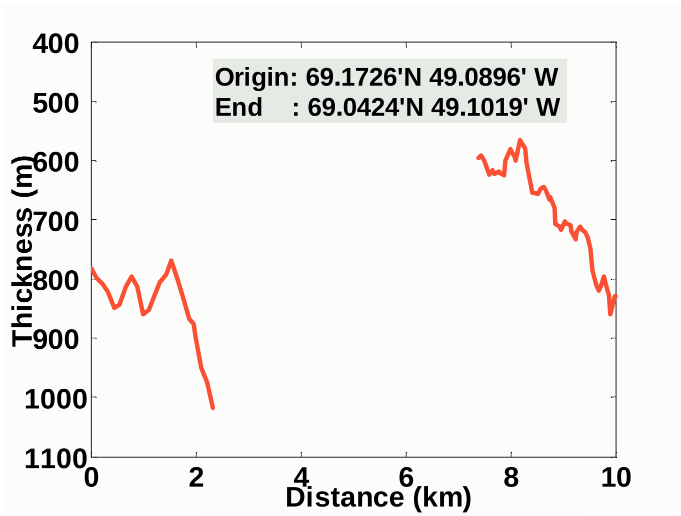
Jakobshavn Channel – Data Synthesis

3D Map of bed terrain using –

- Measured Data – From Depth Sounder
- Seismic Data – From Seismic Soundings
- Synthetic Data
- “Dummy” Data Points





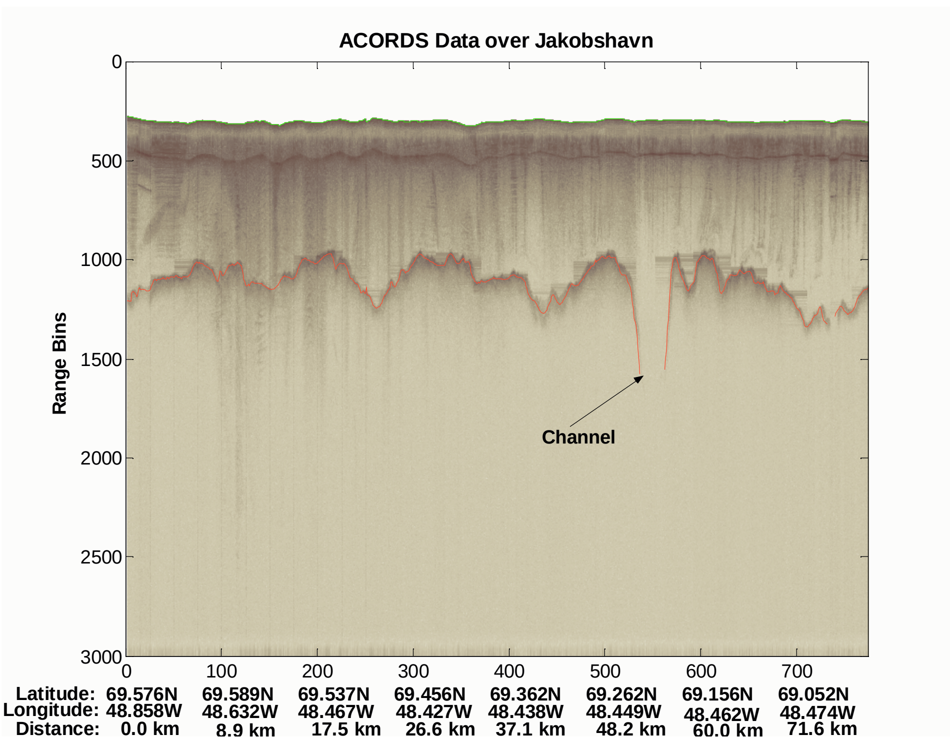


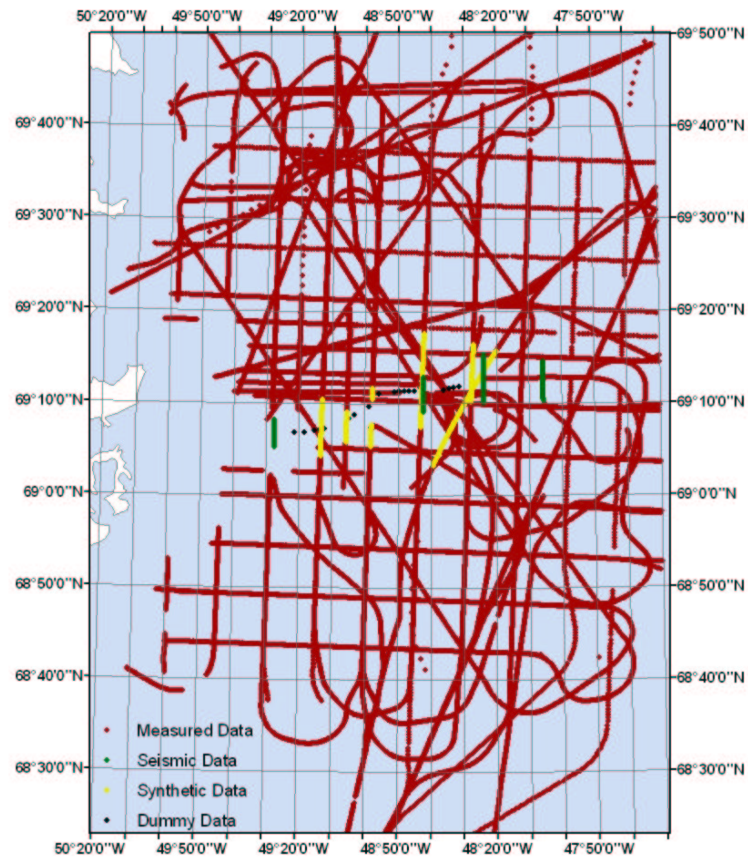
Information and Telecommunication Technology Center

University of Kansas

Jakobshavn Channel – Data Synthesis (Contd.)

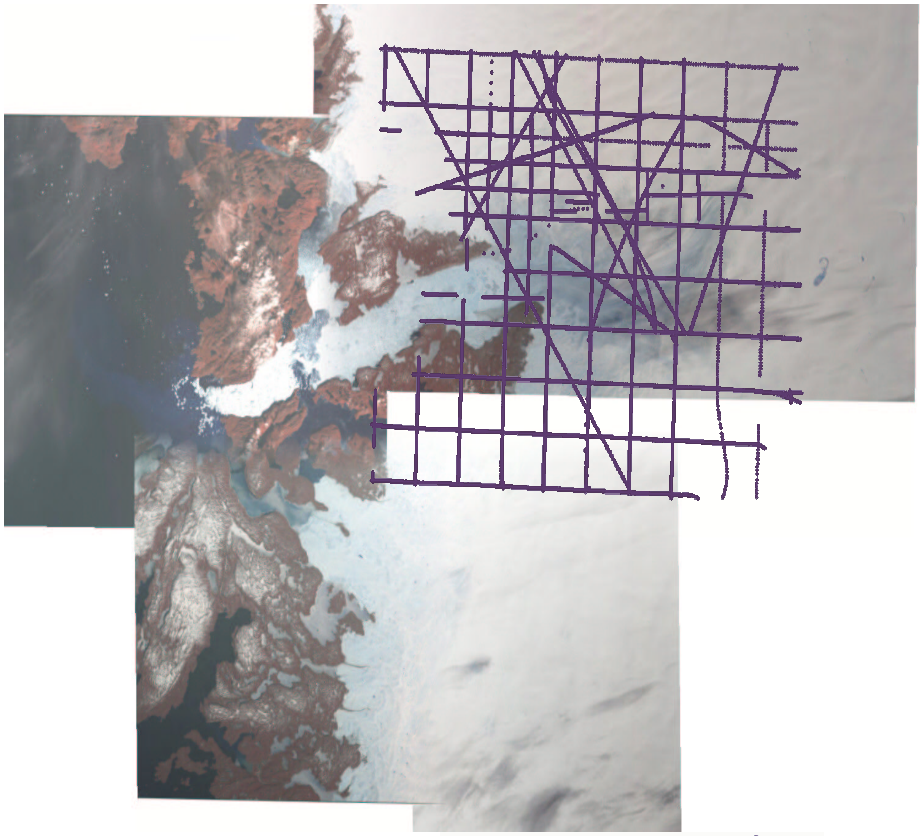
- Synthetic Data – Data synthesized from the depth sounder data across the channel using channel depth information from seismic soundings





Jakobshavn Channel – Data Synthesis (Contd.)

- "Dummy" Data Points – Thickness data points along the channel
  - Thickness information conforming to the seismic sounding data
  - Number of points kept to the minimum
  - A more "true" interpolation of the channel topography in areas that lack data

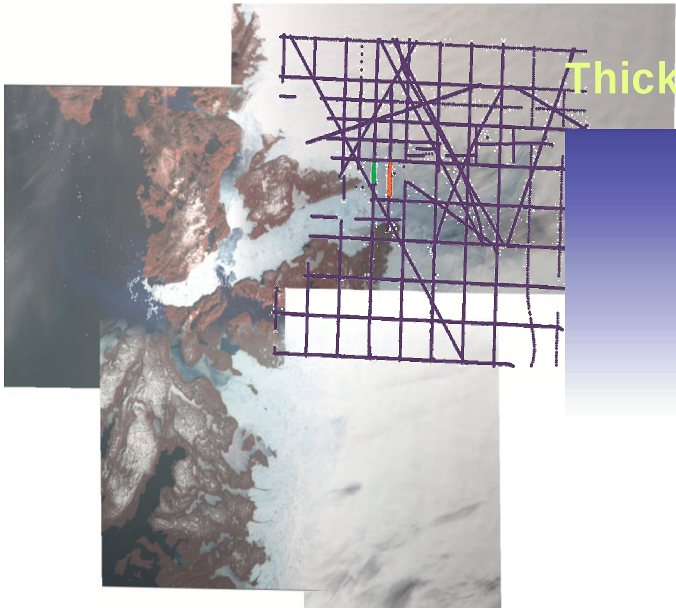


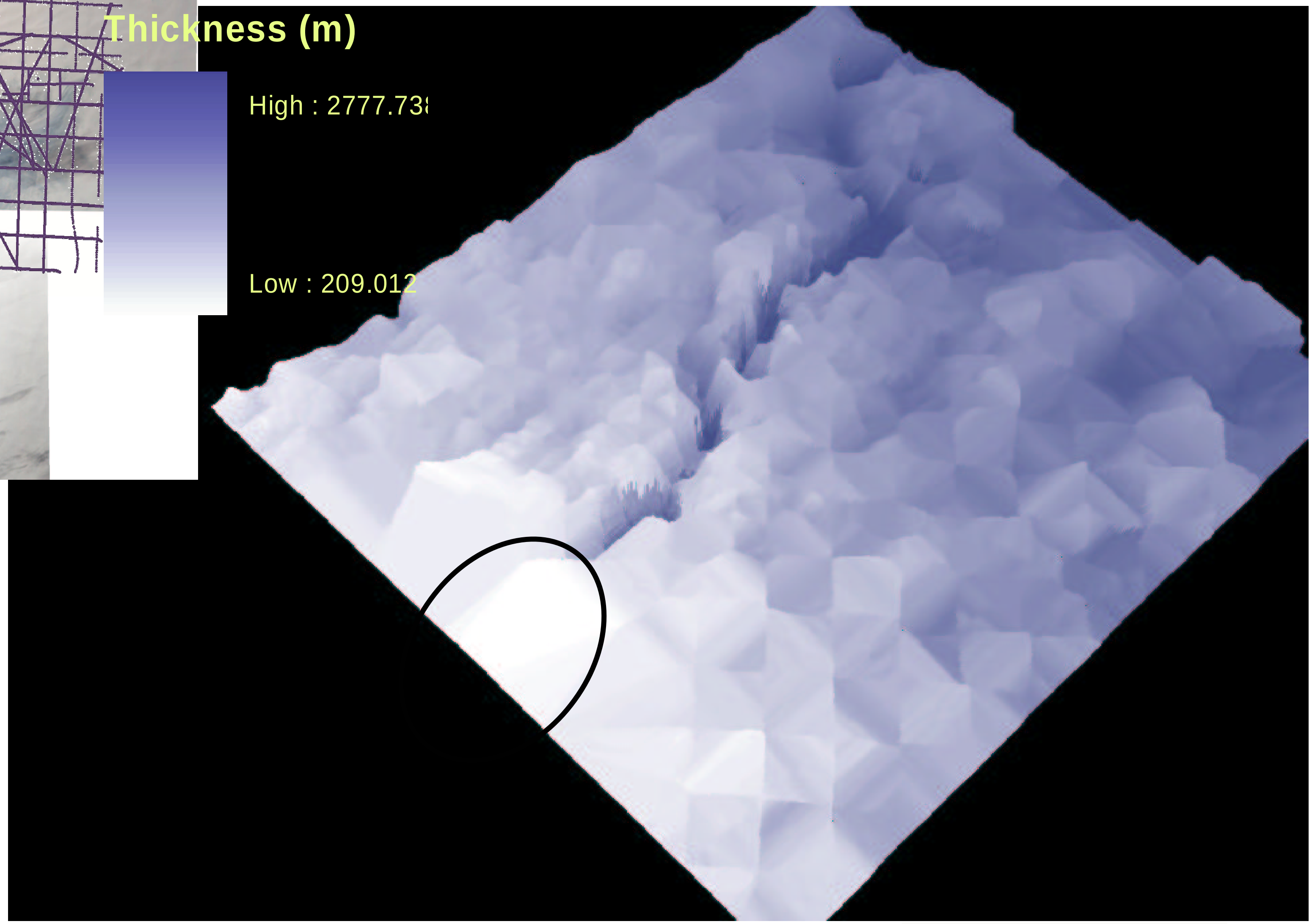
- Measured and synthesized data are integrated and interpolated to continuous surface

Jakobshavn – Kriging Design

- Quantifying the spatial dependency – Least squares fit for the semivariance plot
  - Exponential fit
    - Mean std. Error – 0.0001
    - Std. RMS Error – 0.6708
  - Spherical fit
    - Mean std. Error – -0.00113
    - Std. RMS Error – 0.33
  - Sill – 166 km
  - Cell size – 200 m
  - Design for Channel
    - Exponential
      - Mean std. Error – -0.001
      - Std. RMS Error – 0.9639
    - Sill – 230 km
    - Cell Size – 50m

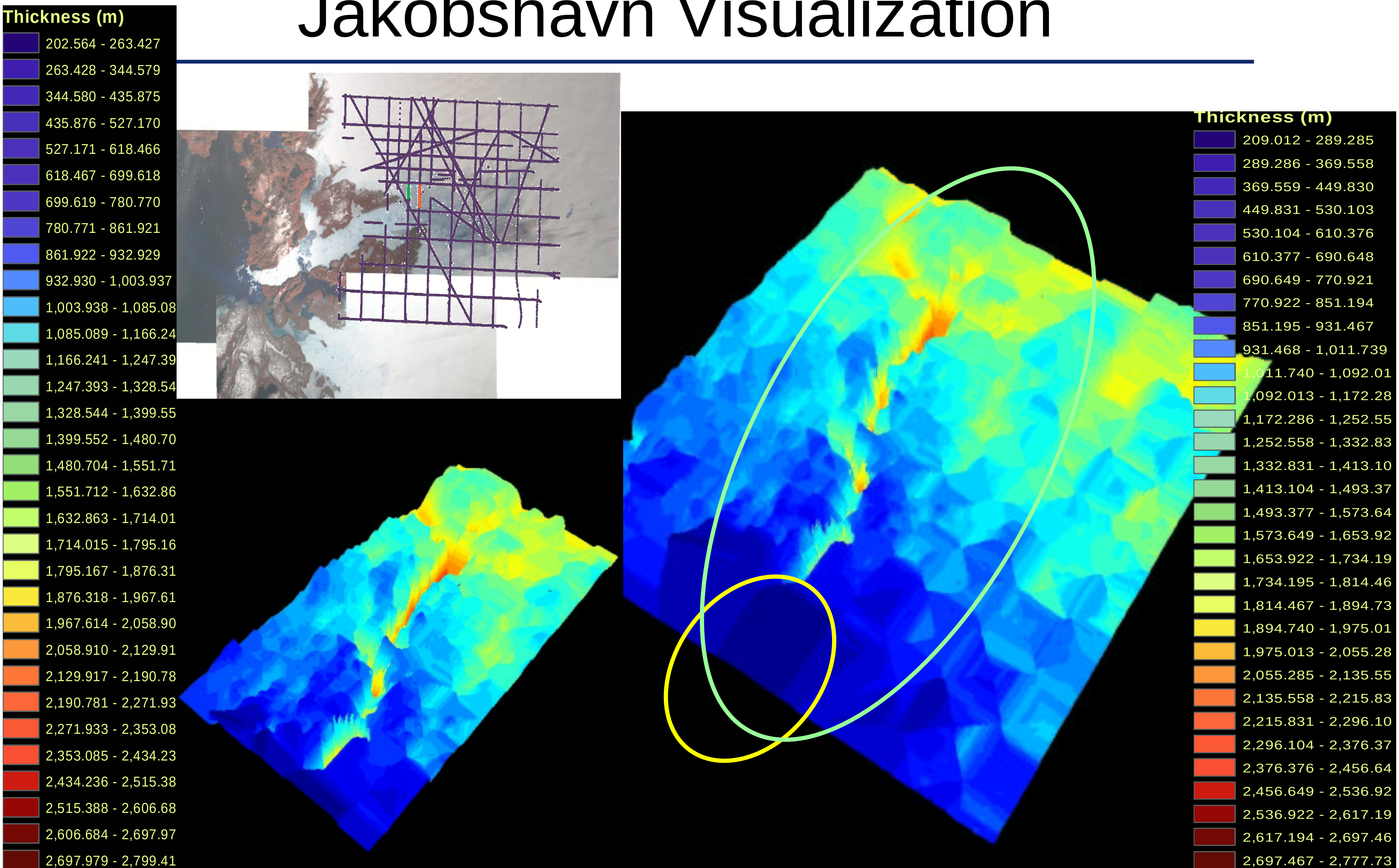
Jakobshavn Visualization





Unreliable interpolation along the channel near the calving front for a width of about 15 km because of absence of thickness data

Jakobshavn Visualization

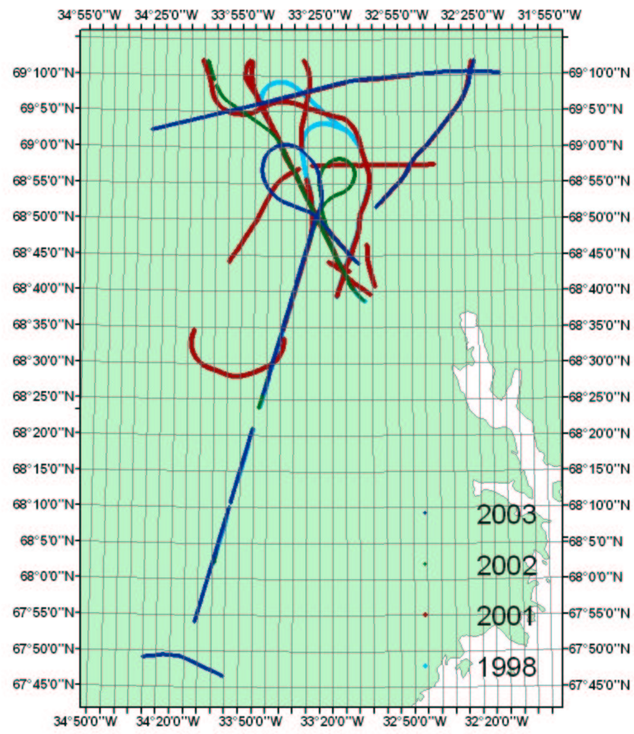


Information and Telecommunication Technology Center

University of Kansas

Kangerlussnaq – Depth Sounder Data

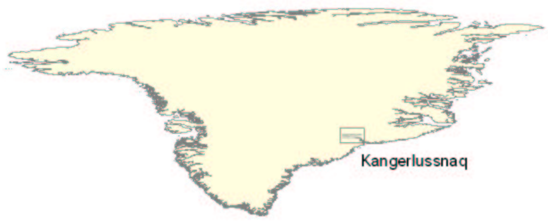
- Depth sounder measurements from 1998 to 2003
- Dense data at the center – More accurate interpolation
- Average spacing between data points is 130m

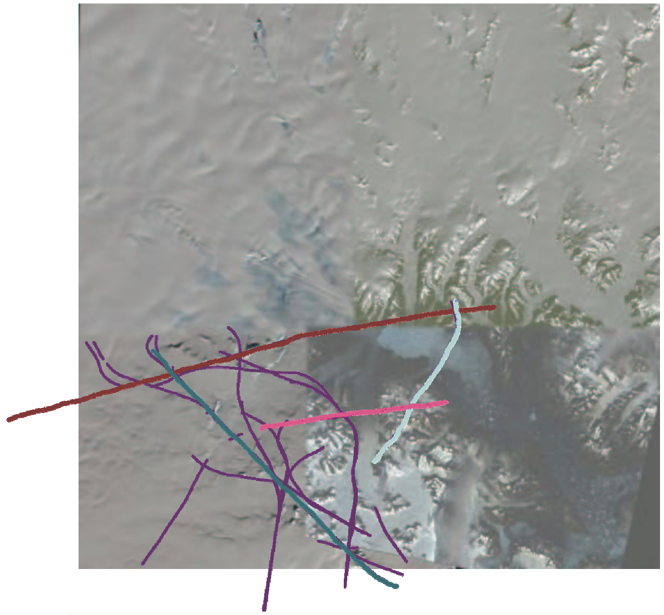


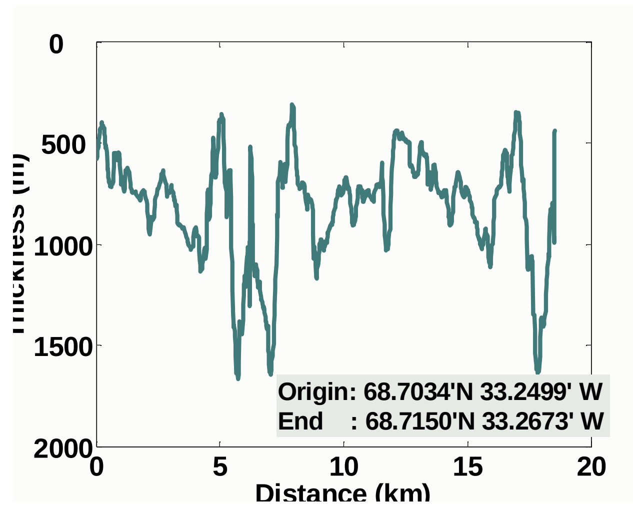
Information and Telecommunication Technology Center

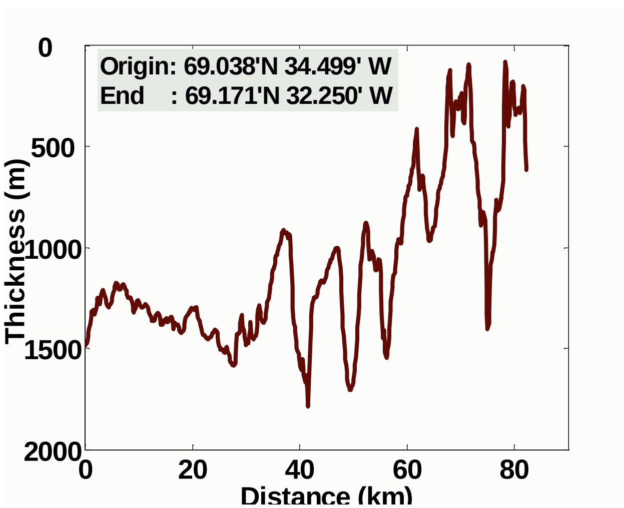
University of Kansas

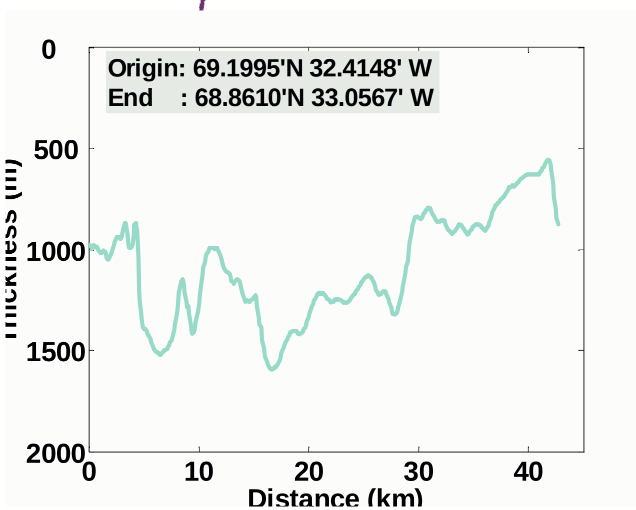
Kangerlussnaq (Contd.)

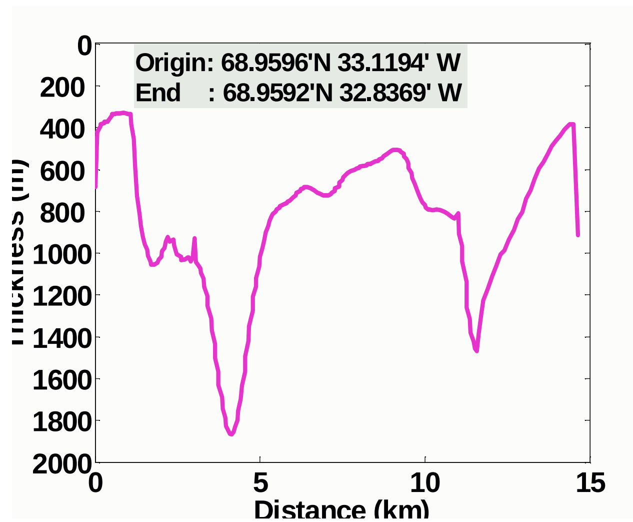












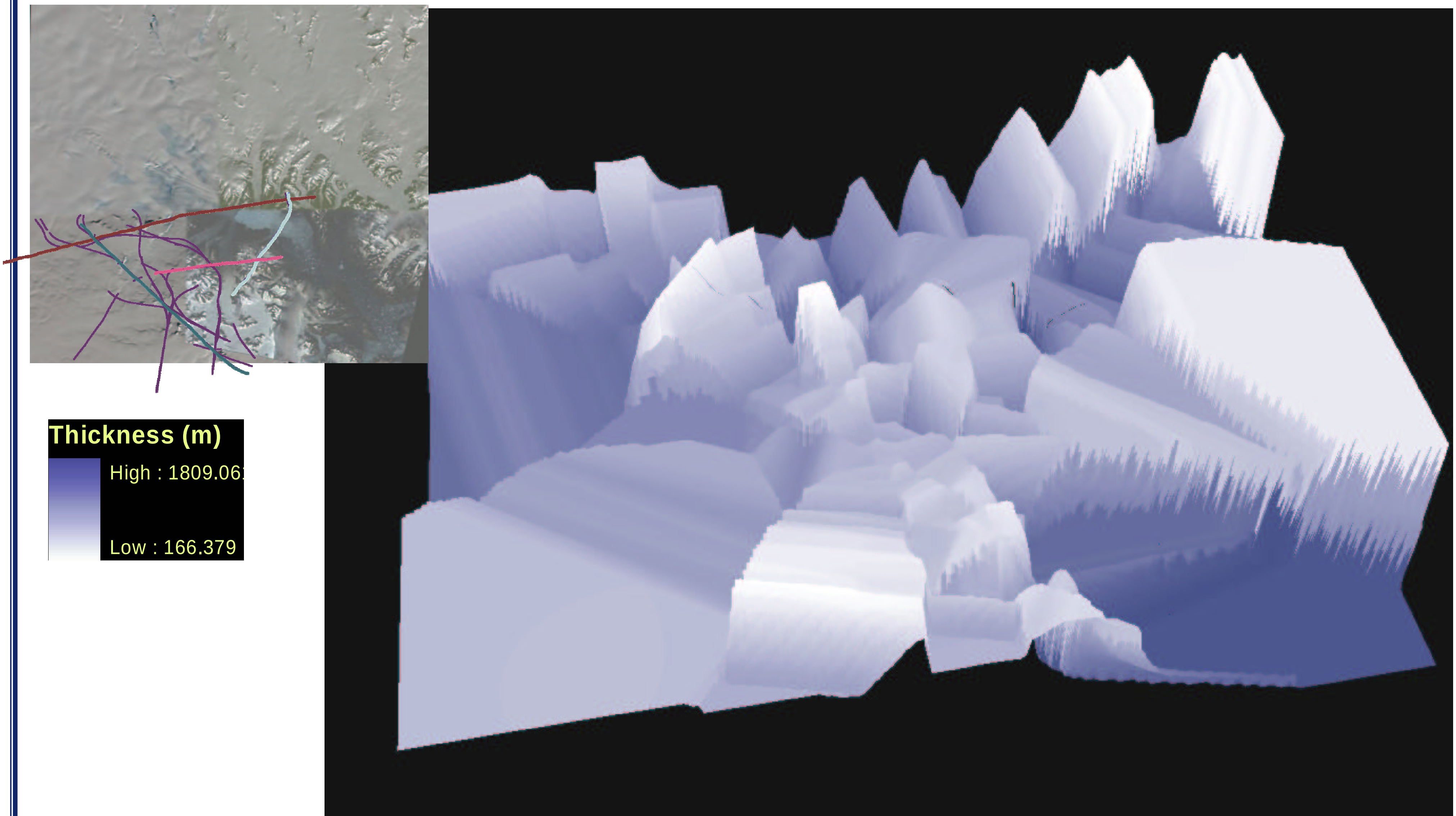
Information and Telecommunication Technology Center

University of Kansas

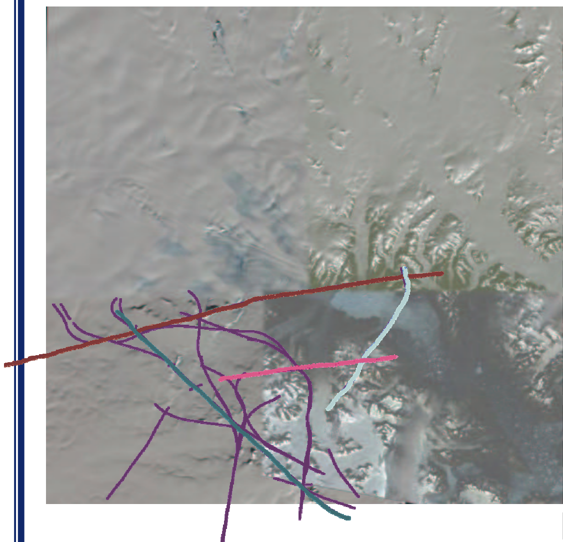
Kangerlussnaq – Kriging Design

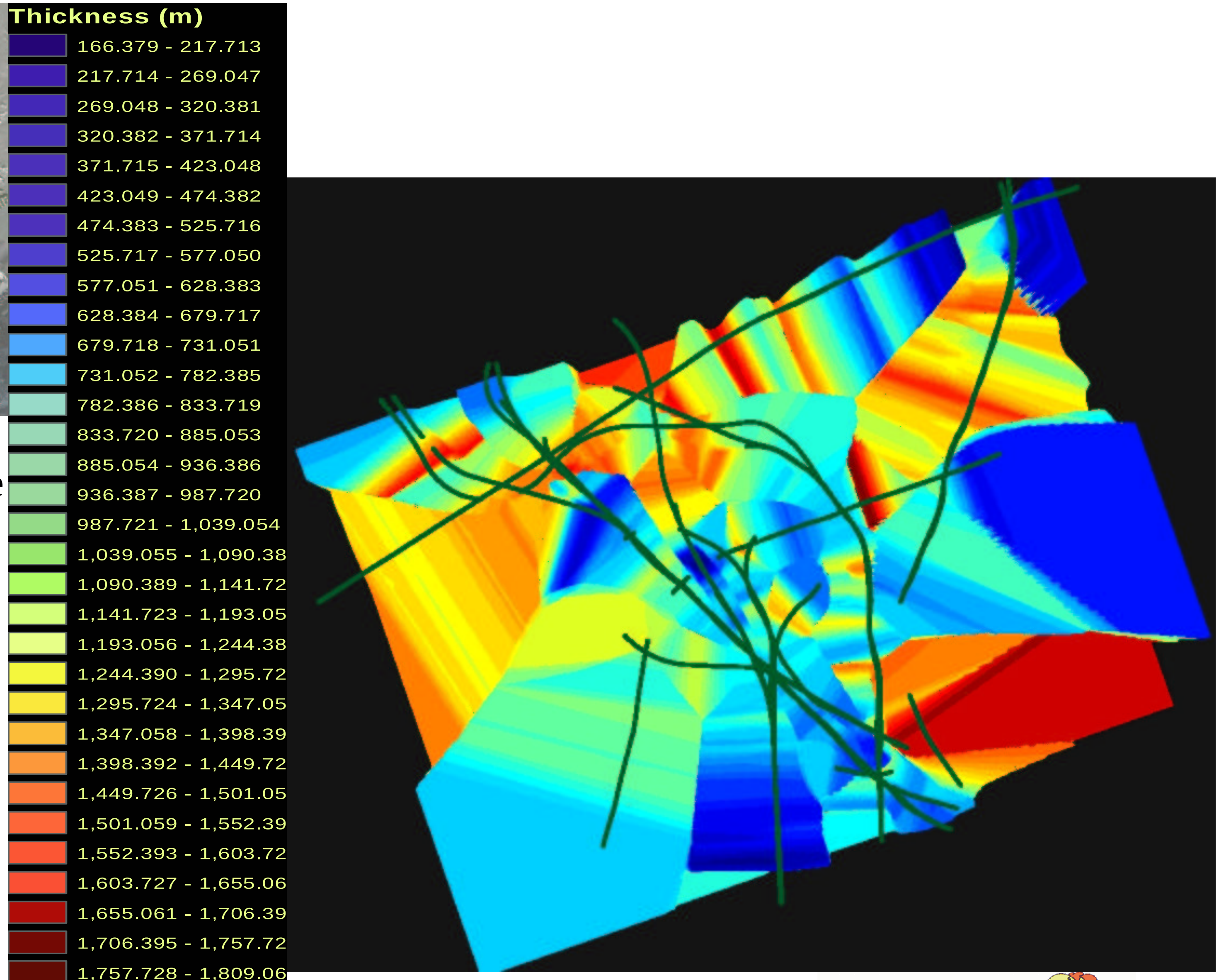
- Quantifying the spatial dependency among thickness values – Least squares fit for Semivariogram
  - Exponential Fit : Mean Std. Error – 0.0004
  - Spherical Fit : Mean Std.Error – 0.003103
- Sill – 158.18km
- Cell Size – 100m
  - Output cell size smaller than input cell size – Finer resolution

Kangerlussnaq – Visualization



Kangerlussnaq – Visualization





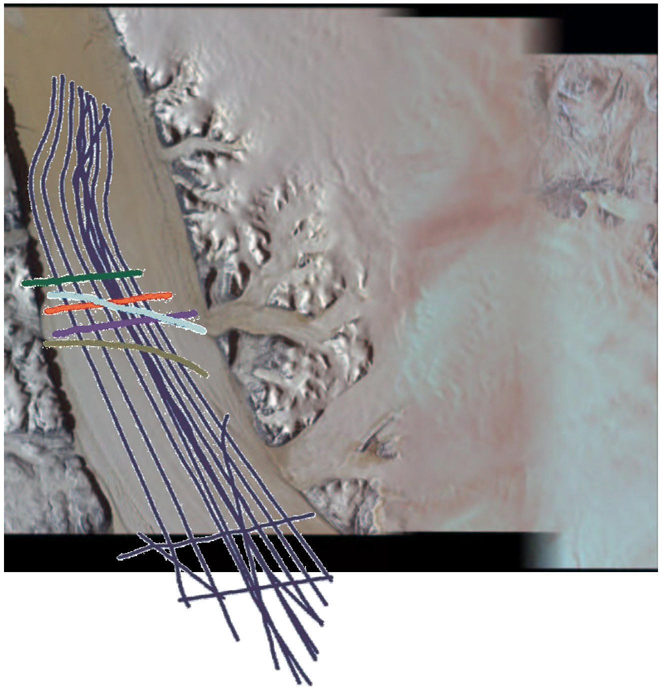
Values at the center of the interpolated image are closer to the true values because of the large volume of input data to interpolate from.

Petermann

- Largest glacier in Northern Greenland

- Depth sounder measurements - 1995 to 2003

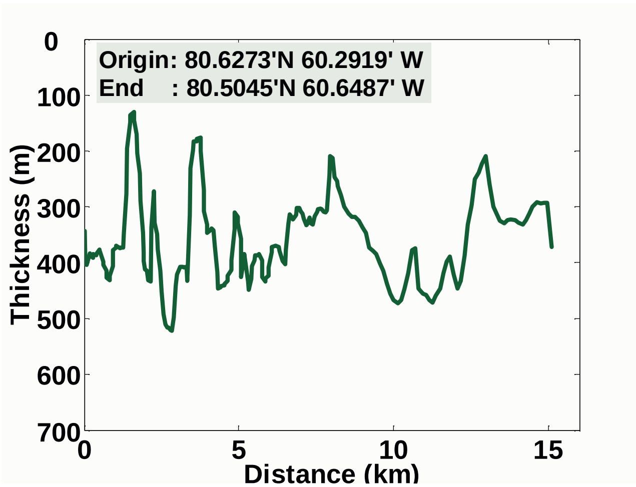
- Distribution of data
  - Bottom of channel – 3.5 km
  - Near the calving front – 1.8 km

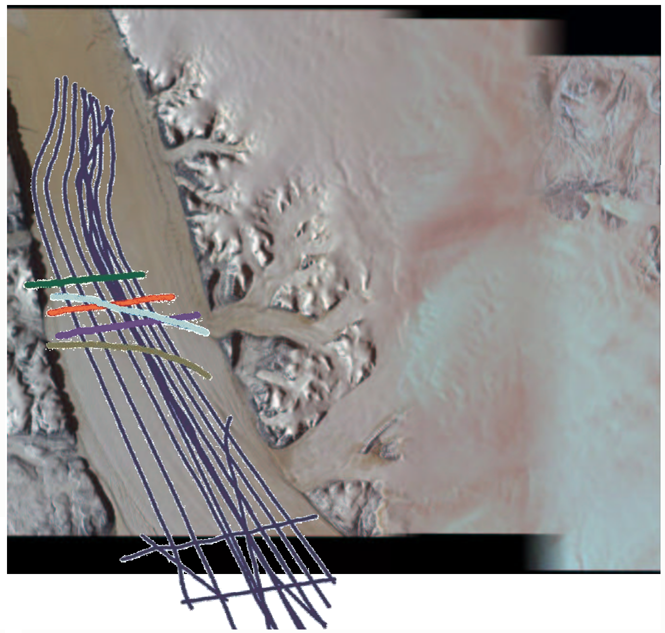


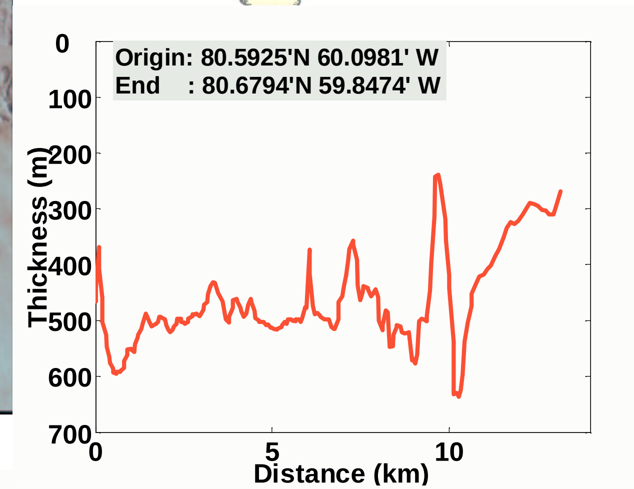
- Crossovers (mostly from 2003 experiment) spaced 5 km apart – used to assess accuracy of data set

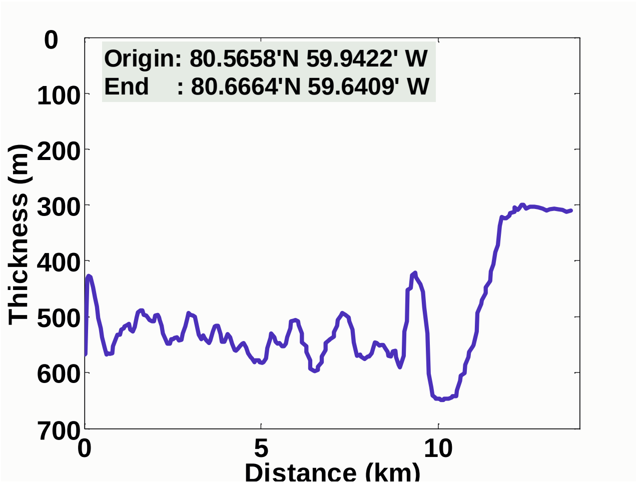
- Erroneous data corrected by crossover analysis

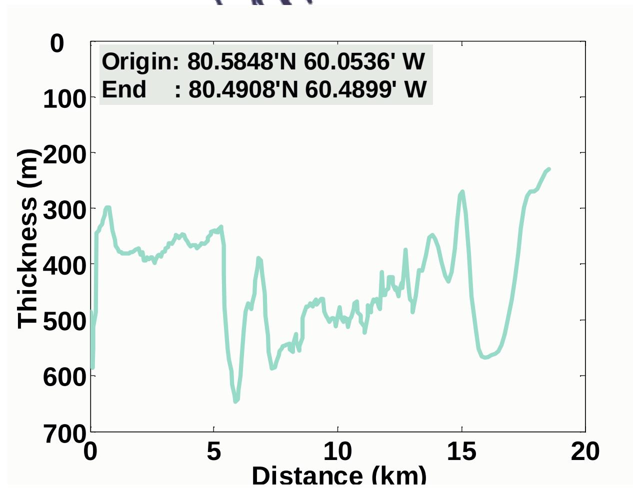
Petermann (Contd.)

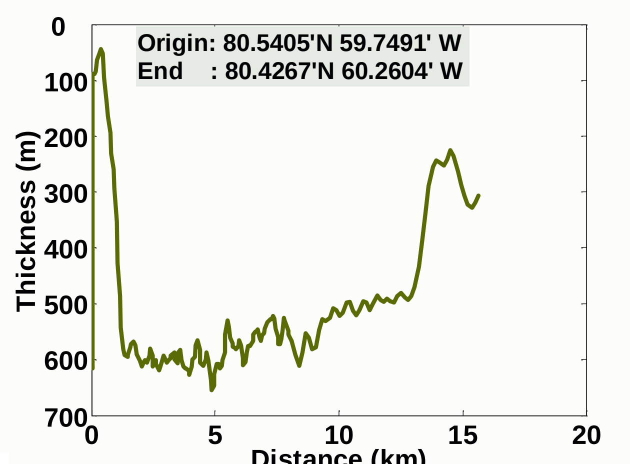












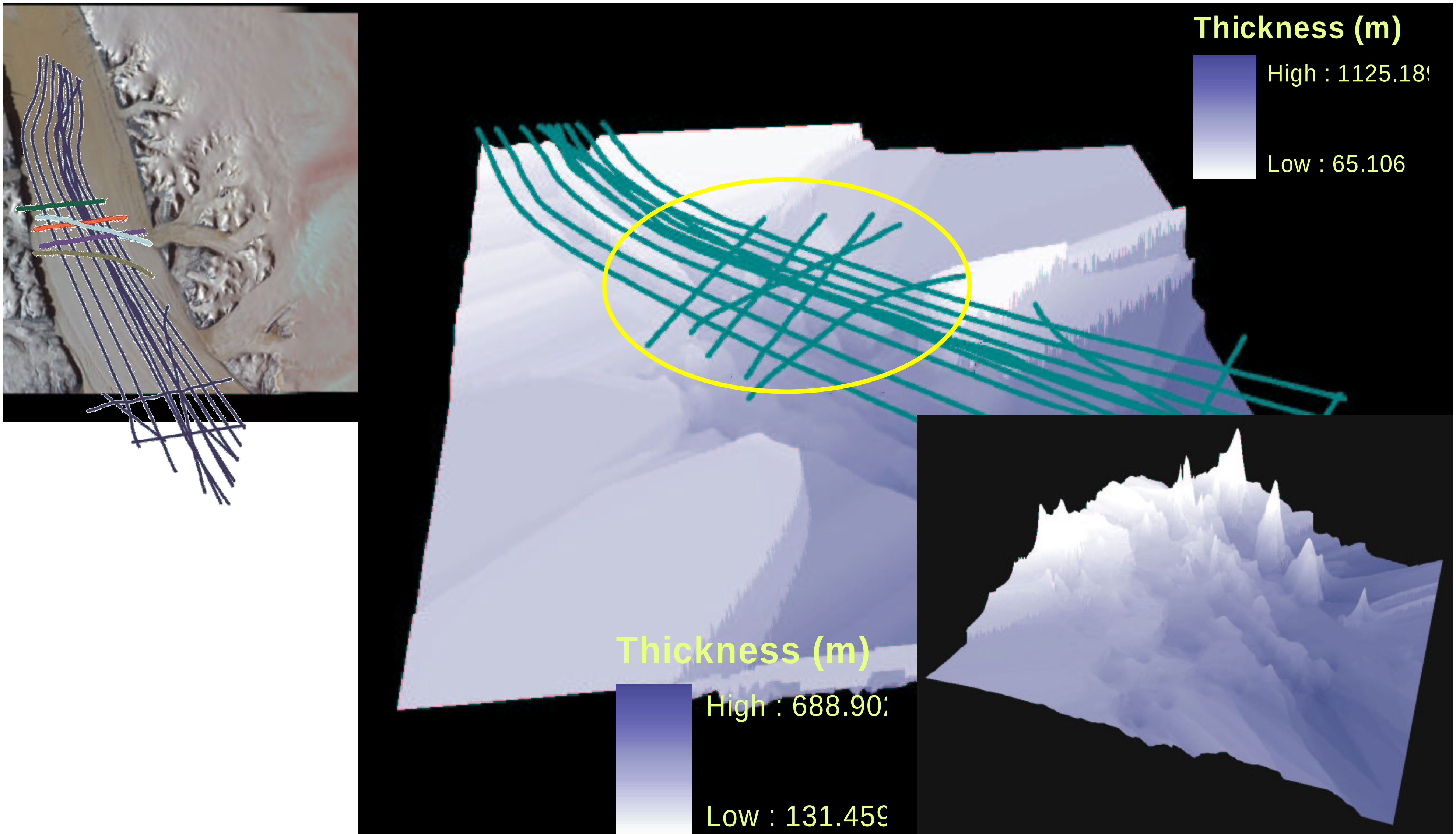
Information and Telecommunication Technology Center

University of Kansas

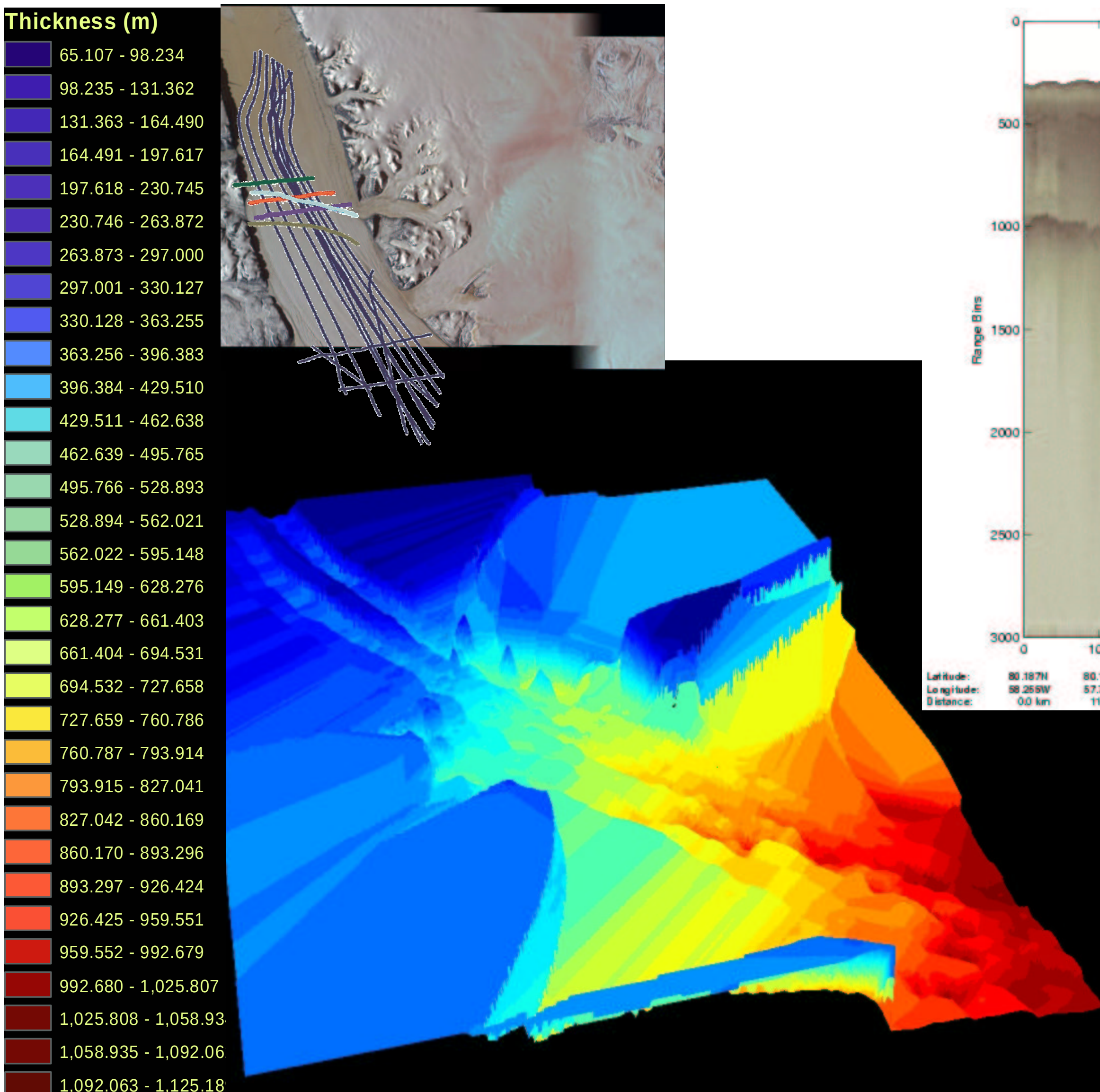
Petermann – Kriging Design

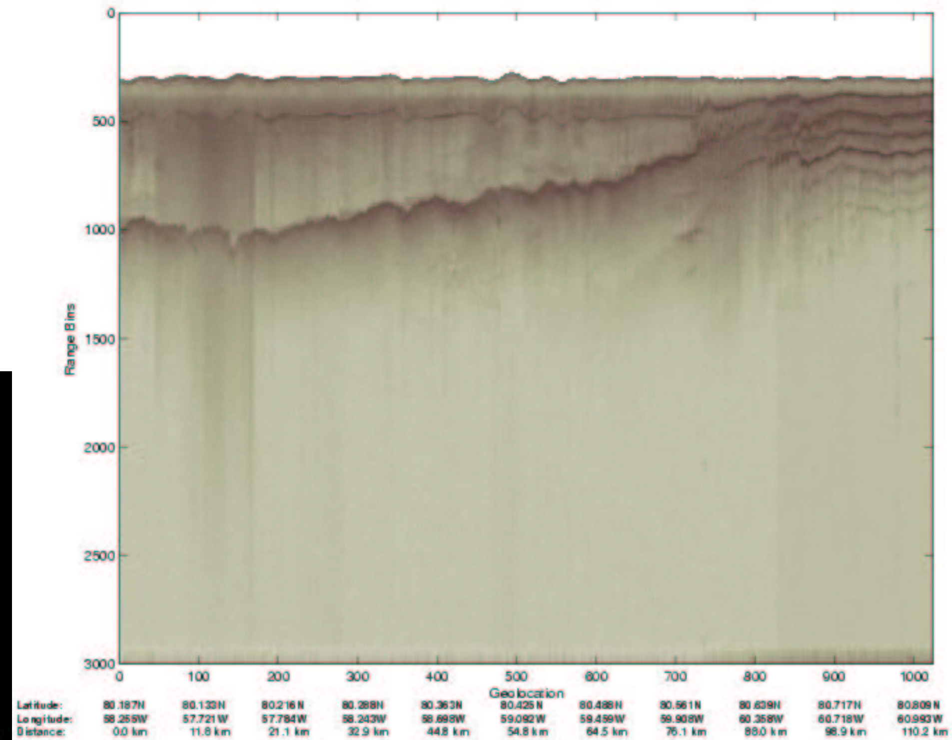
- Quantifying the spatial dependency – Least squares fit for the Semivariogram
  - Almost similar degree of precision for spherical and exponential fits
    - Exponential Fit : Mean Std. Error – 0.007345
    - Spherical Fit : Mean Std. Error – 0.0012
- Sill – 145 km
- Cell size – 100m

Petermann - Visualization



Petermann - Visualization





- Grounding Line – Rapid decrease in thickness from 450m to 60m within 30km along the channel
- Medial moraines along the centerline of the channel near the calving front

Outline

- Motivation
- Radar Depth Sounder System Description
- Signal Processing
- Data Interpolation
- Implementation on Glacier Data
- Conclusion and Future Work

Conclusion

- First Airborne measurements over West Antarctica – Ice thickness measured over 99% of flightlines
- Depth Sounder Data processed for thickness measurement
  - Signal processing techniques applied to improve SNR, reduce coherent noise, enhance spatial resolution
- Thickness data from past 6 years modeled into 3D image of bed terrain – Better understanding of glacial flow and other artifacts
- Digital Thickness Map for bed of Jakobshavns Isbrae, Petermann, Kangerlussnaq

Future Work

- Gridded flightlines for Kangerlussnaq , denser spacing of 1 km
- Measurement over Petermann, near the calving front – Better understanding floating tongue
- DEM for surface combined with the generated digital thickness grid for bed – bed elevation grid for outlet glaciers

Thank You

Information and
Telecommunication
Technology Center

University of Kansas