Ice sheet mass balance from satellite altimetry

Kate Briggs (Mal McMillan)

Outline

- Background
- Recap - 25 year altimetry record
- Recap - Measuring surface elevation with altimetry
- Measuring surface elevation change
- Determining ice sheet mass changes
- Sources of uncertainty

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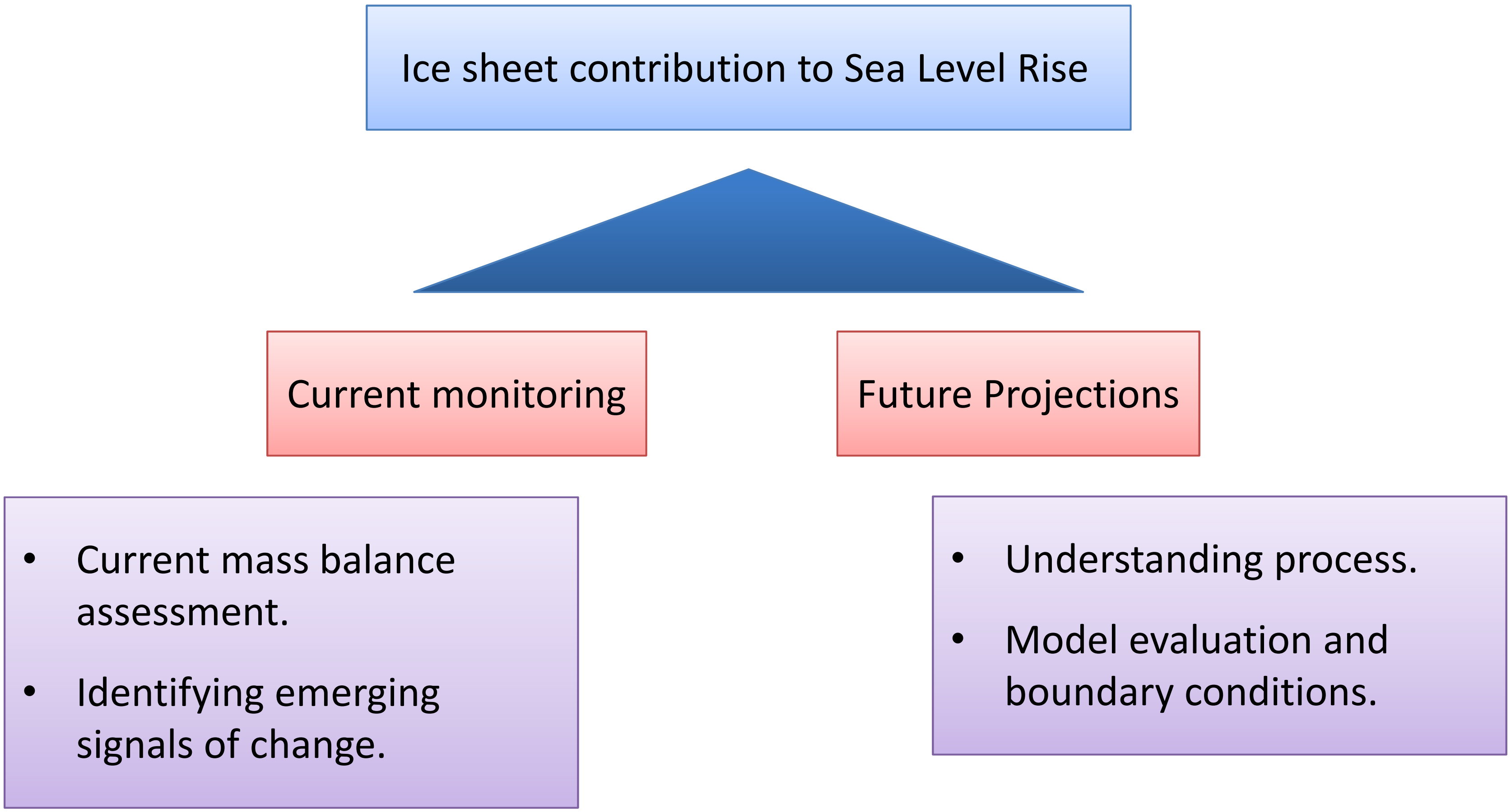
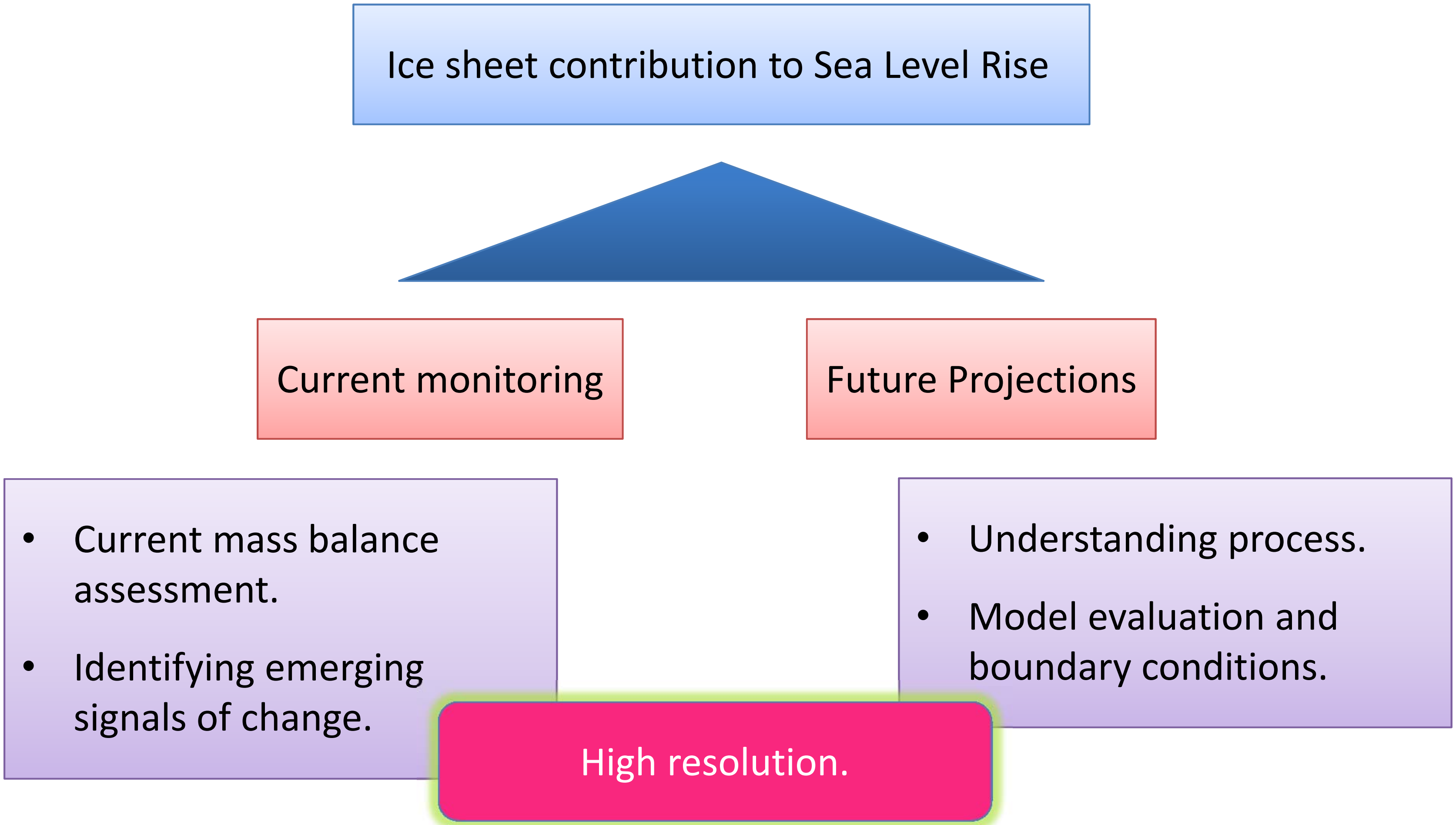
- Recap- 25 year altimetry record
- Recap - Measuring surface elevation with altimetry
- Measuring surface elevation change
- Determining ice sheet mass changes
- Sources of uncertainty
- Current challenges

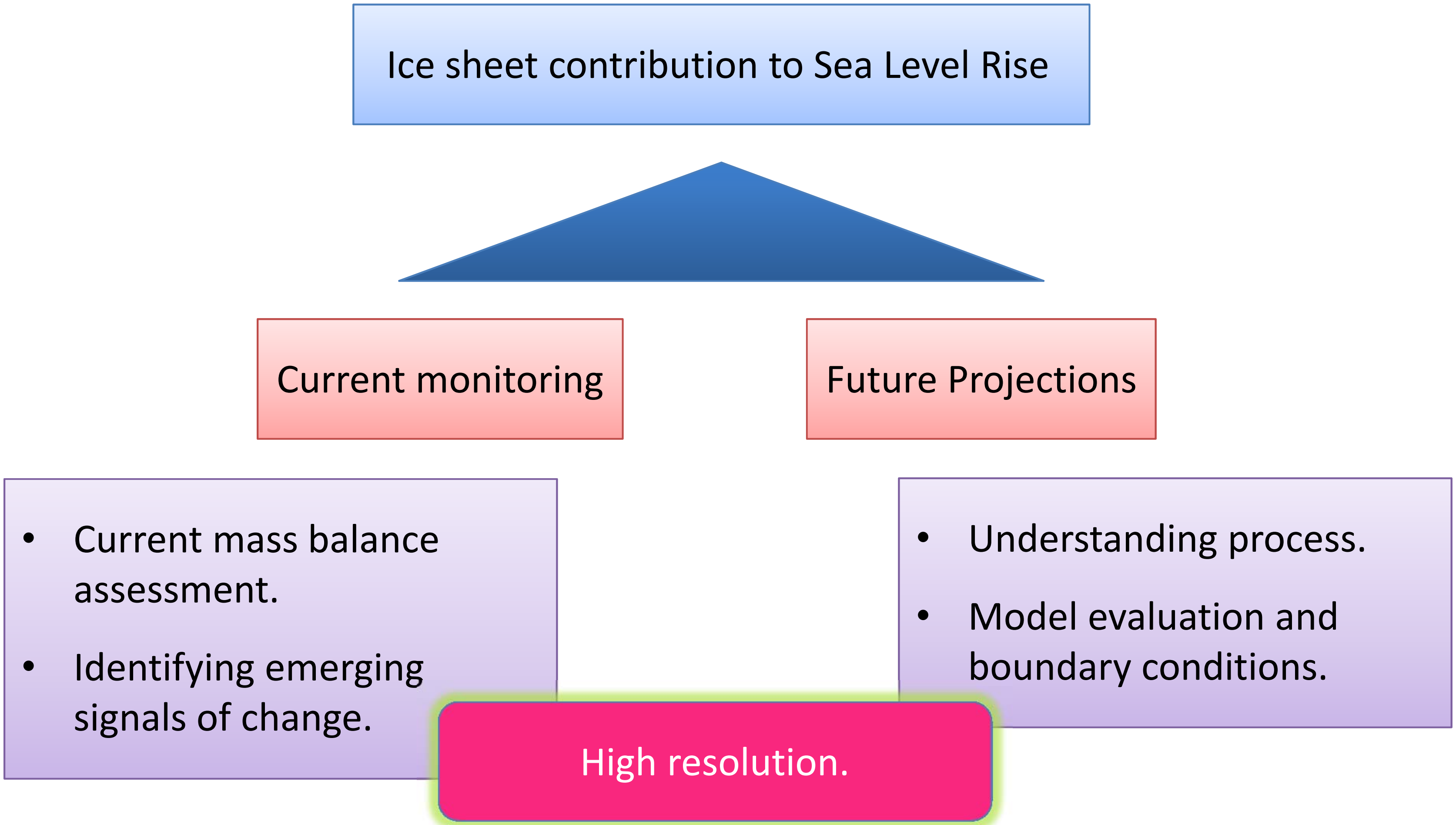
Ice sheet contribution to Sea Level Rise


Ice sheet contribution to Sea Level Rise
Current monitoring
Future Projections
• Current mass balance assessment.
• Identifying emerging signals of change.
• Understanding process.
• Model evaluation and boundary conditions.



Aiming to resolve the dominant variability of the ice sheet system:

- **Spatial** – evolution of individual glacier systems.
- **Temporal** – seasonal fluctuations in mass.



Altimetry:

- **Spatial** -- 1 – 10 km.
- **Temporal** -- monthly.

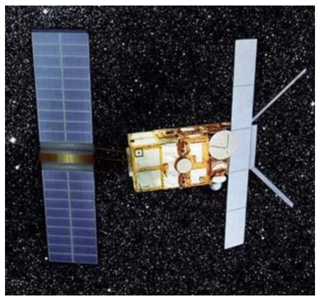
A 25 year record of change

* Focus here on radar altimetry but large overlap with laser altimetry *

Polar orbiting radar altimeter missions

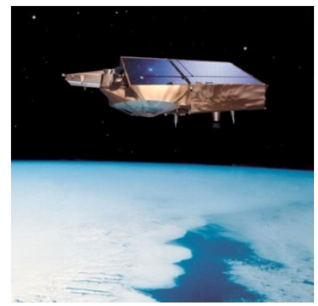
ERS-1

ERS-2

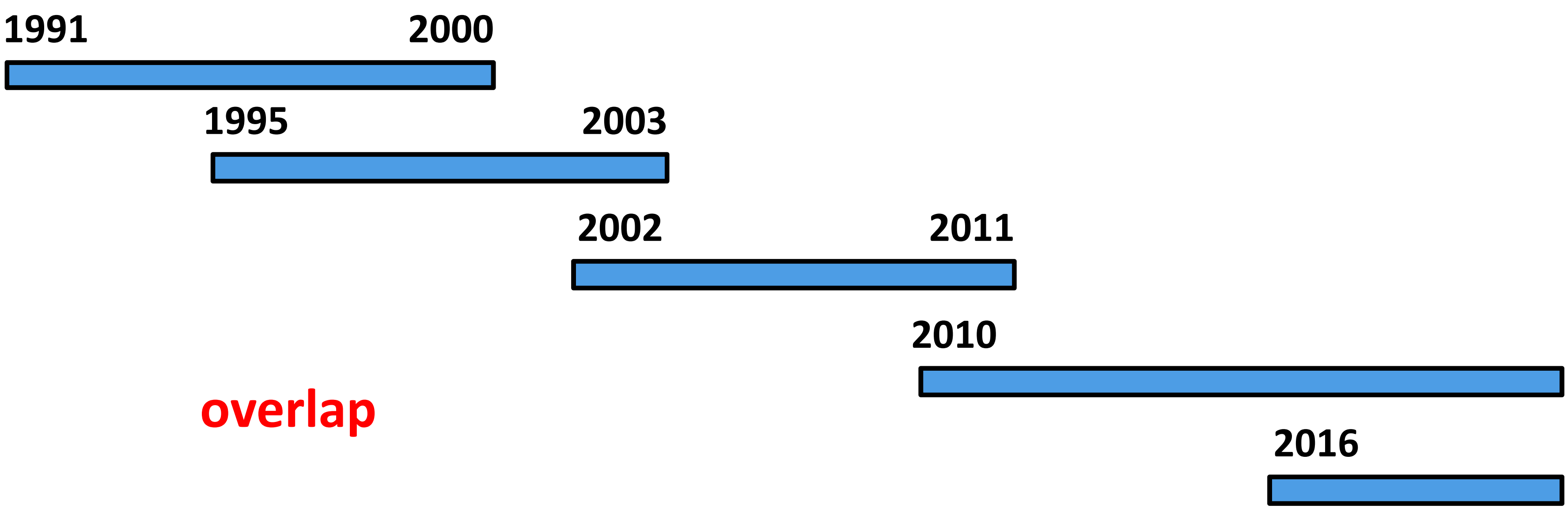


ENVISAT

CryoSat-2



Sentinel-3



Polar orbiting radar altimeter missions

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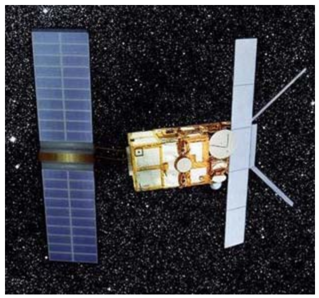

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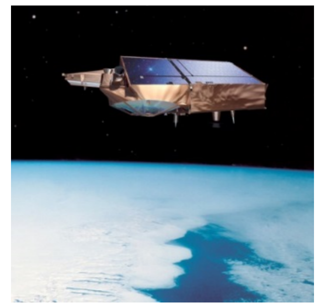


Sentinel-3

Repeat measurement every ~ 35 days

369 day repeat

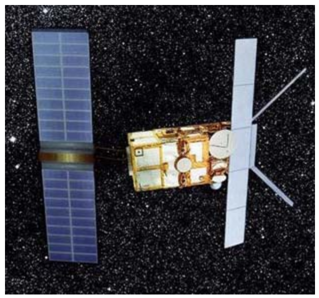
(30 day subcycle)

27 day repeat

Polar orbiting radar altimeter missions

ERS-1

ERS-2



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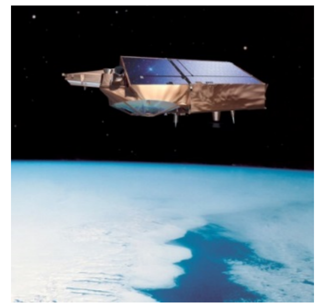
CryoSat-2



Sentinel-3

Repeat measurement every ~ 35 days

369 day repeat

(30 day subcycle)

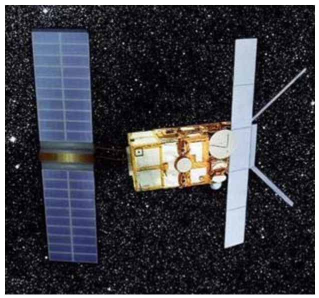
27 day repeat

Regular, near continuous record of surface elevation change

Polar orbiting radar altimeter missions

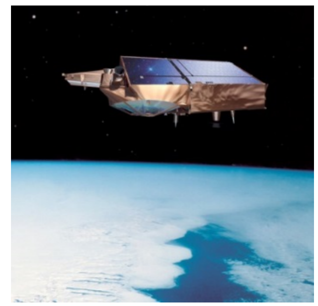
ERS-1

ERS-2



ENVISAT

CryoSat-2



Sentinel-3

Delay-Doppler / SAR processing

Interferometer

Low resolution altimetry

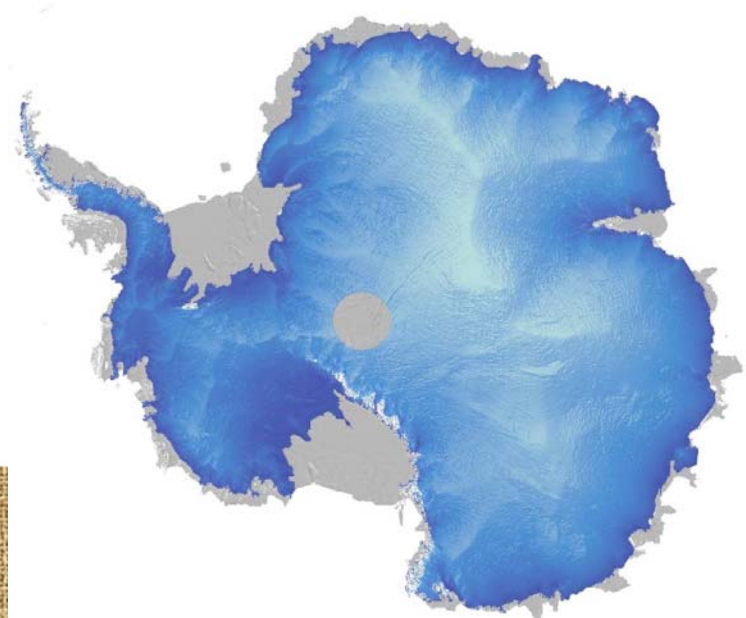
High resolution altimetry

Recap - Measuring surface elevation

Measures time taken for electromagnetic pulse to be reflected back from Earth's surface.

Measures time taken for electromagnetic pulse to be reflected back from Earth’s surface.

Surface elevation of the ice sheet.



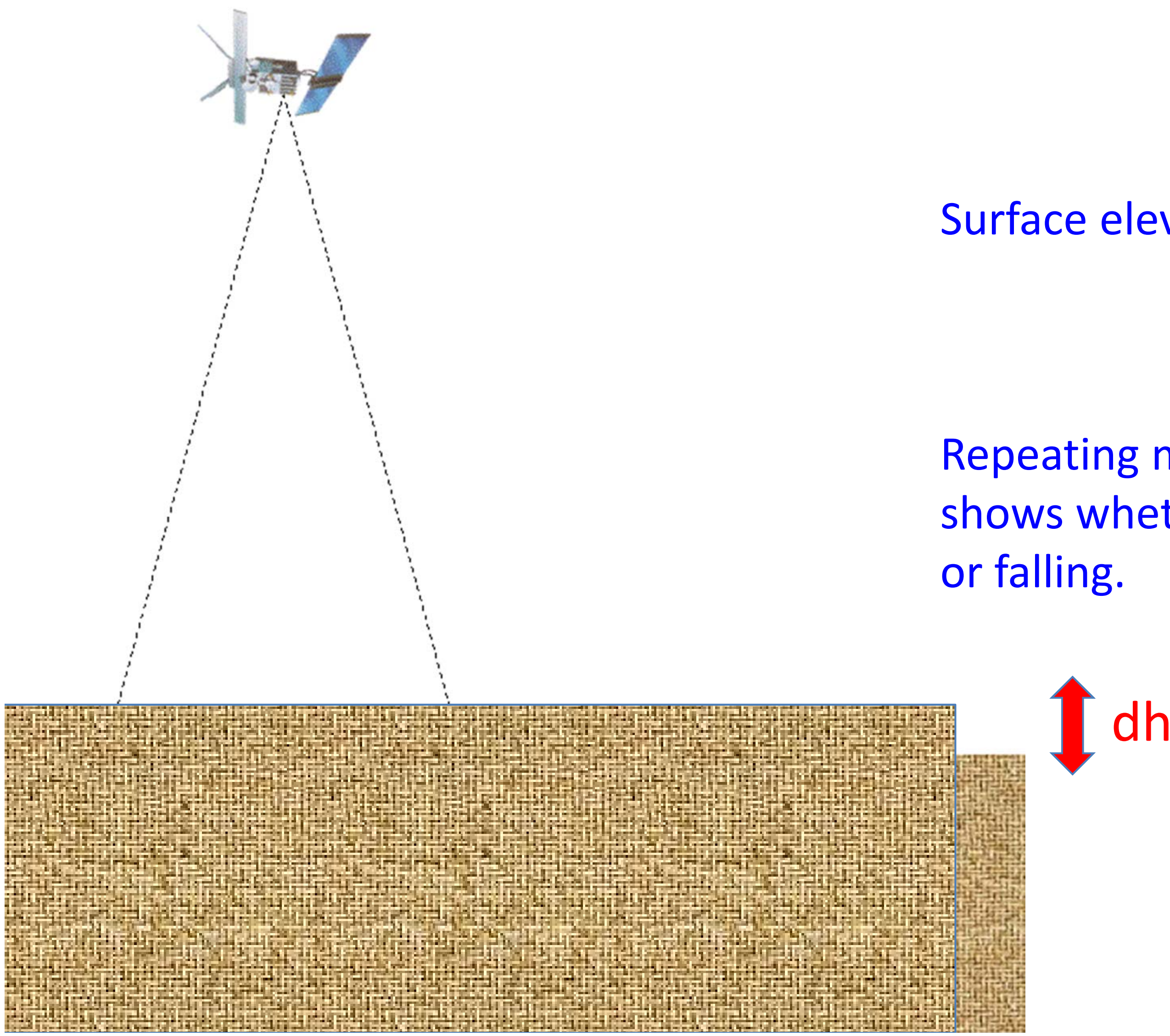
Measures time taken for electromagnetic pulse to be reflected back from Earth's surface.

↓

Surface elevation of the ice sheet.

↓

Repeating measurements in time shows whether the surface is rising or falling.



Measuring surface elevation change

- Cross-over method
- Repeat track
- Plane fit method

Cross-over Method

1. Identify intersections of satellite tracks

2. Form time-series of elevation (plus uncertainty) at each crossing point

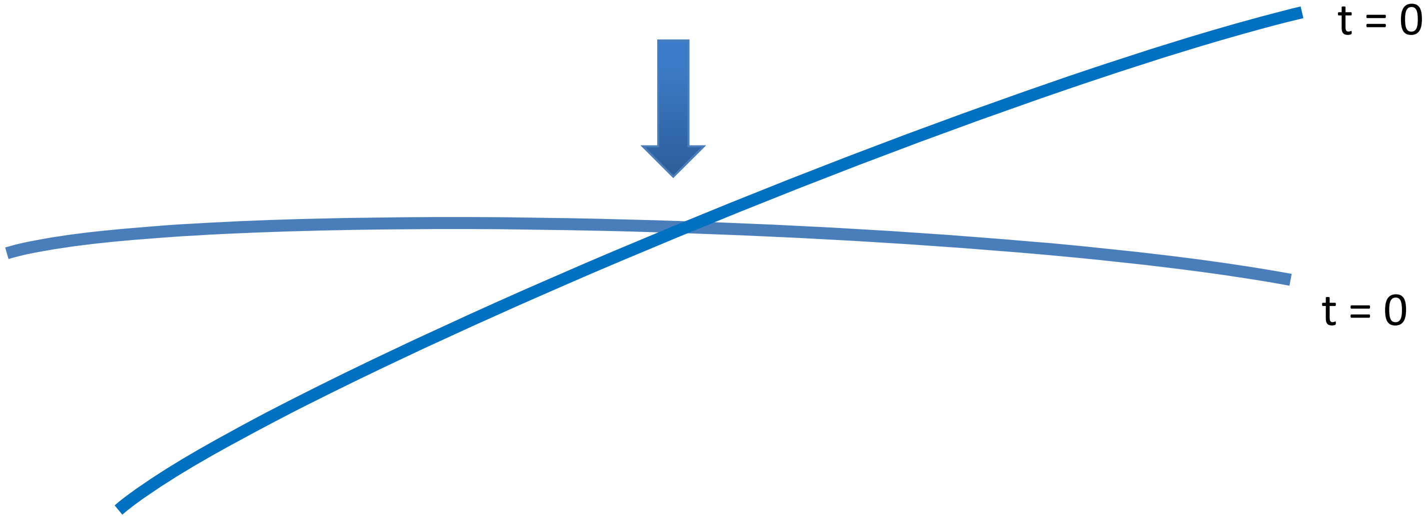
3. Spatially average data to reduce uncorrelated noise, e.g. 10 x 10 km

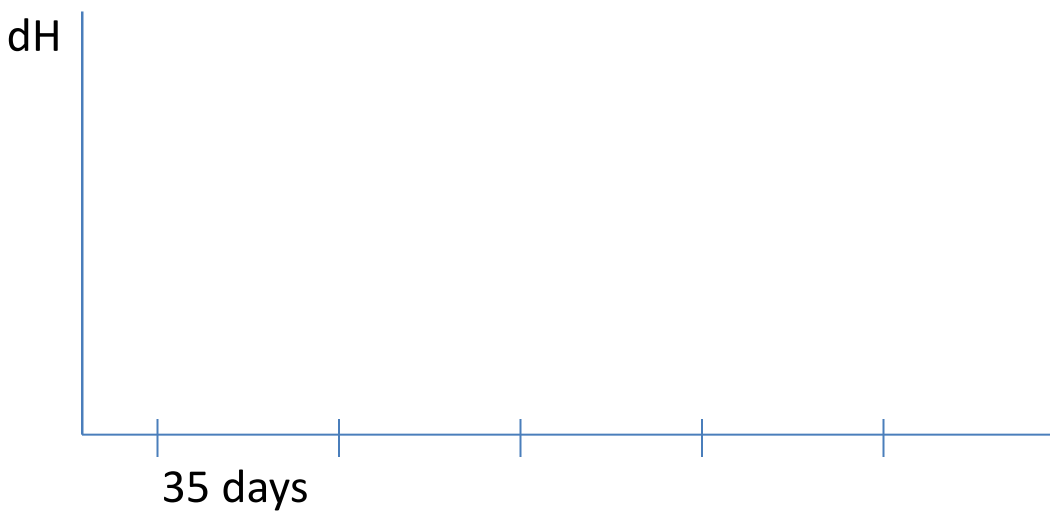
4. Fit model to each gridded time-series, e.g. linear + sinusoidal

5. Retrieve elevation rates

6. Account for omission areas

Cross-over Method





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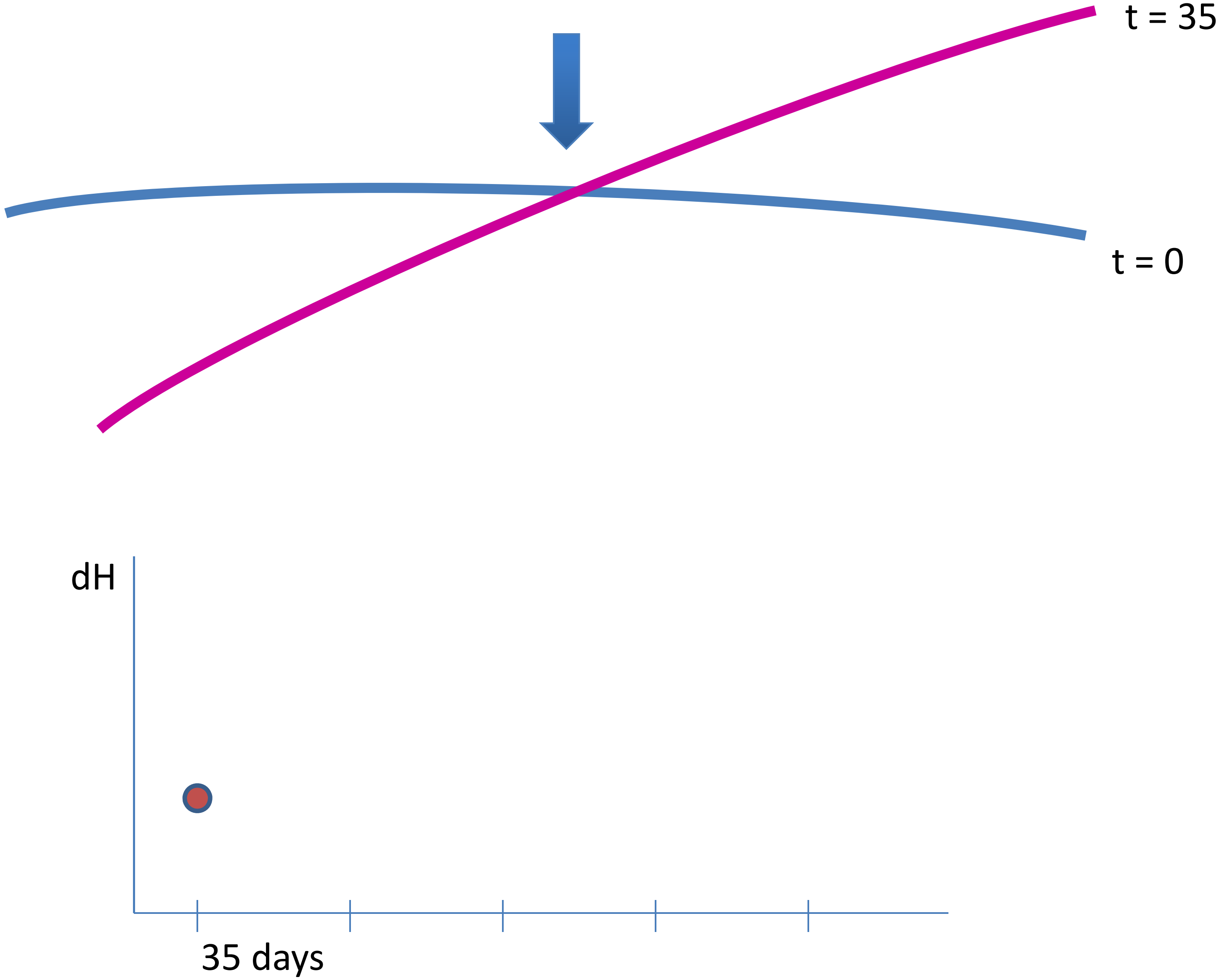

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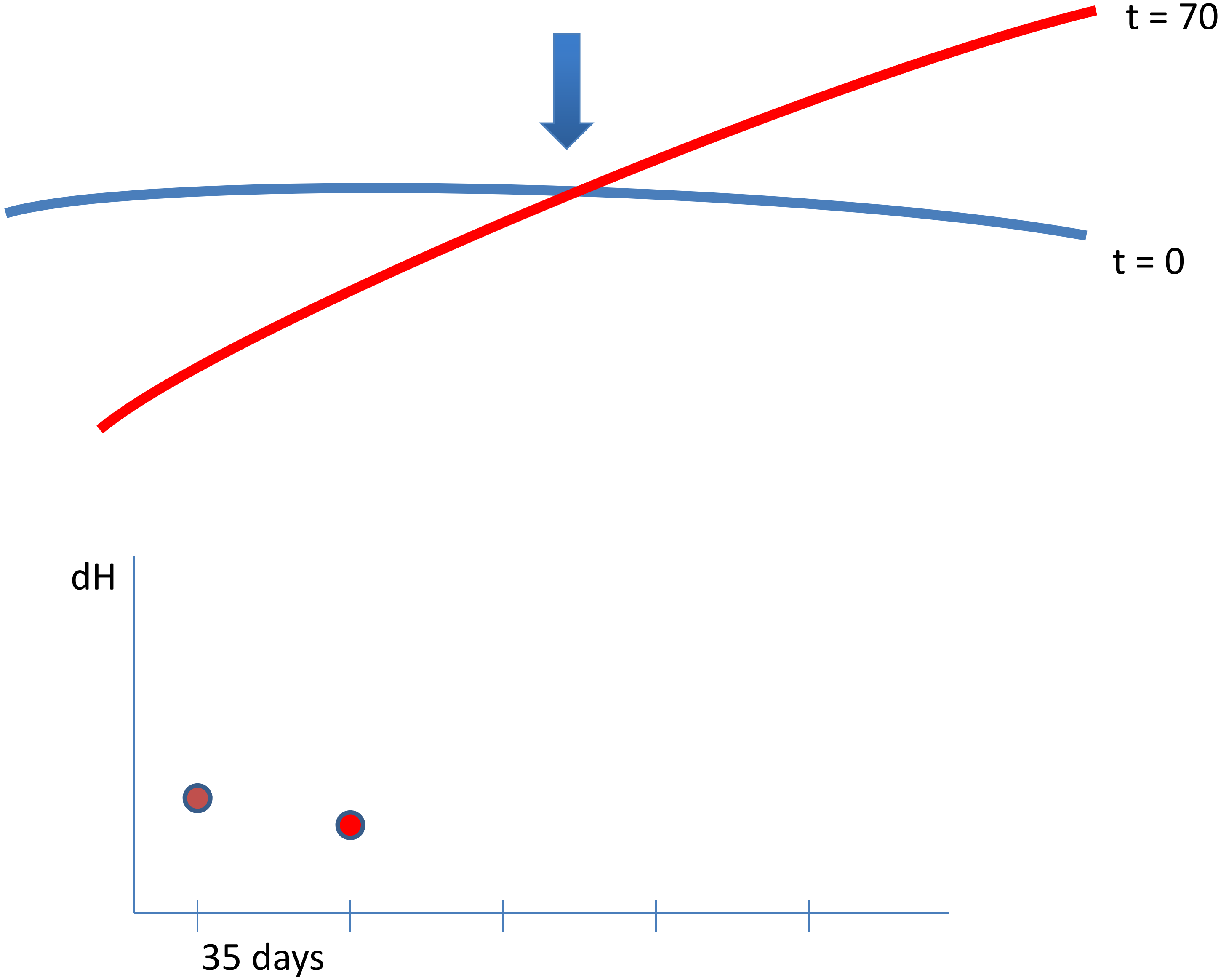

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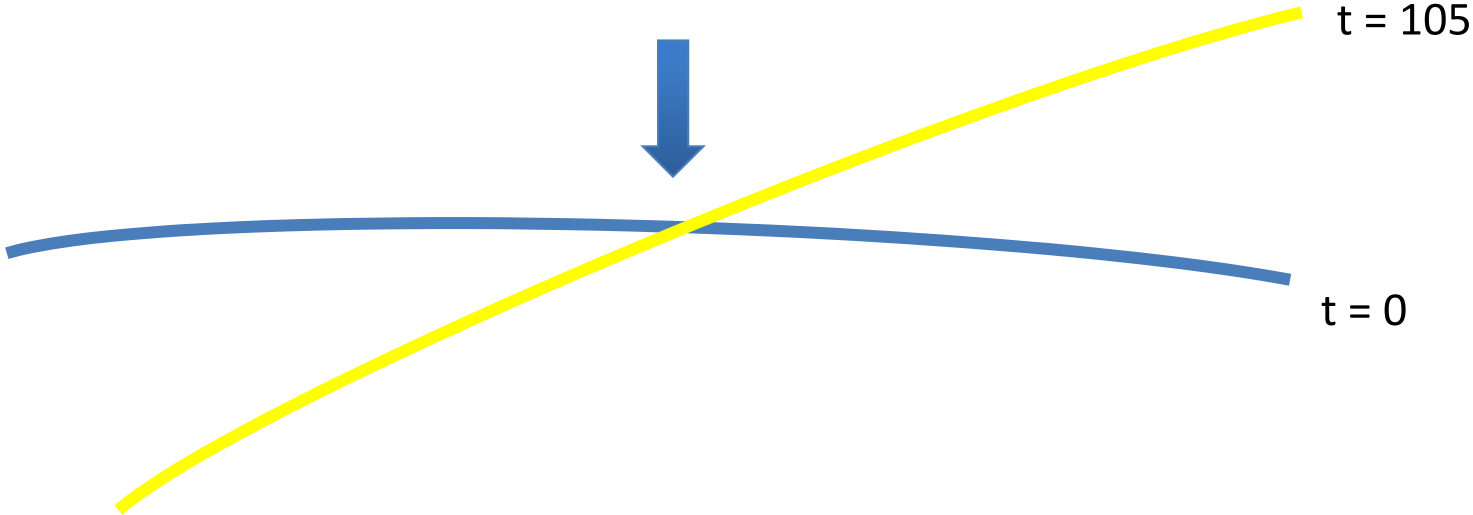

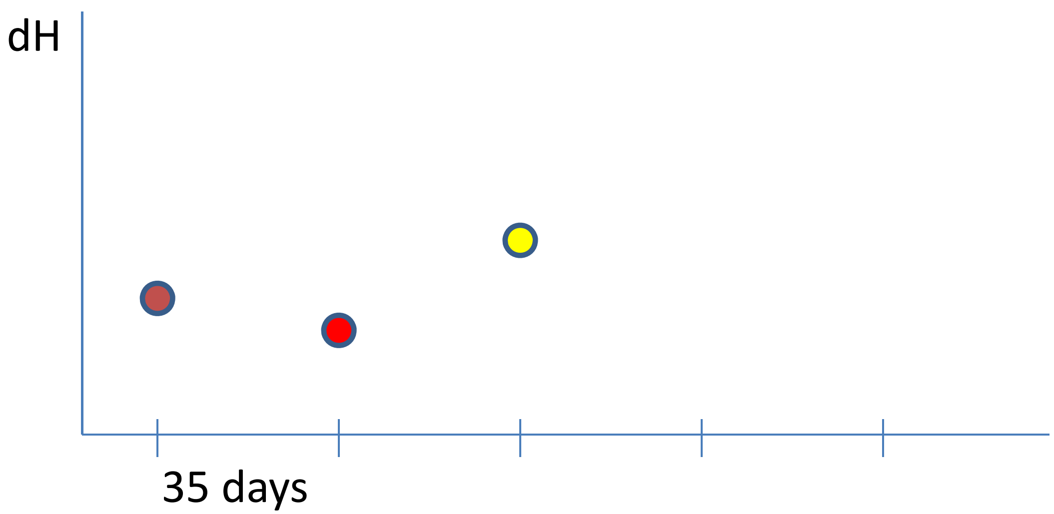

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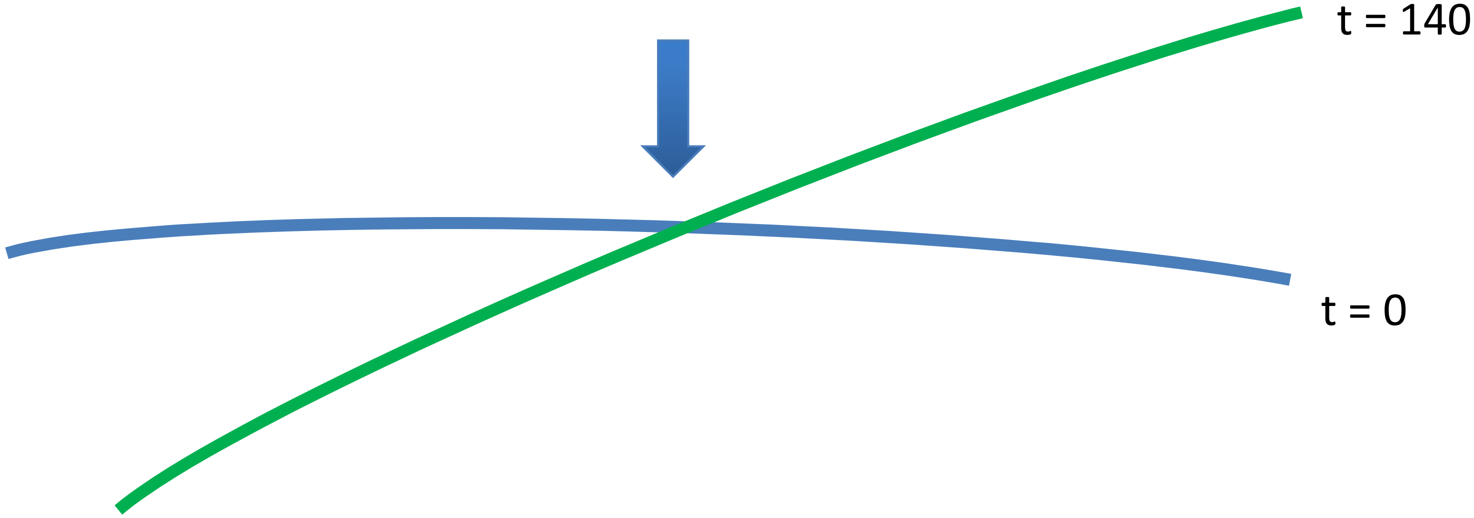

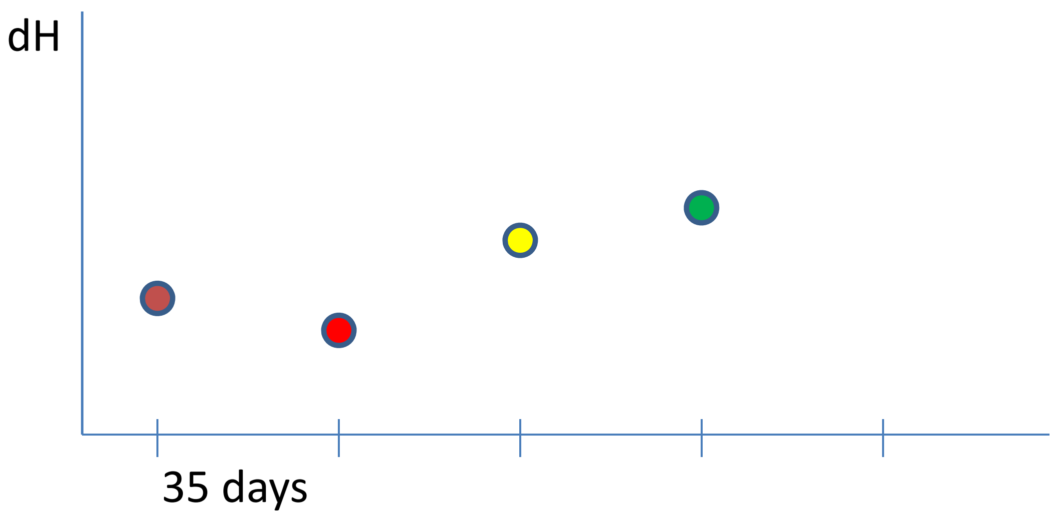

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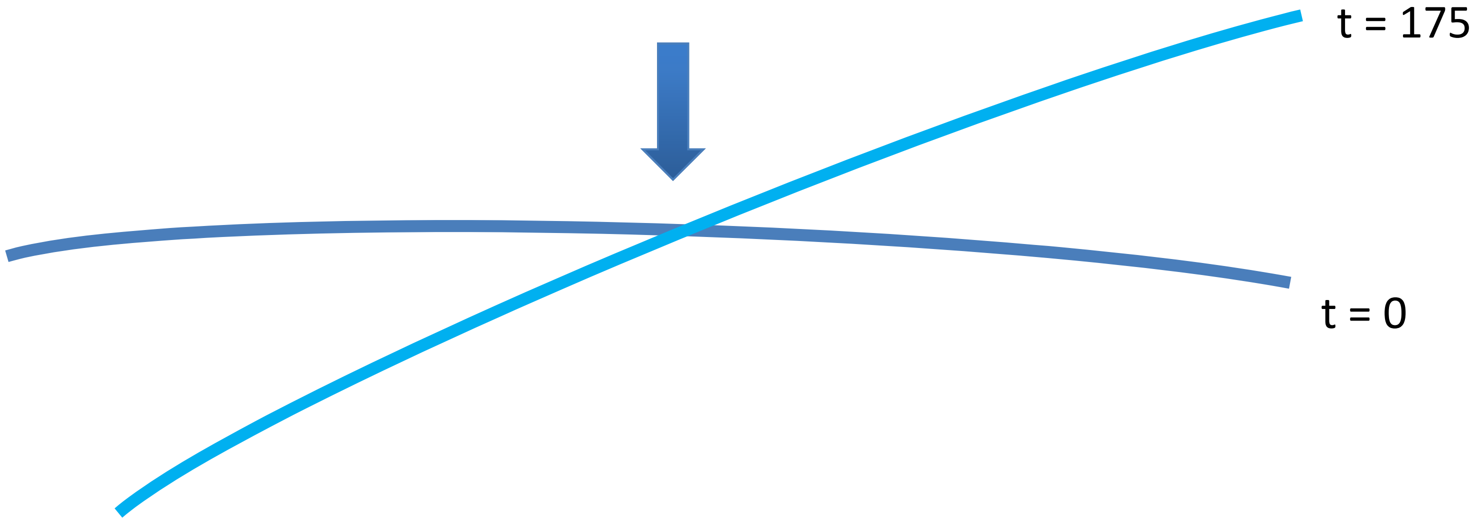
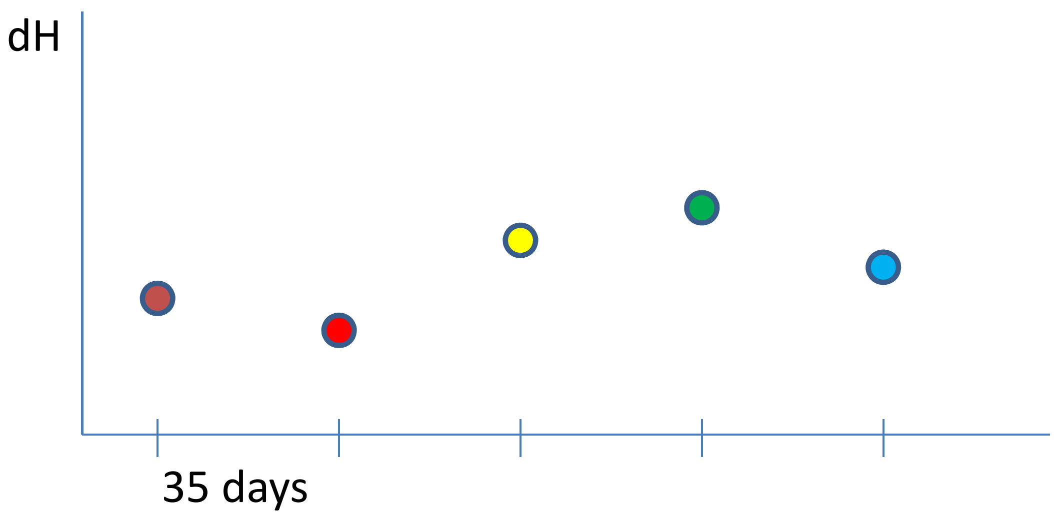
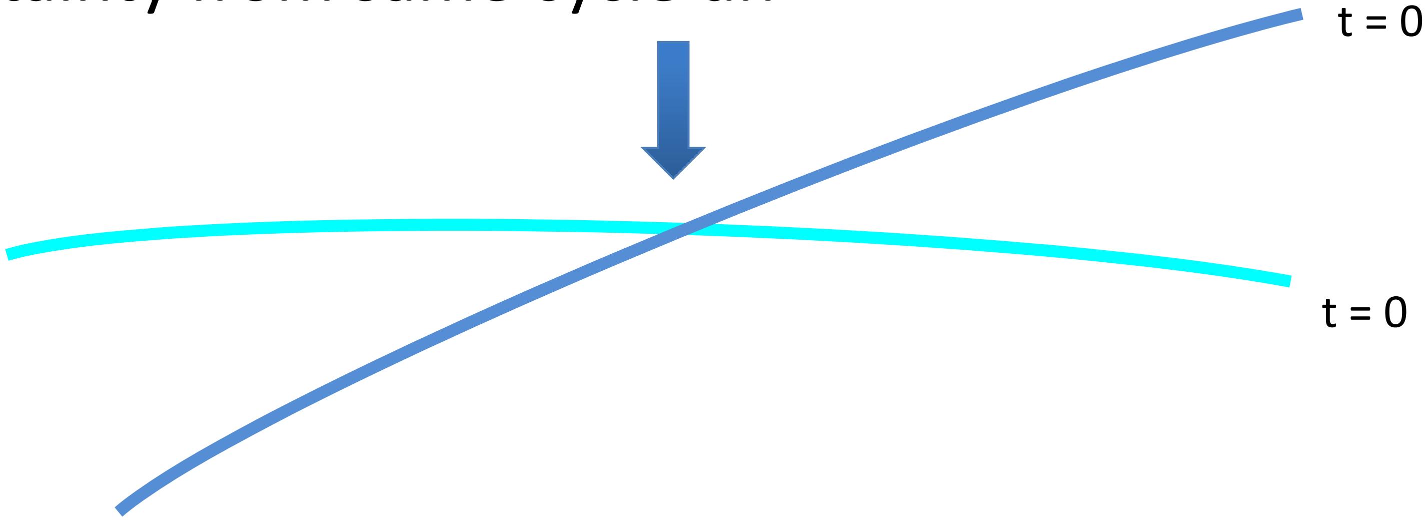
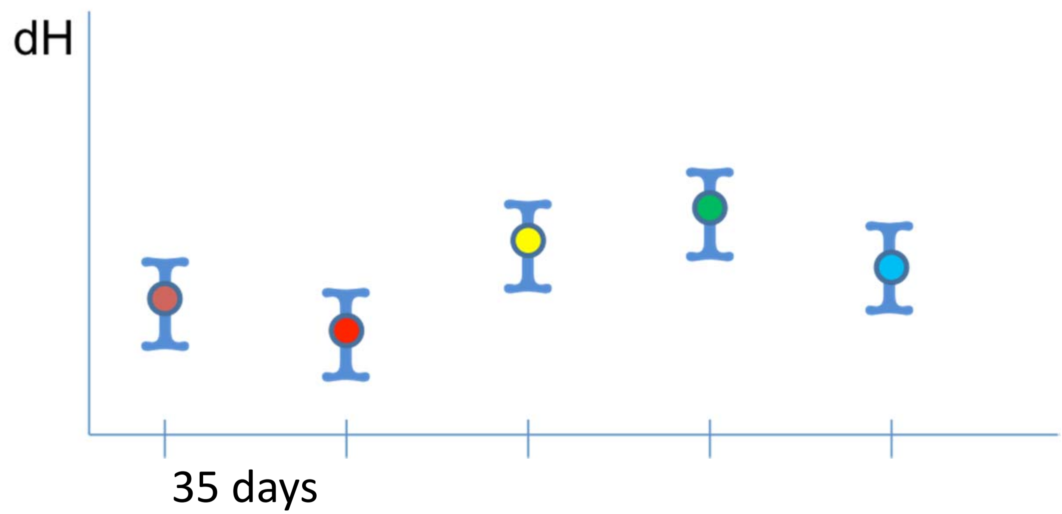


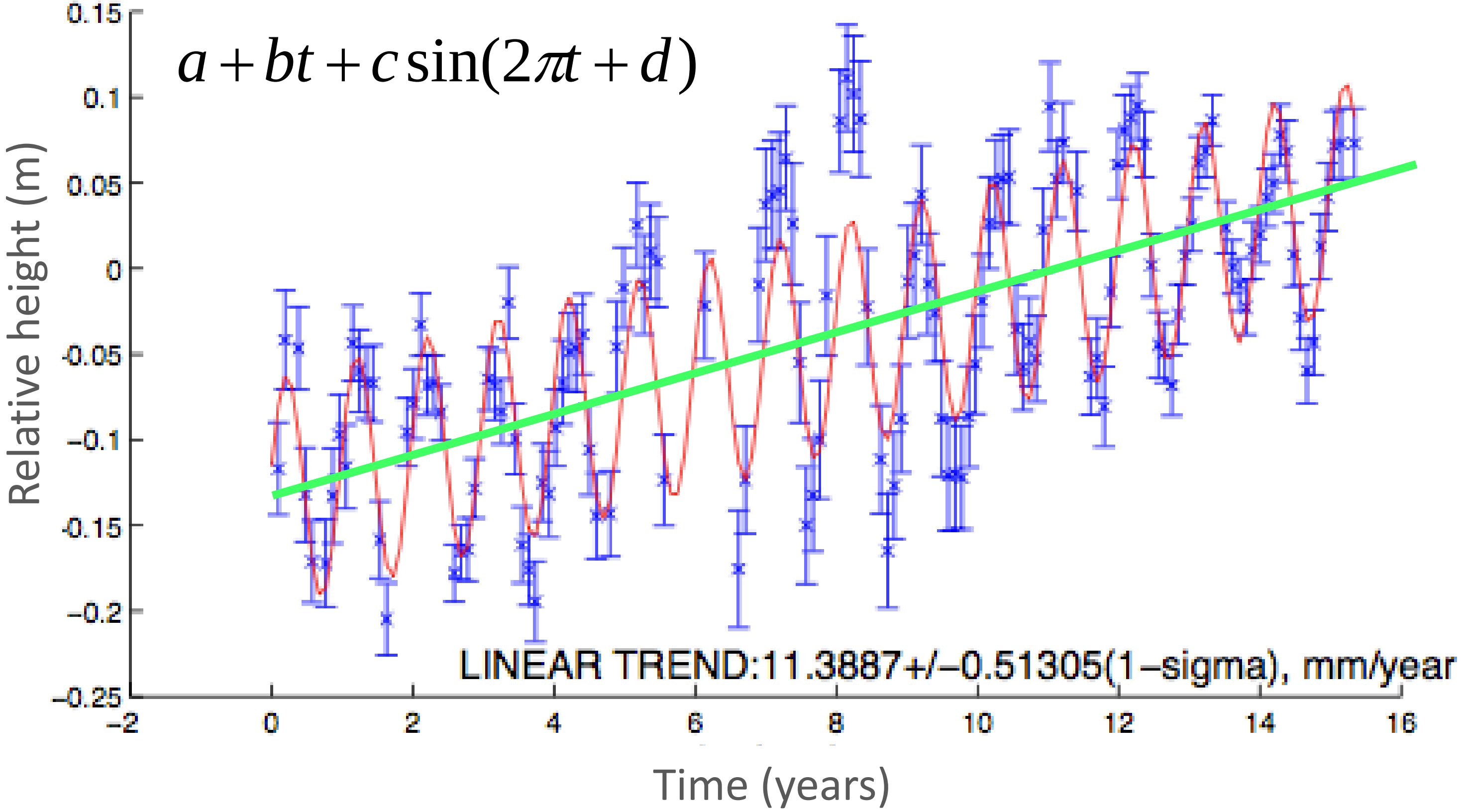


Uncertainty from same cycle dh





Fit model to gridded time series and retrieve elevation rate



Repeat Track Method

1. Split satellite track into kilometer scale segments
2. Define a model for elevation fluctuations within each segment (account for topography and dhdt)
3. Least squares fit of model to data within each segment
4. Retrieve model parameters (includes surface elevation, elevation rate) and associated uncertainty
5. Remove poorly constrained solutions
6. Retrieve elevation time series using model fit
7. Account for omission areas

Repeat Track Method

1. Split satellite track into kilometer scale segments.
2. Define a model for elevation fluctuations within each segment.

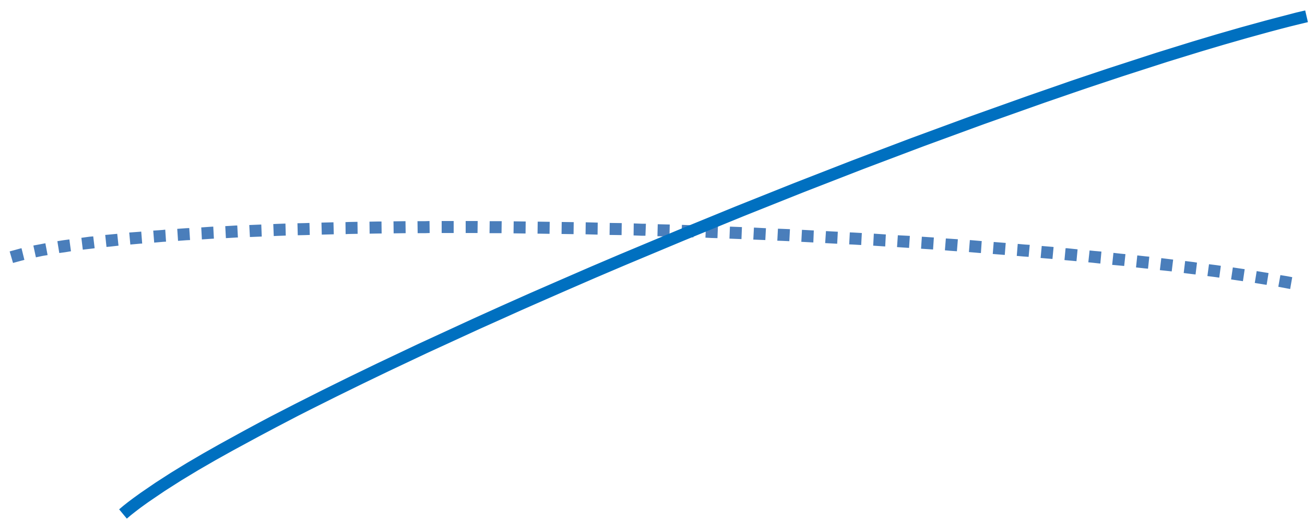
   Least squares fit of model to data within each segment.

   Retrieve model parameters and associated uncertainty (includes elevation rate).

Alternative: External DEM

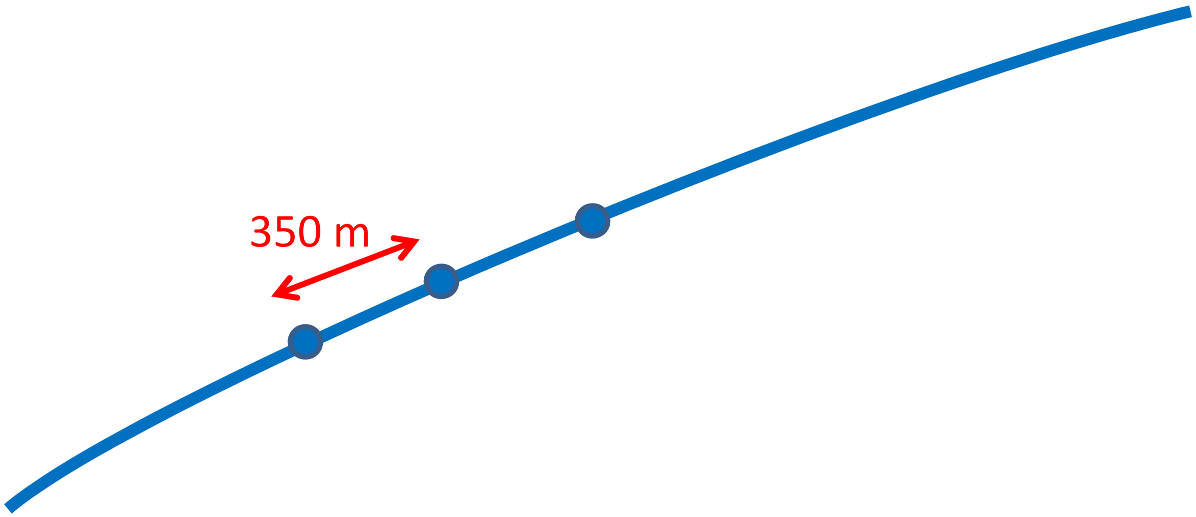
5. Remove poorly constrained solutions.
6. Retrieve elevation time series using model fit.
7. Account for omission areas.

Repeat track method



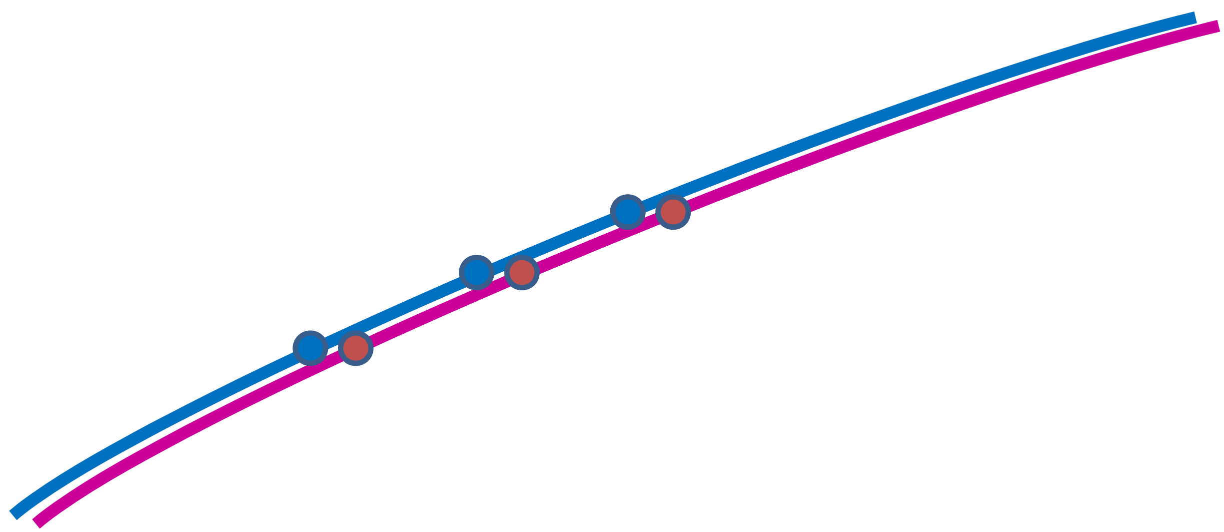
Don’t just utilise data at orbit crossing point….

Repeat track method



.... use all data along the satellite track.

Accumulate data from repeat tracks



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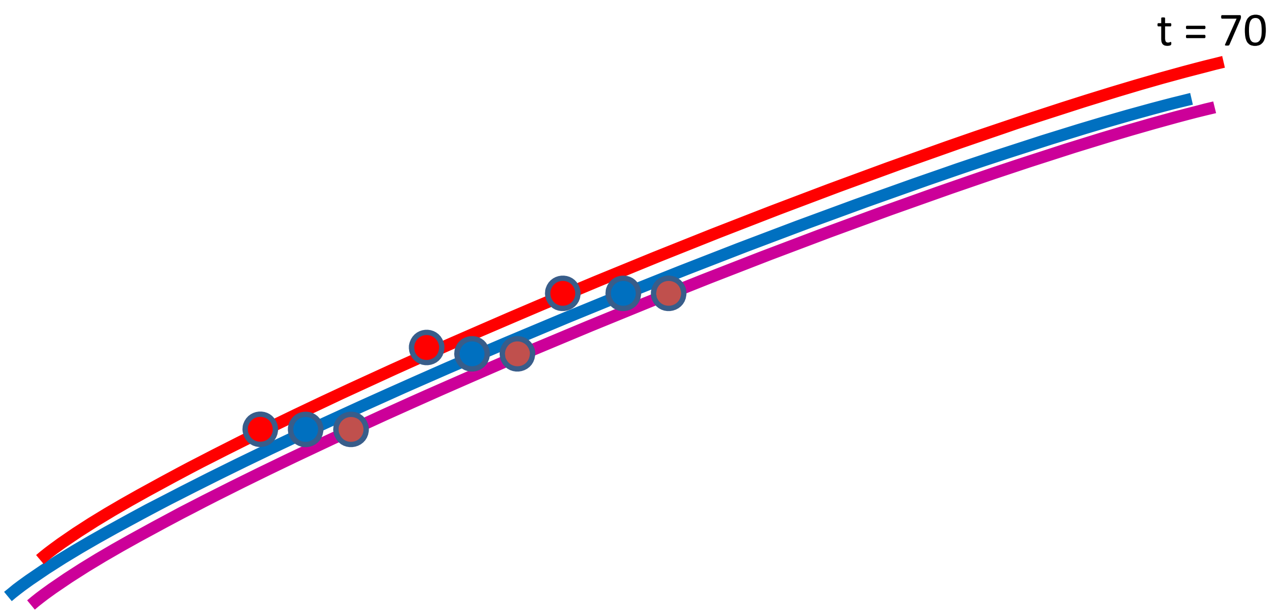

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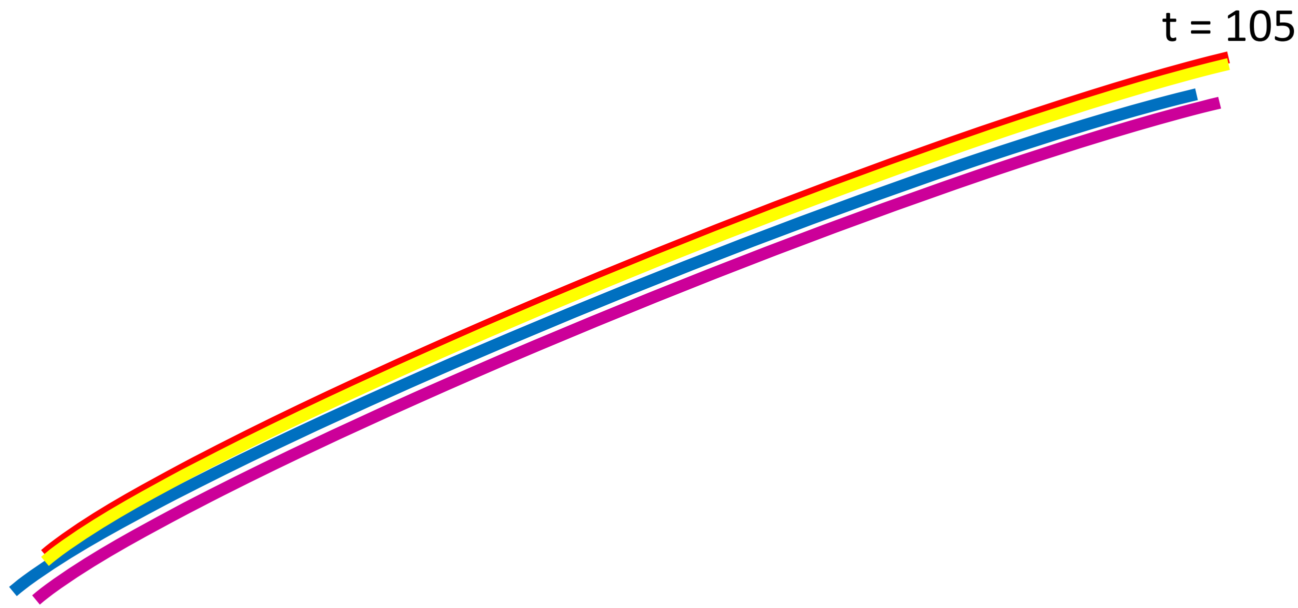

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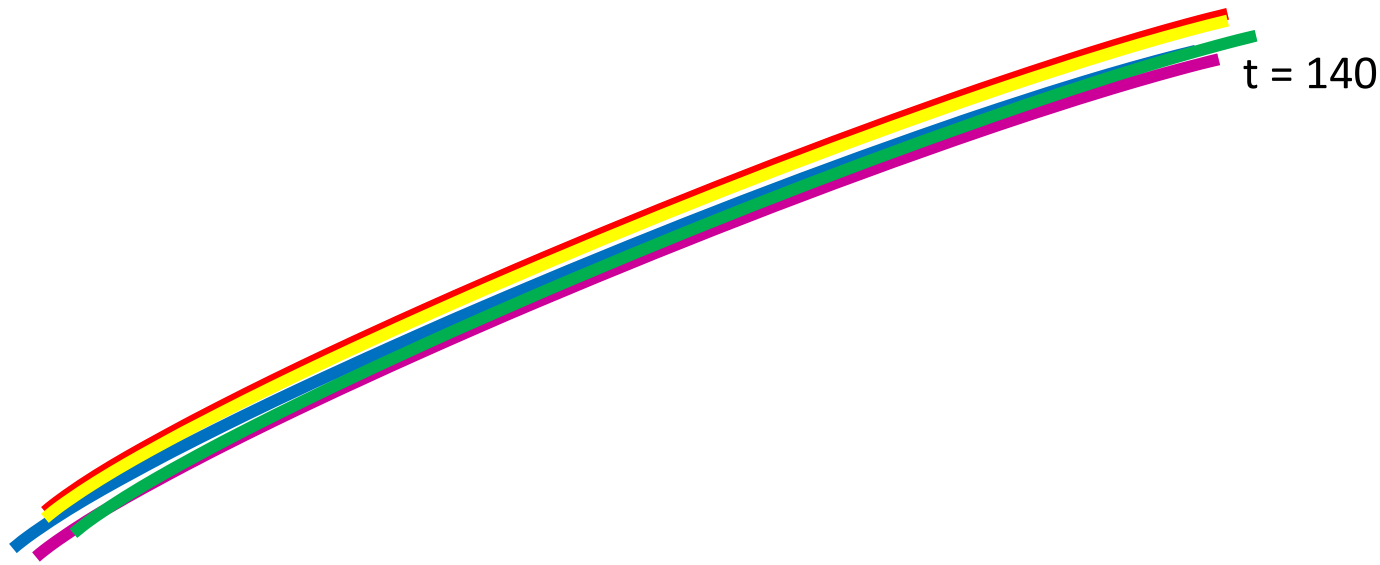

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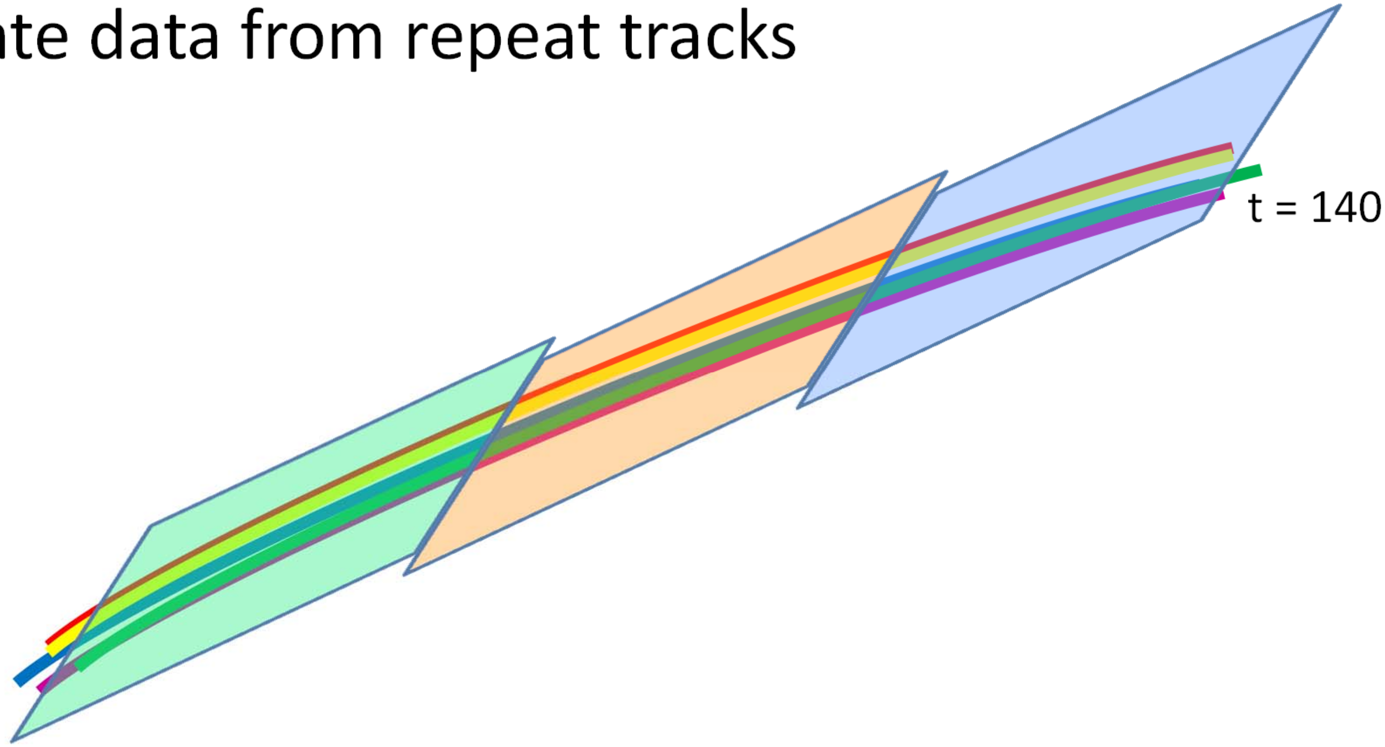
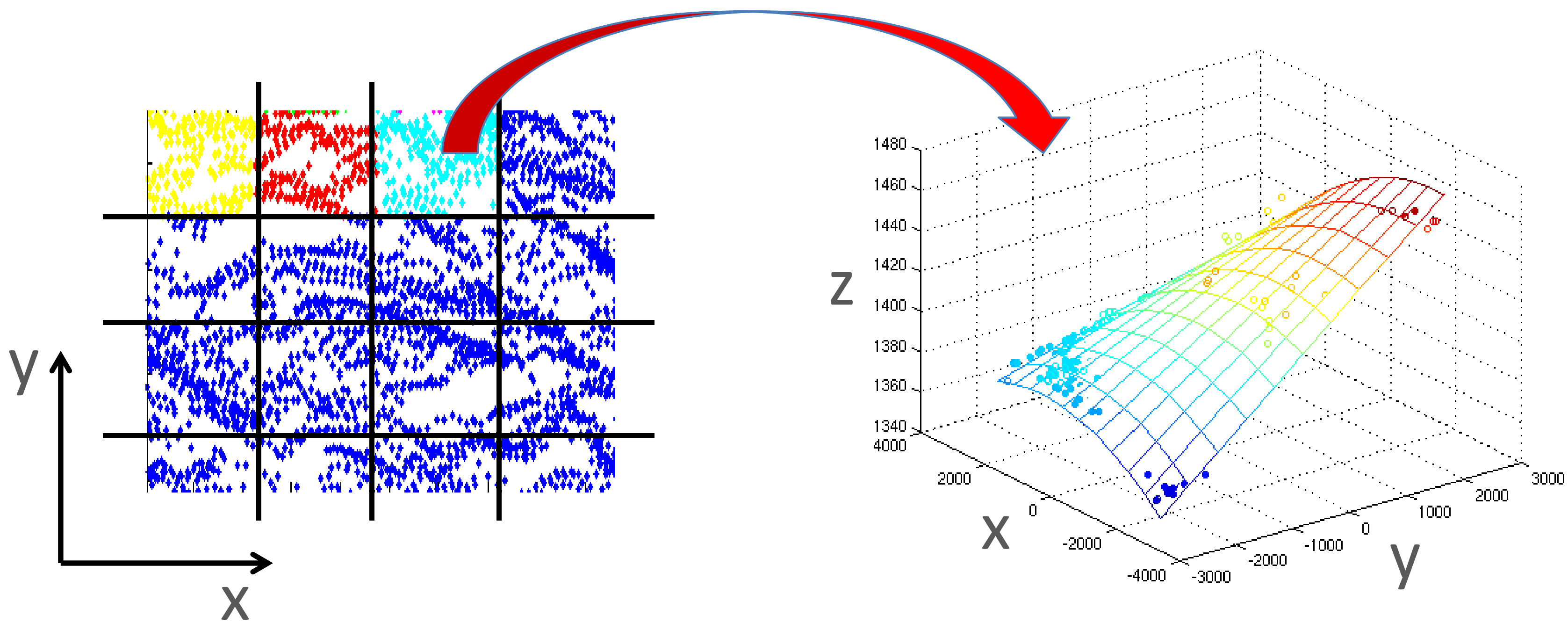


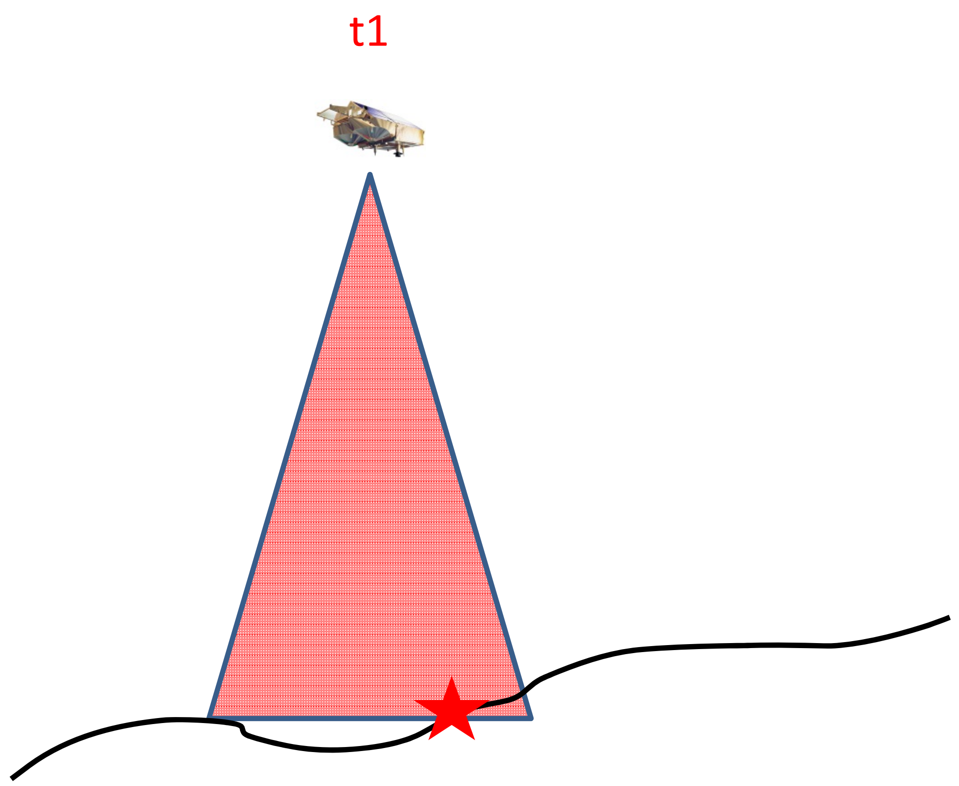
- Cut data up into segments along track.
- Data within each track segment are dispersed in space and time, and so solve simultaneously for both spatial and temporal components.
- Retrieve elevation rate.

Plane fit method

- Modification of repeat track approach.
- Well suited to more homogeneous data sampling (e.g. CryoSat), rather than where data clustered along distinct tracks (e.g. ICESat).
- Group data based on spatial proximity, don't distinguish between tracks.



Influence of surface slope – affects repeat track and model fit



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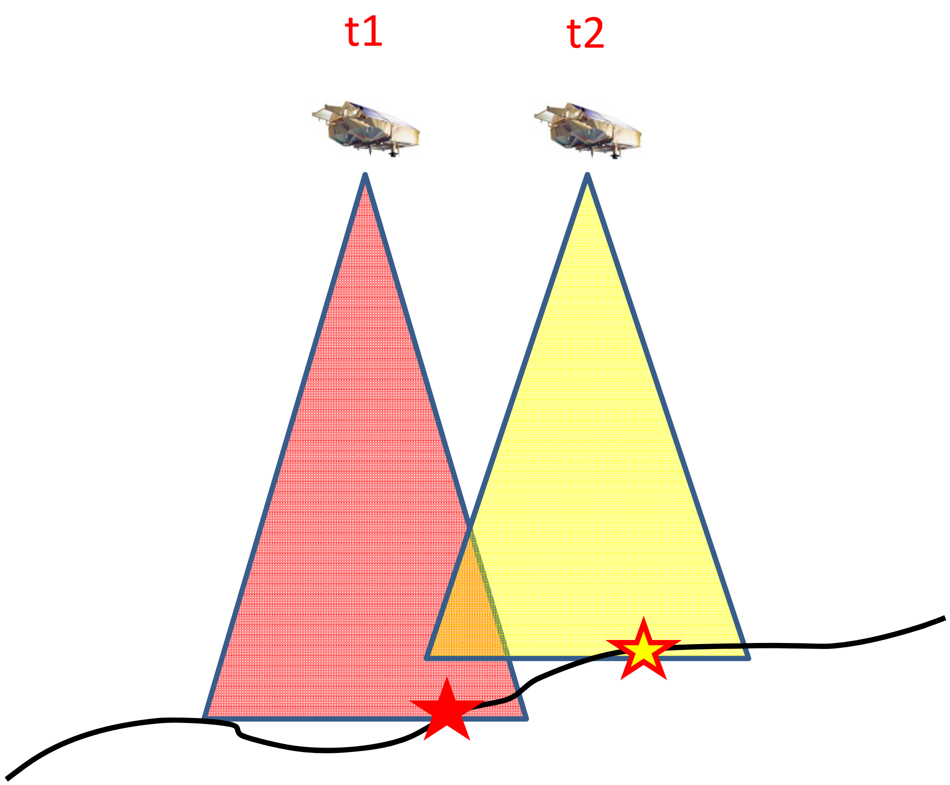

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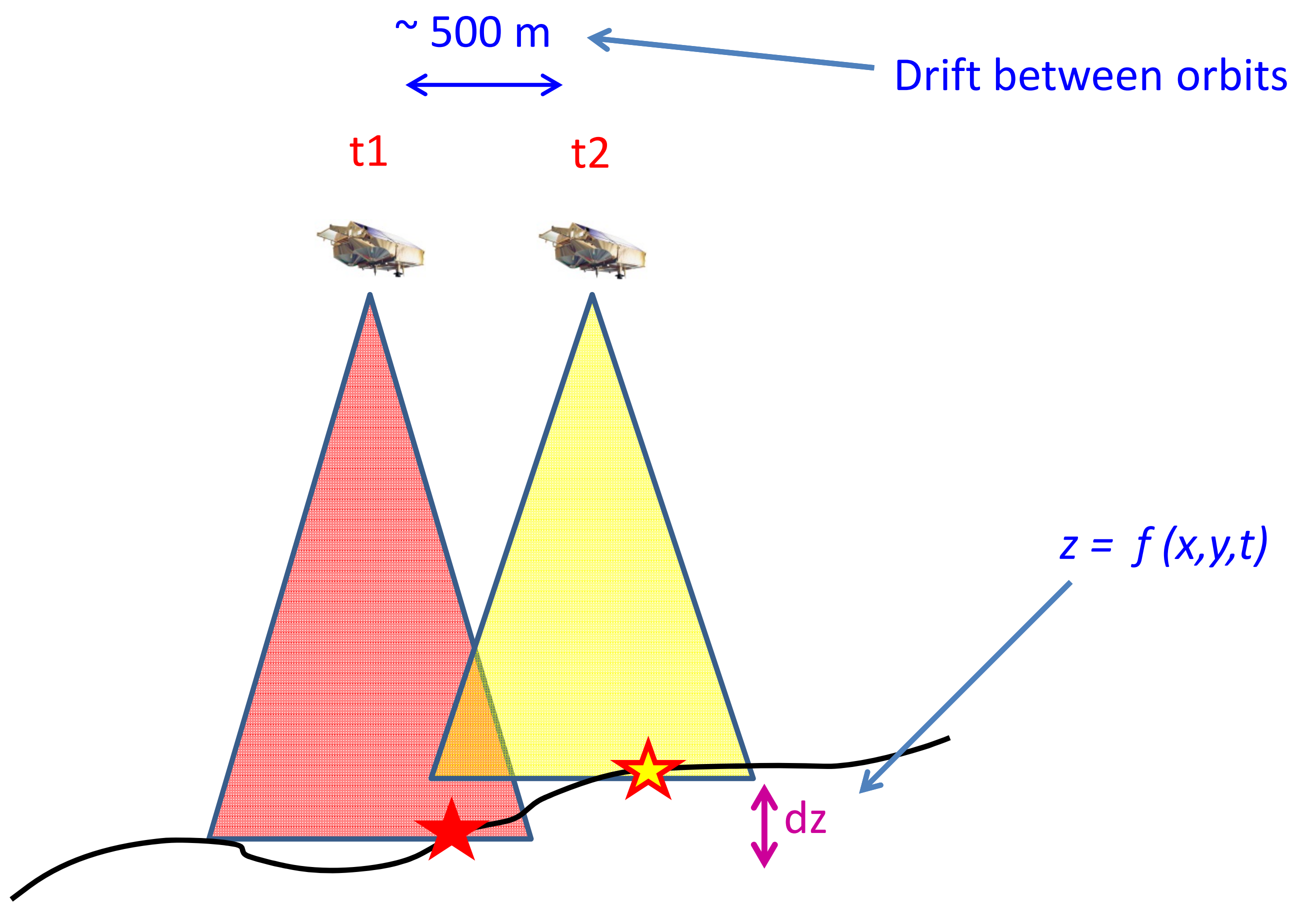
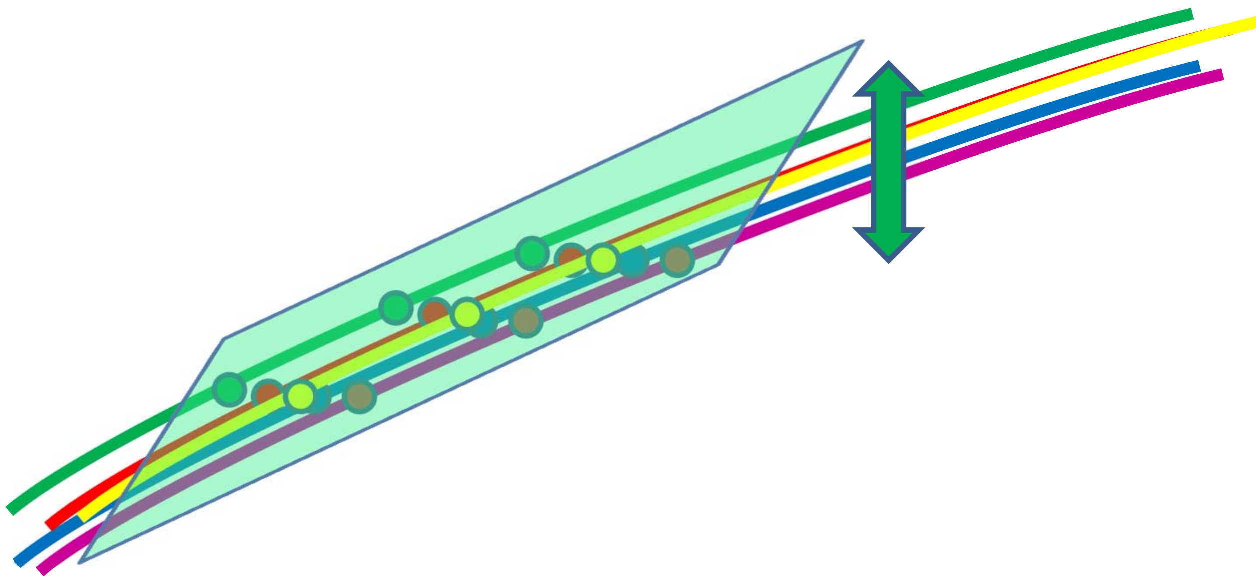


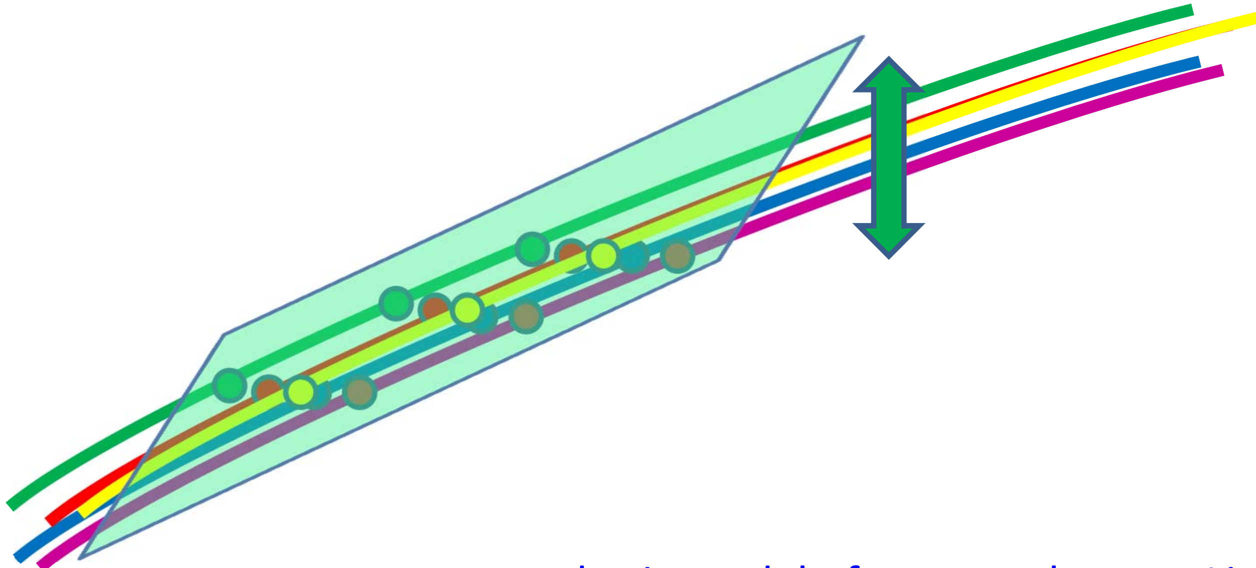
Strategy required to separate elevation changes into spatial and temporal components.

Fit model to data segment and retrieve elevation rate



$$z(x, y, t, h) = \bar{z} + a_0 x + a_1 y + a_2 x^2 + a_3 y^2 + a_4 xy + a_5 h + a_6 t$$

Fit model to data segment and retrieve elevation rate

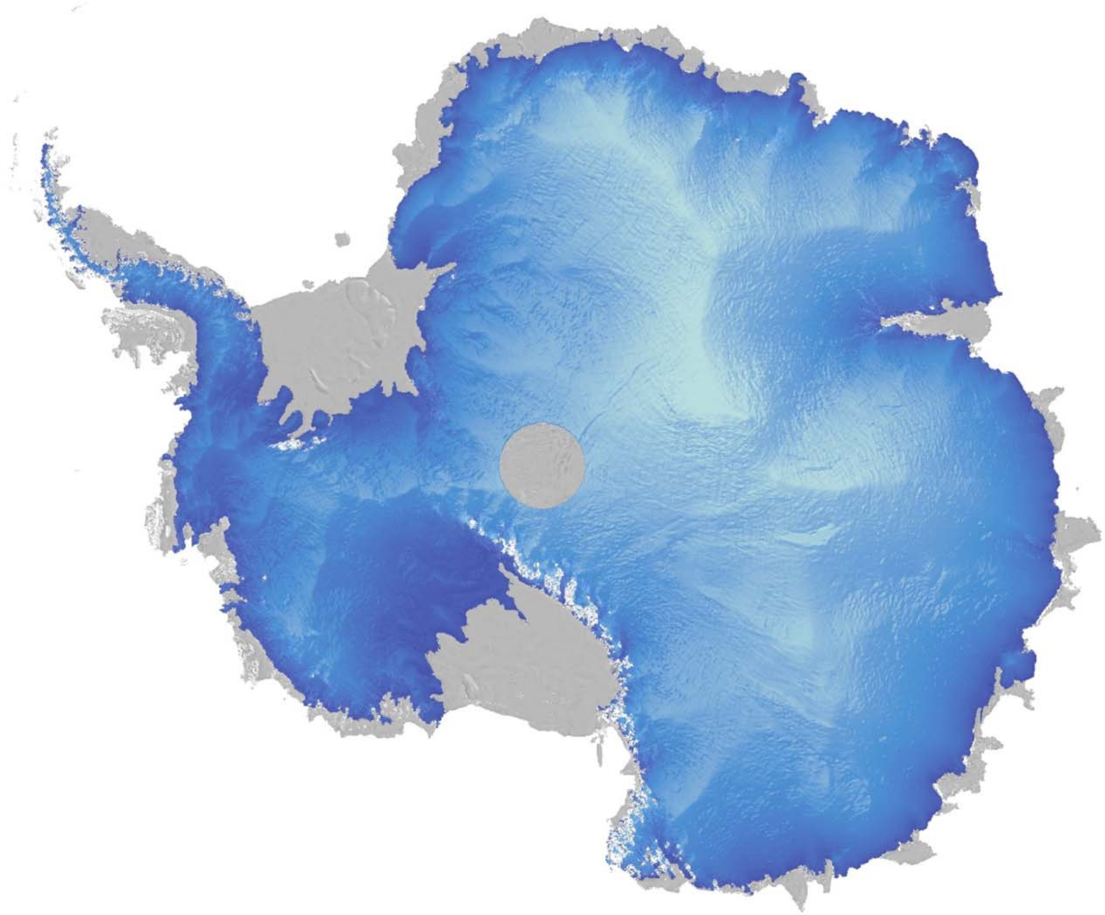


quadratic model of topography

Linear rate of elevation change

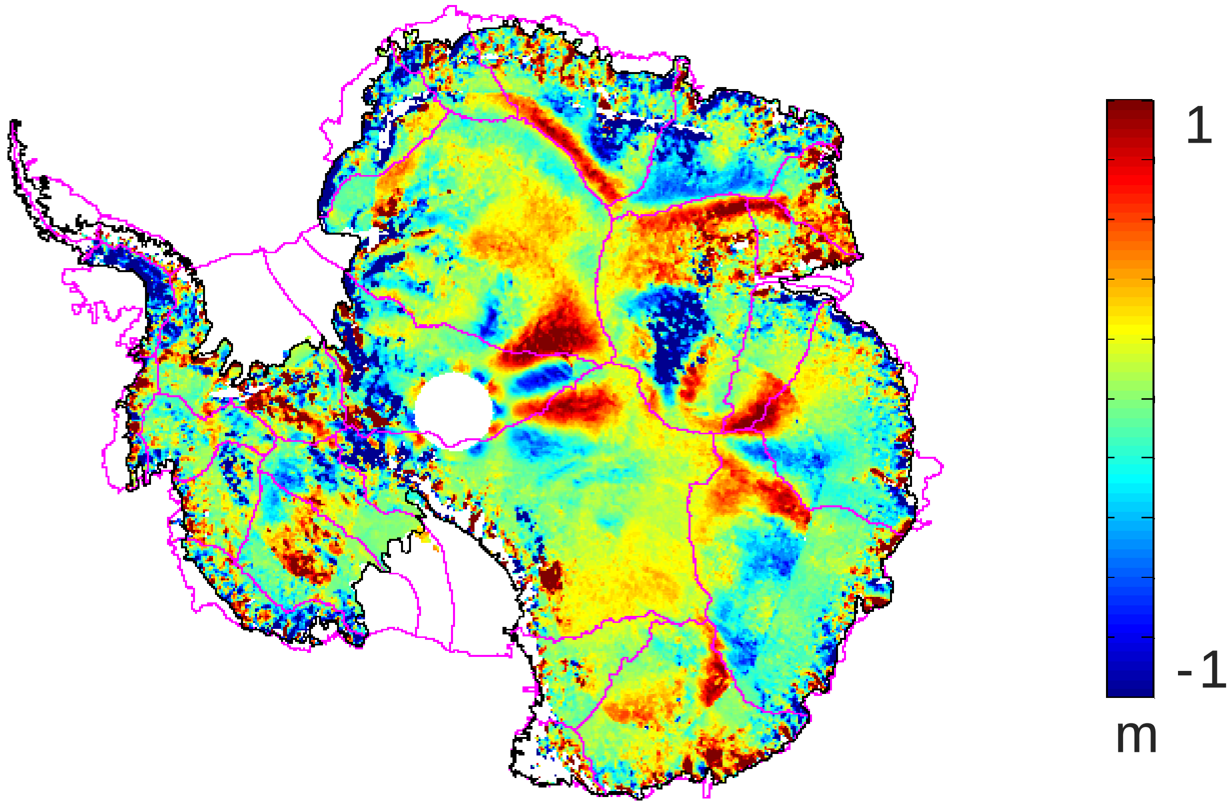
$$z(x,y,t,h) = \bar{z} + a_0x + a_1y + a_2x^2 + a_3y^2 + a_4xy + a_5h + a_6t$$

anisotropic scattering within snowpack



$$z(x,y,t,h) = \bar{z} + a_0x + a_1y + a_2x^2 + a_3y^2 + a_4xy + a_5h + a_6t$$

mean elevation



$$z(x, y, t, h) = \bar{z} + a_0 x + a_1 y + a_2 x^2 + a_3 y^2 + a_4 xy + a_5 h + a_6 t$$

- Difference in penetration depth depending on the direction of the satellite
- Caused by persistent wind driven, directional features of the surface and firn

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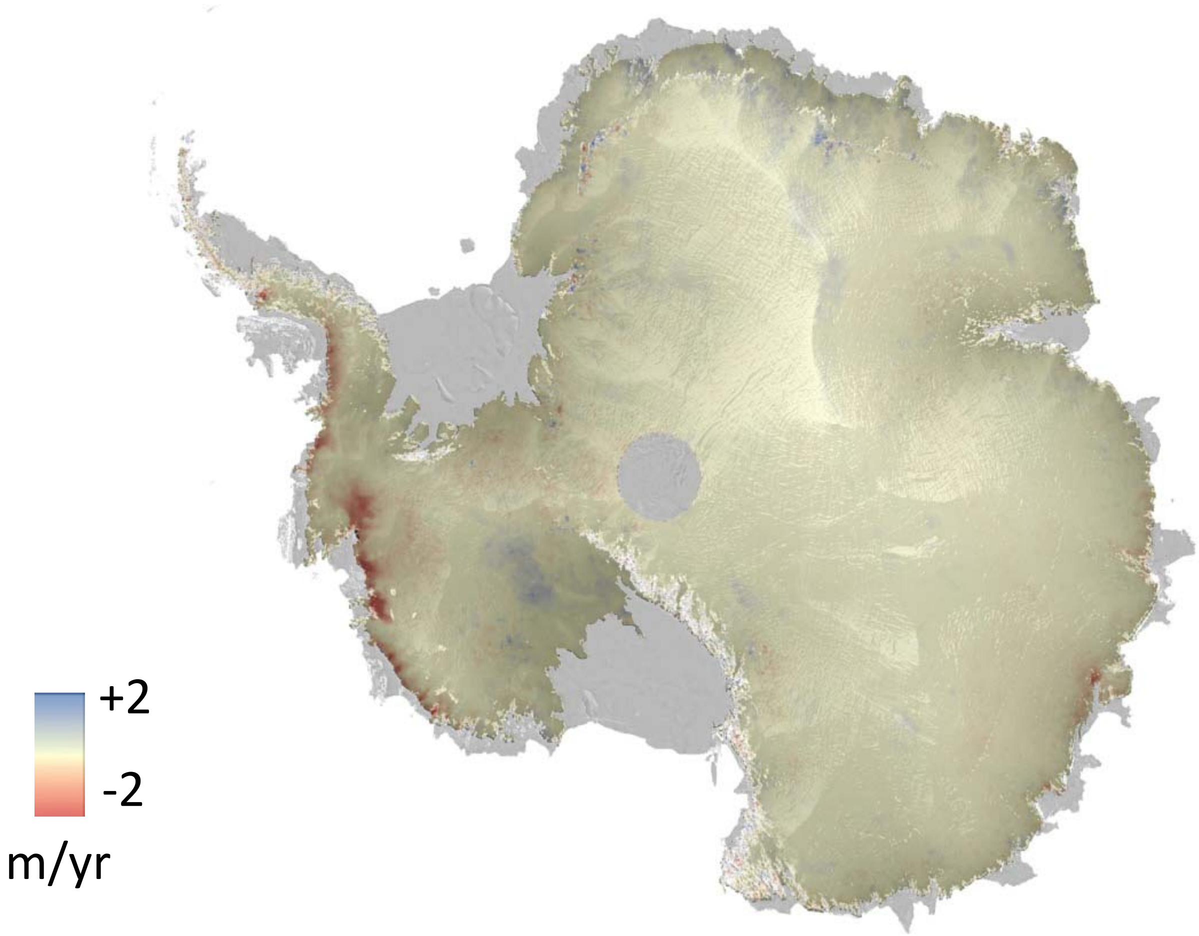

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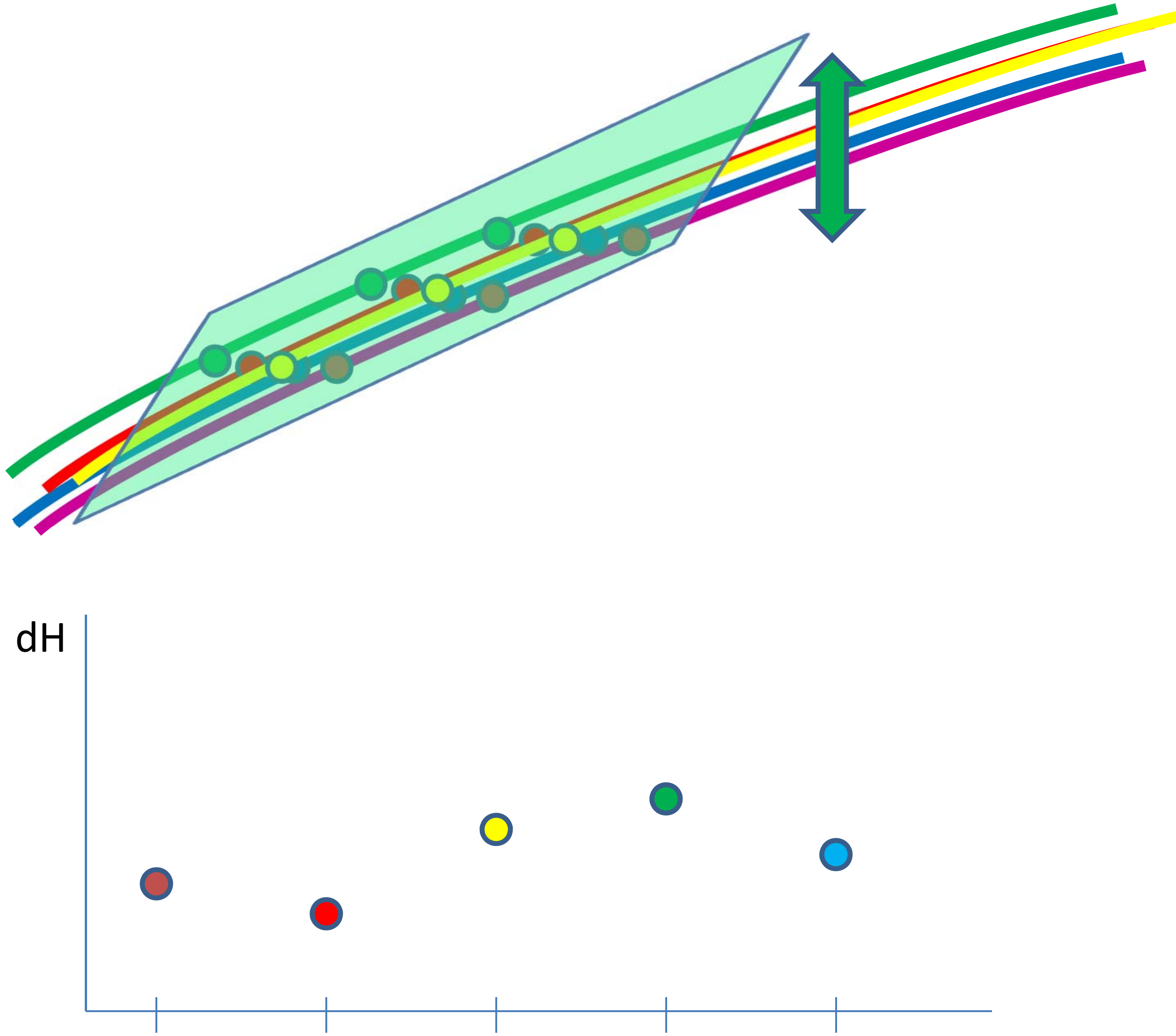
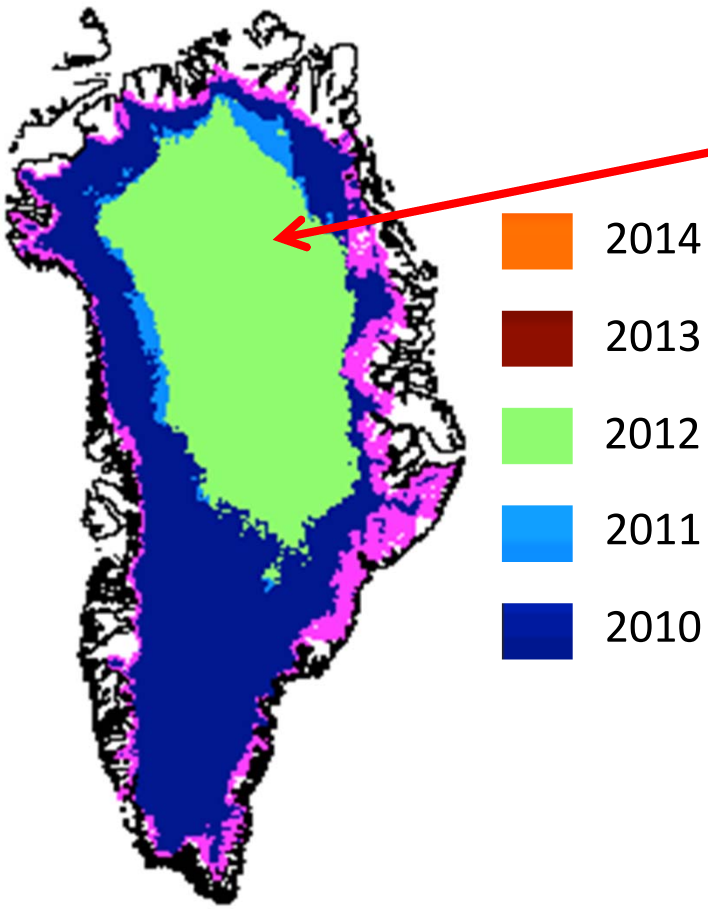
Derive time-series by isolating temporal component



Model fit - Greenland model refinements



RACMO2.3 simulated first year of melt, 2010-2014.

Unprecedented melting in 2012 produced large area undergoing melt for the first time.

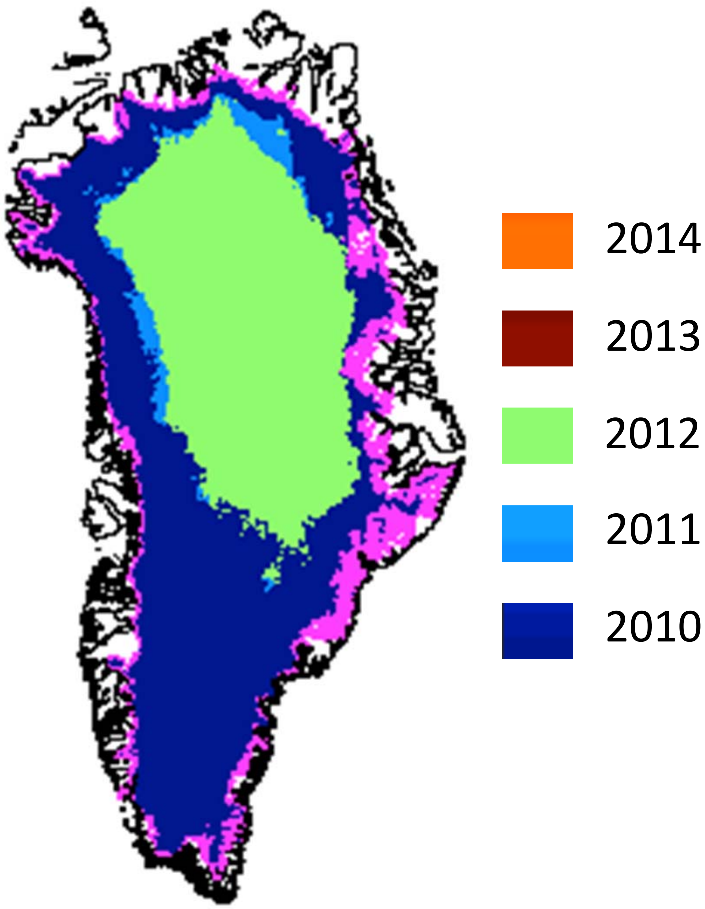
↓

Transition from dry to wet snowpack and ice lens formation.

↓

Affected the depth distribution of backscattered energy.

Model fit - Greenland model refinements



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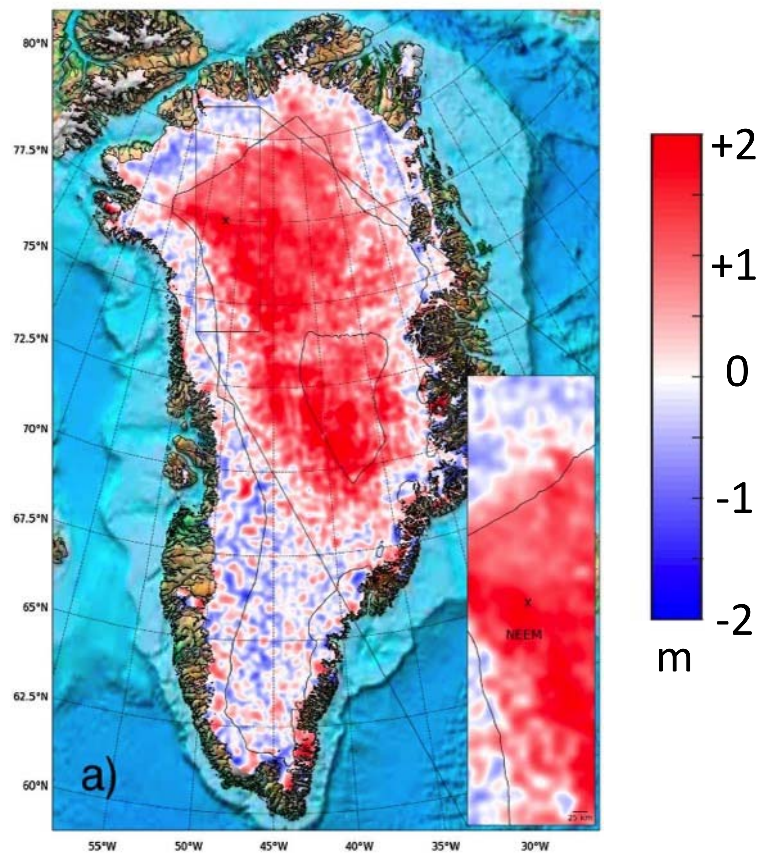
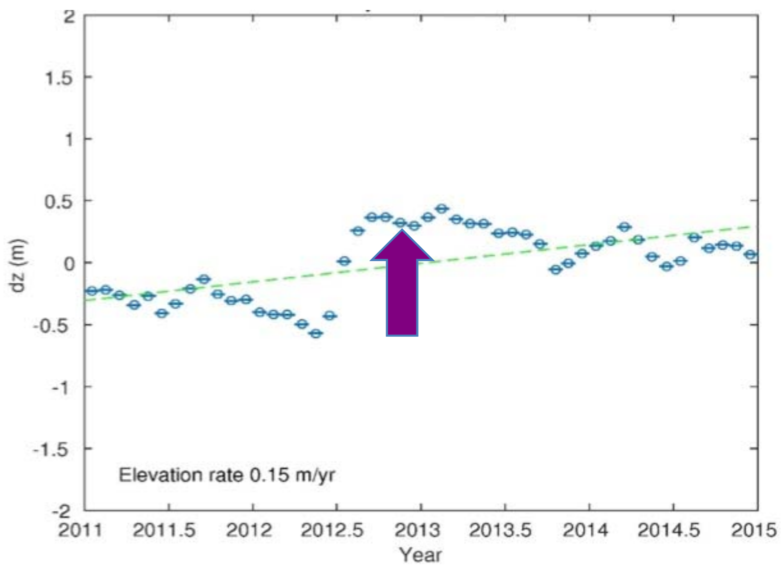


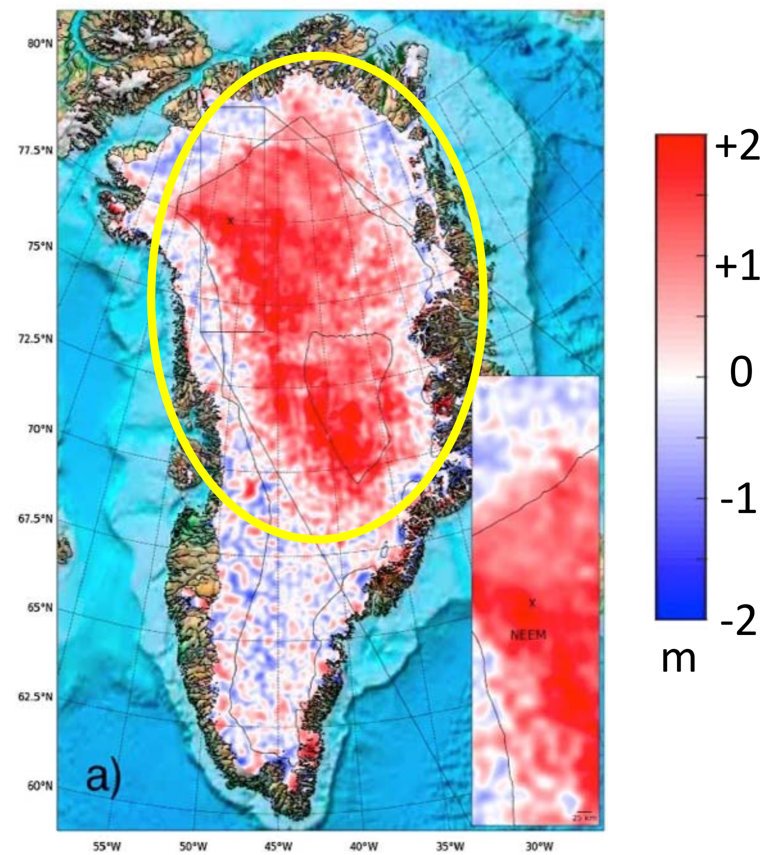
Surface elevation change recorded
by CryoSat-2 during summer 2012.

Nilsson et al. (2015)

Model fit - Greenland model refinements



Additional term introduced into the model fit to account for changes in depth distribution of backscattered energy.

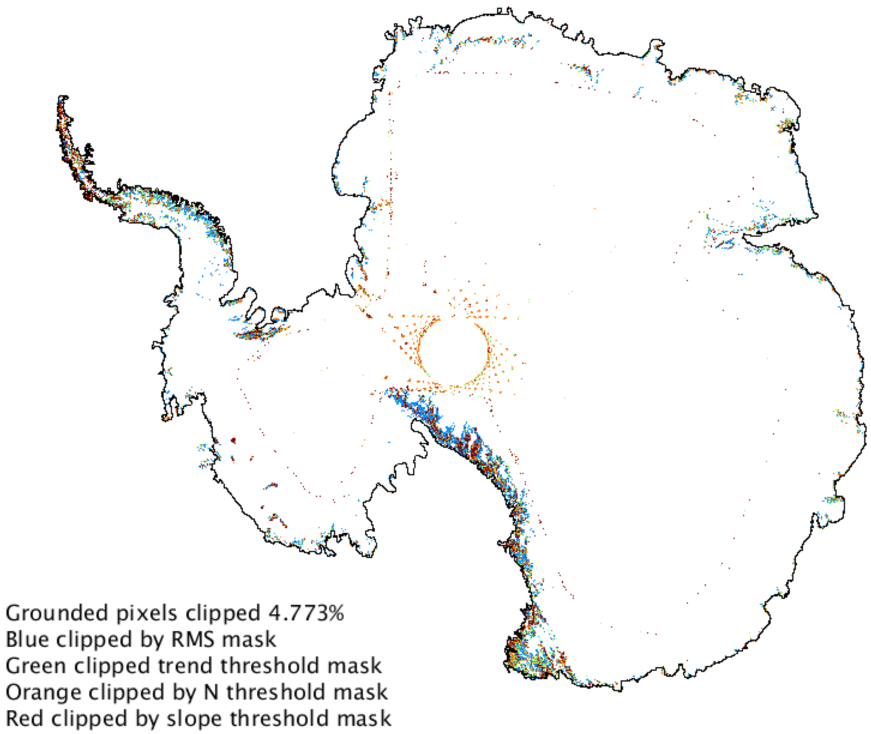


Surface elevation change recorded by CryoSat-2 during summer 2012.

Nilsson et al. (2015)

Remove poorly constrained solutions

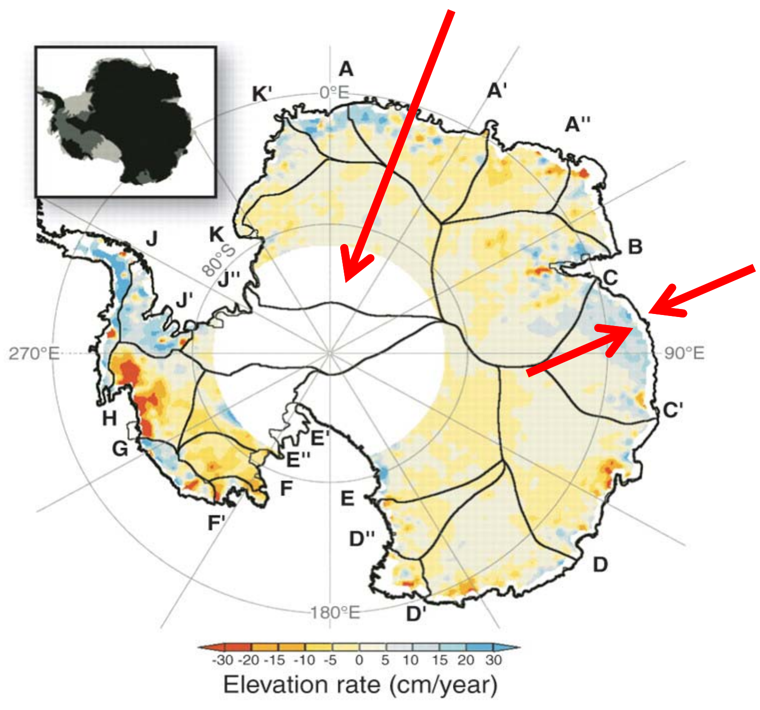
- During model fit, additional parameters (e.g. surface slope) and goodness-of-fit statistics (e.g. RMS of the residuals) are generated.
- These can be used to reject model solutions with large uncertainty or physically unrealistic retrievals.

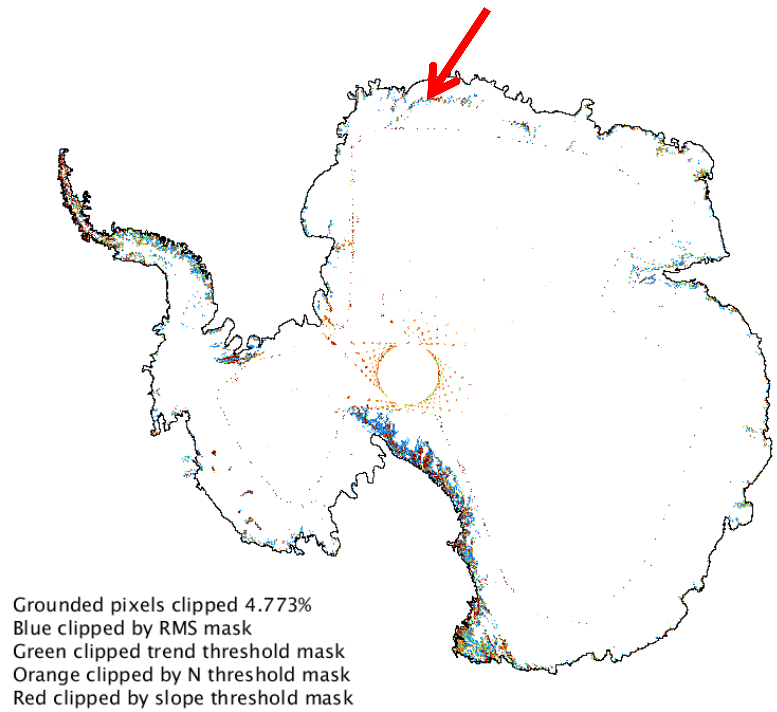


Failure of CryoSat-2 interferometric model fits

Account for omission areas

- coastal regions.
- high latitude region.
- areas where elevation rate retrieval failed.





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1. Statistical approaches:
    - apply the mean elevation rate of each basin to unobserved regions.
    - interpolation, e.g. Delauny triangulation, ordinary Kriging.

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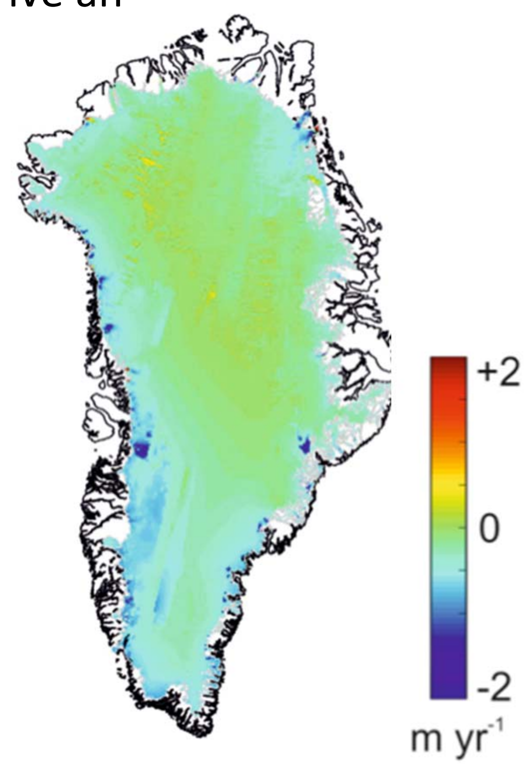
2. Model based approaches:
   - use external data fields, e.g. elevation, velocity, to derive an empirical model of elevation change.
   - model used to fill unobserved regions.

$$\frac{\boldsymbol{dz}}{\boldsymbol{dt}} = a\boldsymbol{l} + b\boldsymbol{z} + c\,\Delta\boldsymbol{v} + d$$

Use multiple linear regression to model elevation rate as a function of latitude (l), elevation (z) and velocity change (Δv).



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   - interpolation, e.g. Delauny triangulation, ordinary Kriging.

2. Model based approaches:
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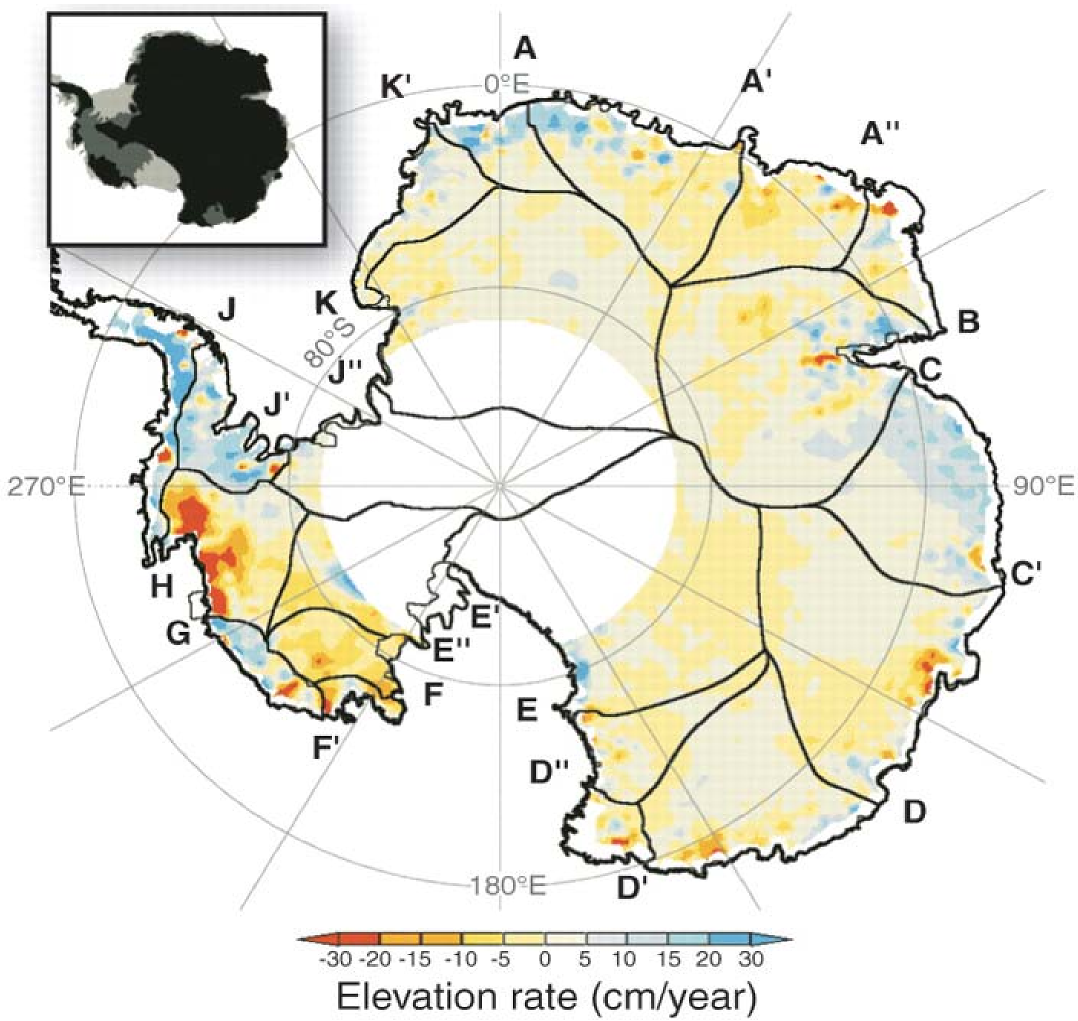
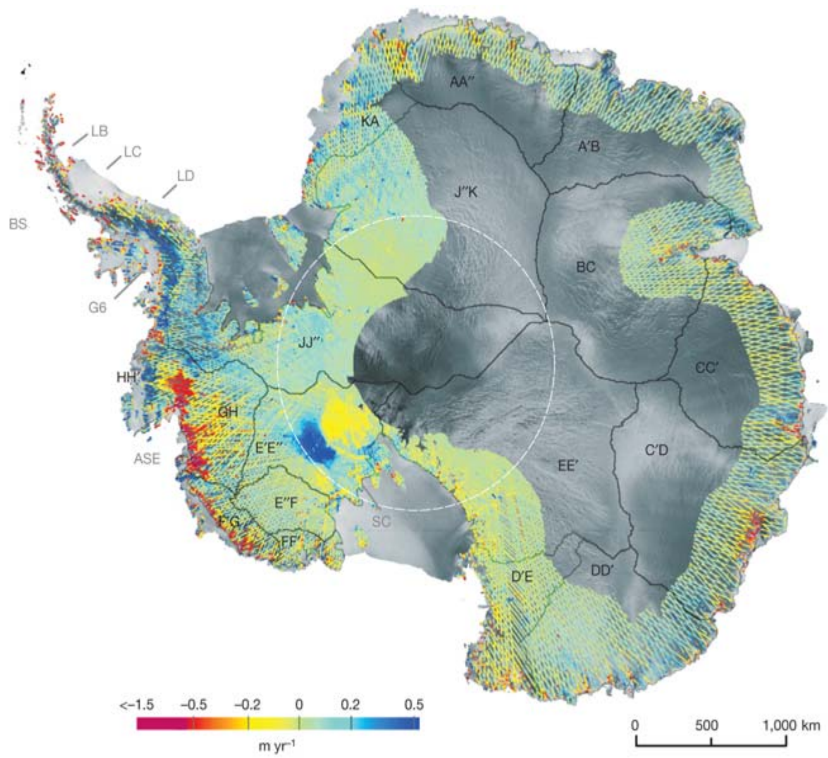
3. Combined approaches:
   - e.g. Kriging with external drift.
   - supplements Kriging with a background field, e.g. velocity, to guide interpolation in data sparse areas.

Cross-over solution - Antarctica

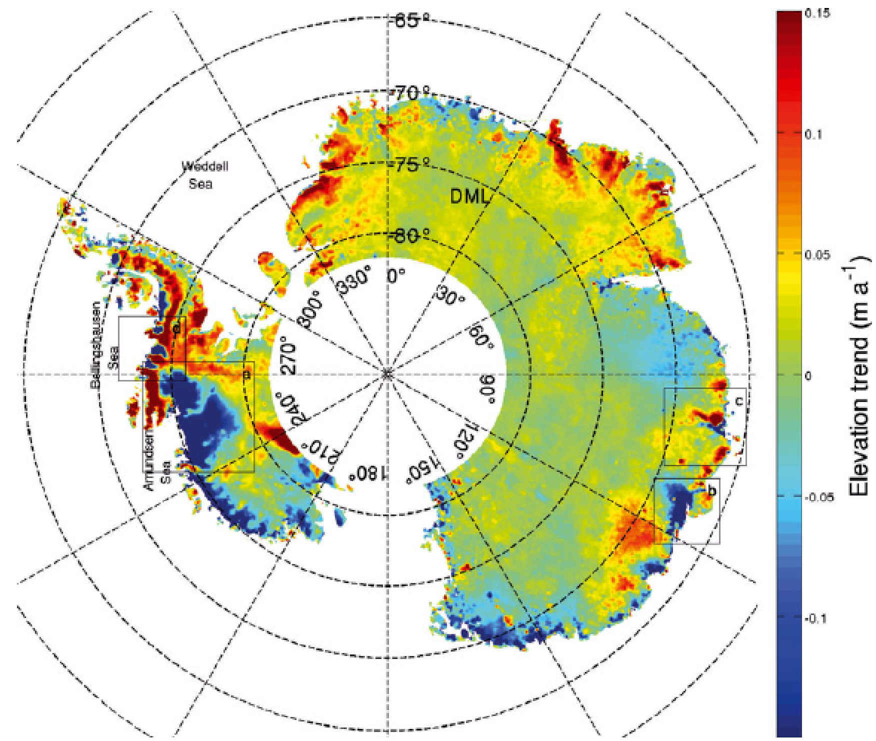


1992-2003 elevation change (Shepherd and Wingham, 2007)

Repeat track solutions - Antarctica



ICESat laser altimetry, 2003-2008

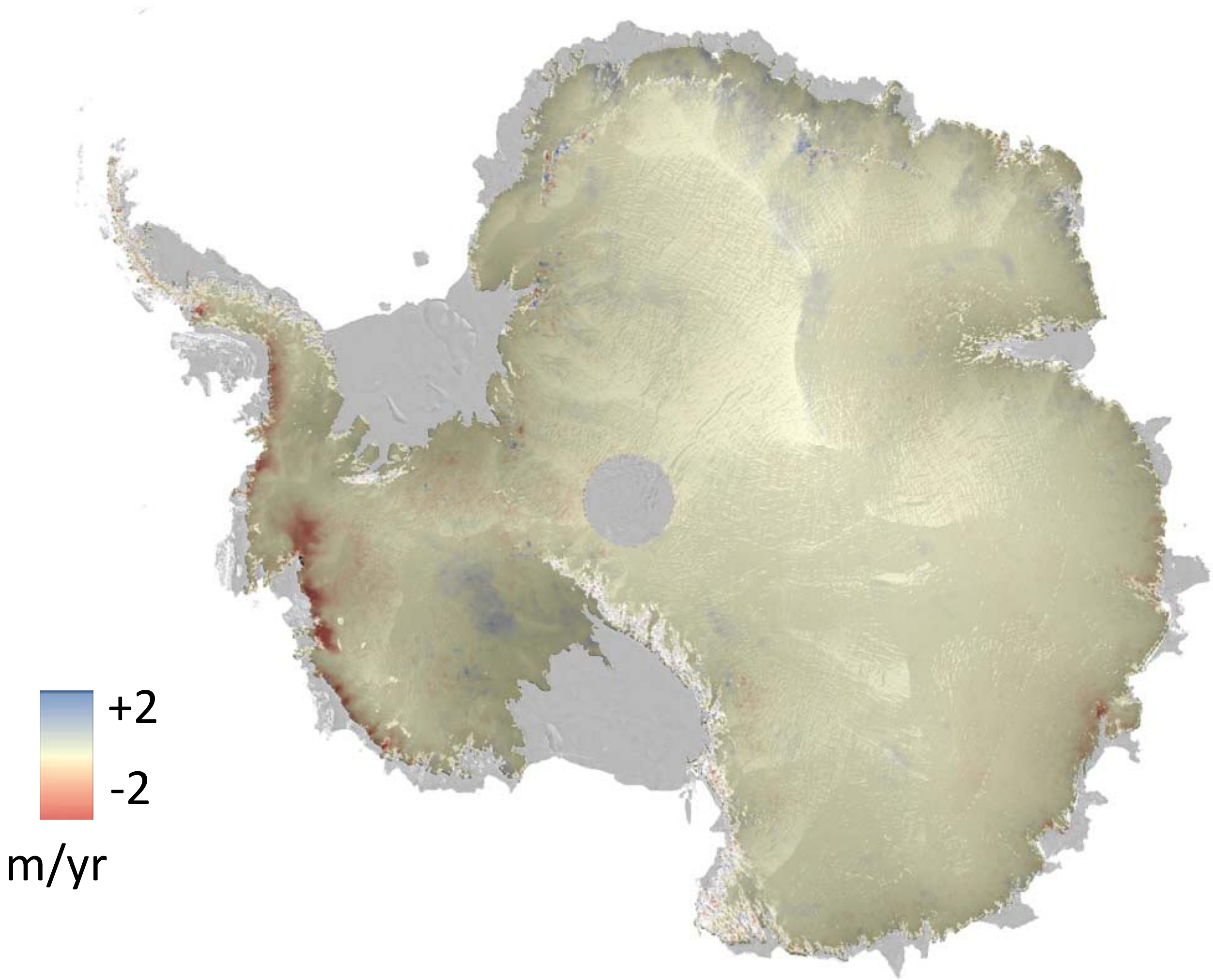


Envisat radar altimetry, 2002-2010

Pritchard et al. (2009)

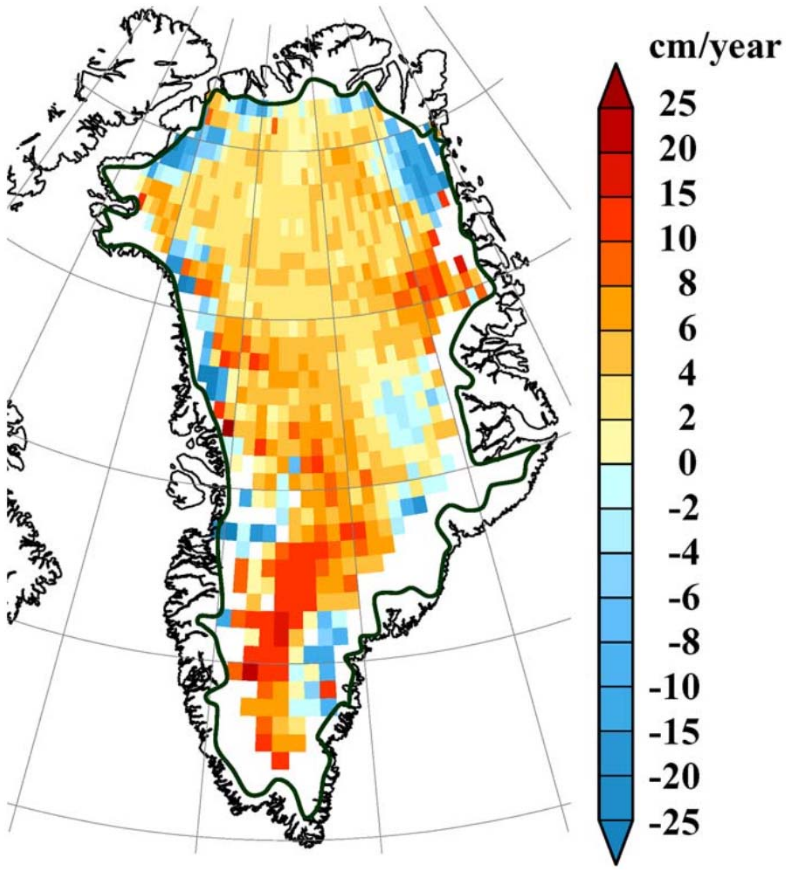
Flament and Remy (2012)

Model fit solution - Antarctica



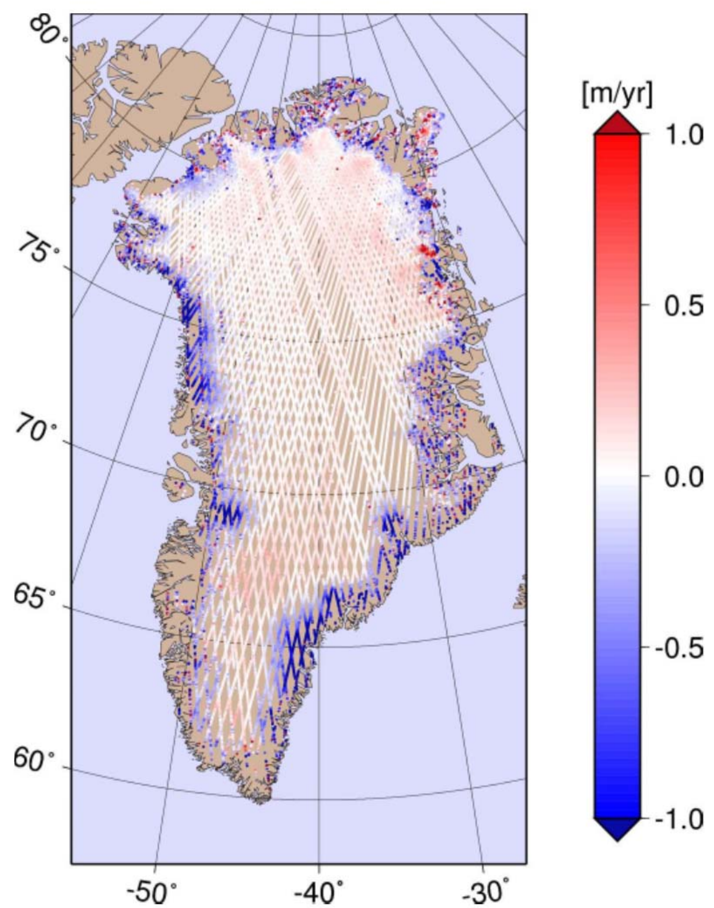
CryoSat-2 radar altimetry, 2010-2013

Cross-over solution - Greenland



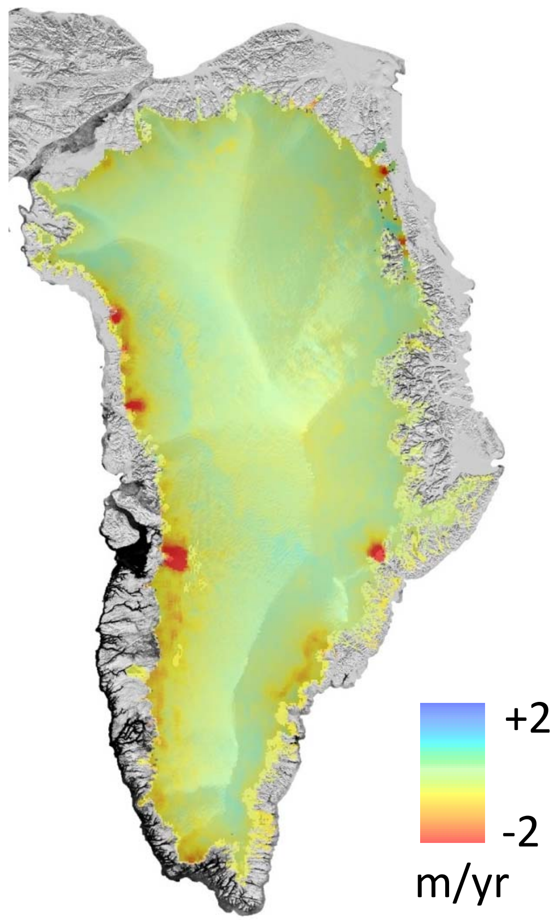
1992-2008 elevation change from radar altimetry
(Khvorostovsky, 2012)

Repeat track solution - Greenland



2003-2008 elevation change from laser altimetry
(Sørensen et al., 2012)

Model fit solution - Greenland



2011-2014 elevation change from radar altimetry,

Cross-over advantages

- The same location is repeatedly sampled in time, resulting in a smaller topographic contribution to dH.
- Uncorrelated measurement errors can be computed from height differences from the same cycle.

Cross-over advantages

- The same location is repeatedly sampled in time, resulting in a smaller topographic contribution to dH.

- Uncorrelated measurement errors can be computed from height differences from the same cycle.

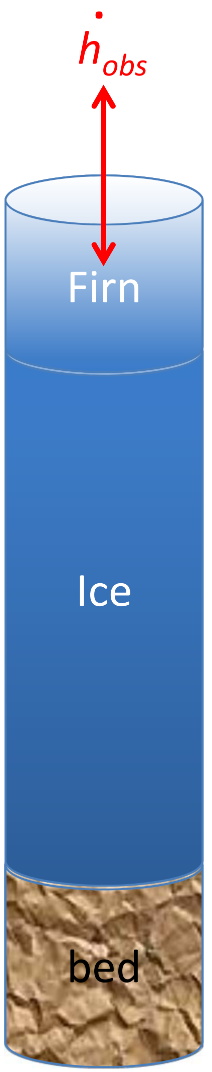
Repeat track / Model fit advantages

- Order of magnitude increase in the number of measurements available.

Determining ice sheet mass changes

Determining ice sheet mass changes

$$\dot{h}_{obs} = \dot{h}_{SMB} + \dot{h}_{dyn} + \dot{h}_{fc} + \dot{h}_{bed} + \dot{h}_{bmb}$$



Elevation changes not associated with change in ice mass

$$\dot{h}_{obs} = \dot{h}_{SMB} + \dot{h}_{dyn} + \dot{h}_{fc} + \dot{h}_{bed} + \dot{h}_{bmb}$$

- firn compaction – change in density but not mass.
- bed elevation:
    - GIA – glacio-isostatic adjustment

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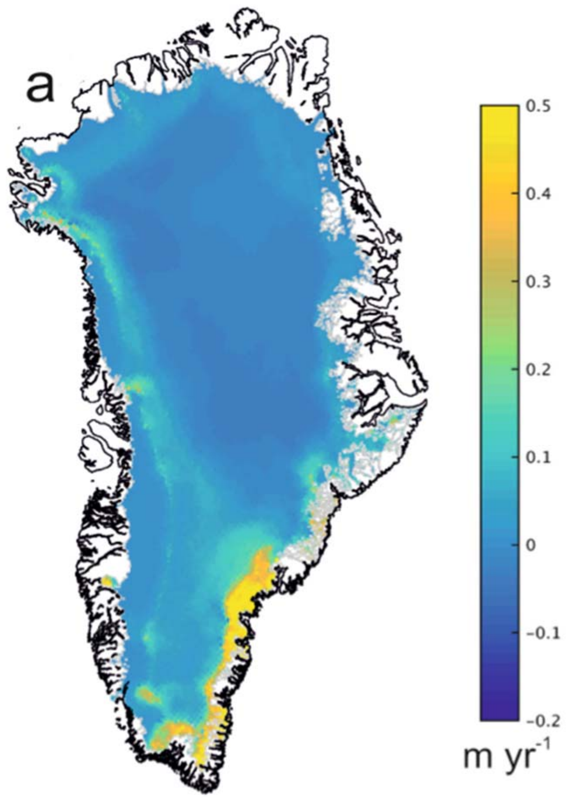
- firn compaction – change in density but not mass.
- bed elevation:
  - GIA – glacio-isostatic adjustment

These contributions can be modelled and either:

- an explicit correction applied to the observed elevation rates, or
- their magnitude included as a term in the uncertainty budget.



2011-2014 rate of elevation change, due to anomalies in firn compaction, from IMAU-FDM.

Determining ice sheet mass changes

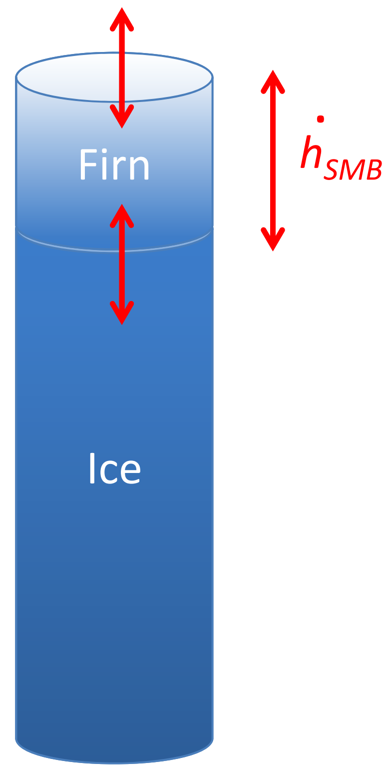
$$\dot{h}_{obs} = \dot{h}_{SMB} + \dot{h}_{dyn} + \dot{h}_{fc} + \dot{h}_{bed} + \dot{h}_{bmb}$$

Basal mass balance – assumed to be negligible (not for ice shelves).

Determining ice sheet mass changes

$$\dot{h}_{obs} = \dot{h}_{SMB} + \dot{h}_{dyn} + \dot{h}_{fc} + \dot{h}_{bed} + \dot{h}_{bmb}$$

Leaves changes in the thickness of the firn and ice column, driven by mass loss or gain.



Firn

Thickness of the firn column changes when **SMB** deviates away from steady state conditions, usually defined as the long term (climatological) mean SMB.

i.e. when mass exchange at the upper and lower boundaries of the firn column are not in balance.

Determining ice sheet mass changes

$$\dot{h}_{obs} = \dot{h}_{SMB} + \dot{h}_{dyn} + \dot{h}_{fc} + \dot{h}_{bed} + \dot{h}_{bmb}$$

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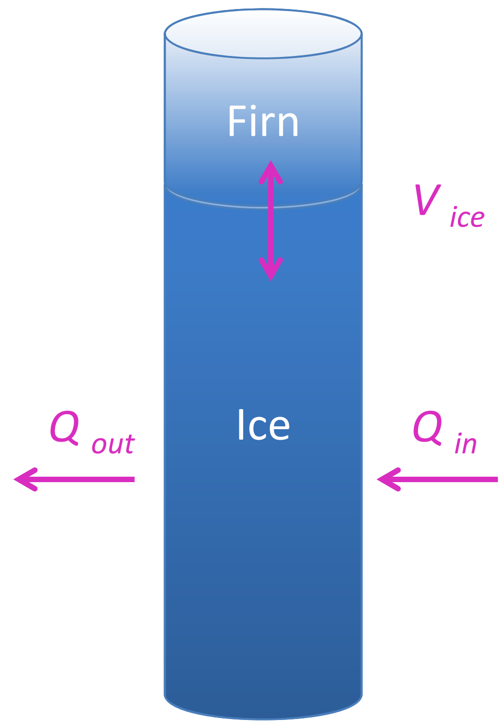


Ice

Thickness of the ice column changes when ice flux into the column is not in balance with ice flux out of the column.

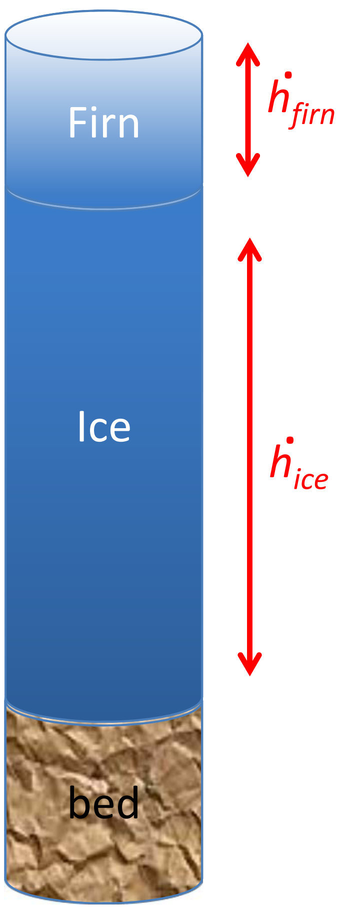
i.e. when mass exchange at the lateral and upper boundaries of the ice column are not in balance.

For example resulting from changes in ice dynamics.

Determining ice sheet mass changes

- To convert from elevation change to mass change, need the density of the mass gained or lost.

- Therefore need to partition observed elevation changes according to whether they have occurred within the firn or the ice column.



Determining ice sheet mass changes

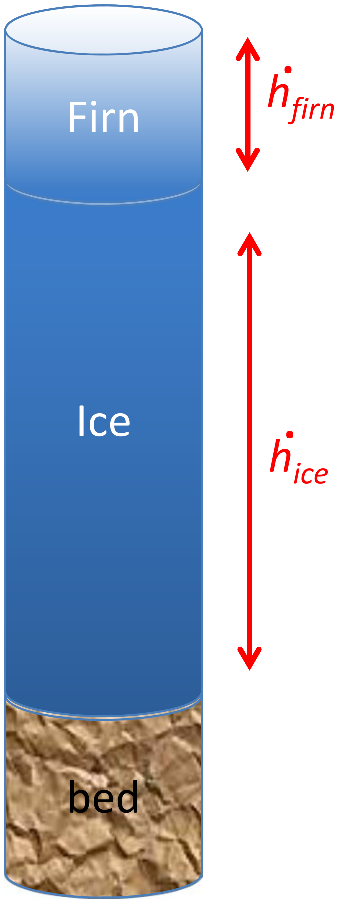
- To convert from elevation change to mass change, need the density of the mass gained or lost.

- Therefore need to partition observed elevation changes according to whether they have occurred within the firn or the ice column.

- 2 strategies:

  1. Use an empirical model to define regions undergoing dynamic and SMB driven changes.

  2. Use a firn model to simulate SMB driven changes and isolate the underlying ice dynamic imbalance.



1. Use an empirical model to define regions undergoing dynamic and SMB driven changes.

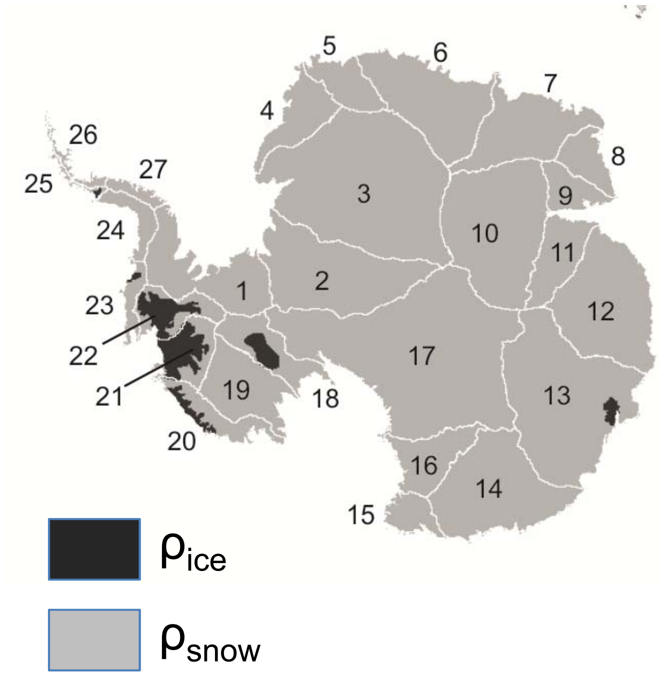
Simple model

Binary model for Greenland:

- ρ_{snow} > ELA
- ρ_{ice} < ELA

Binary model for Antarctica:

- ρ_{snow} < T_{dyn}
- ρ_{ice} > T_{dyn}

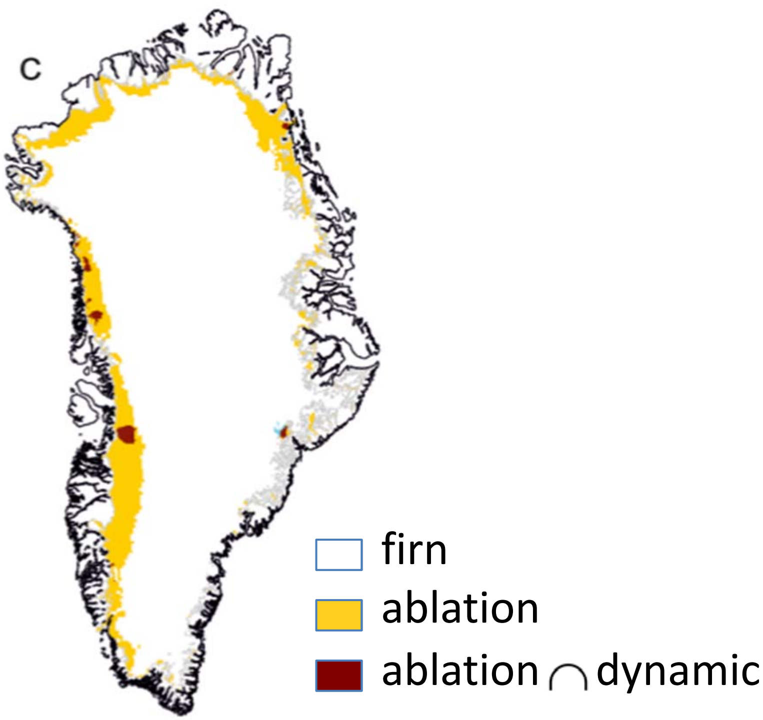


T_{dyn} is a threshold based on auxiliary data, for example elevation rate and velocity.

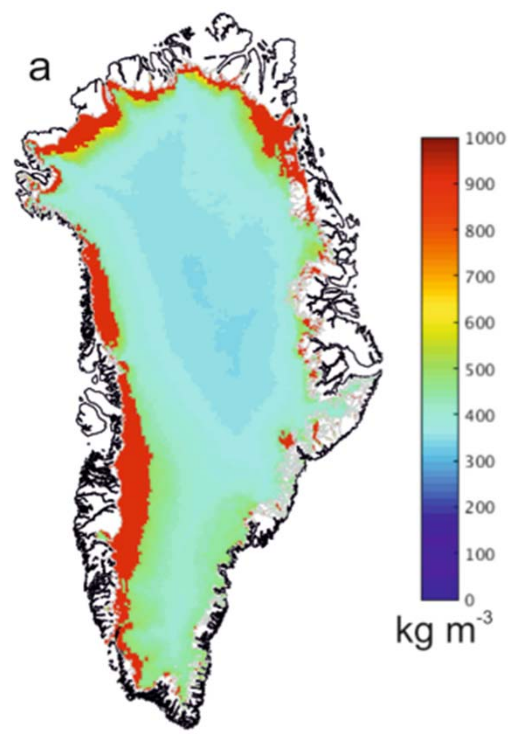
1. Use an empirical model to define regions undergoing dynamic and SMB driven changes.

Refined model

Simulate spatial and temporal variations in ρ_{snow} and use auxiliary datasets to identify regions of ice dynamic imbalance.



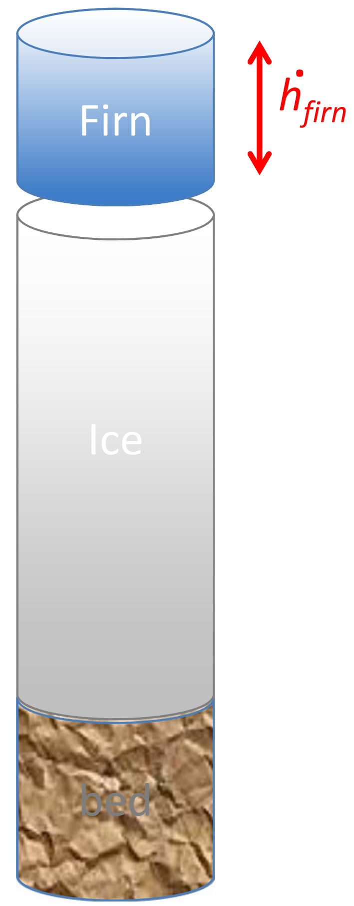
Greenland density model definition.



Greenland density model.

2. Use a firn model to simulate SMB driven changes and isolate the underlying ice dynamic imbalance.

- Model SMB thickness changes, including deposition, removal and compaction.
- Subtract modelled SMB thickness change from observed change to estimate dynamic thickness change of underlying ice column.
- Convert ice thickness change to mass at density of ice.
- Add modelled SMB mass change from regional climate model to get total mass balance.



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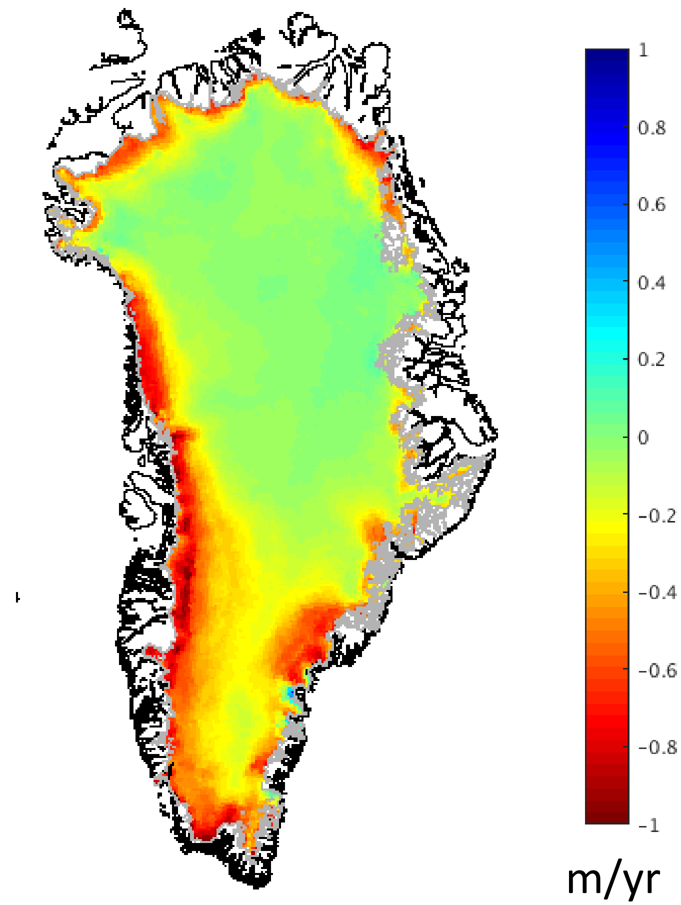

IMAU-FDM rate of SMB driven thickness change, 2011-2014.

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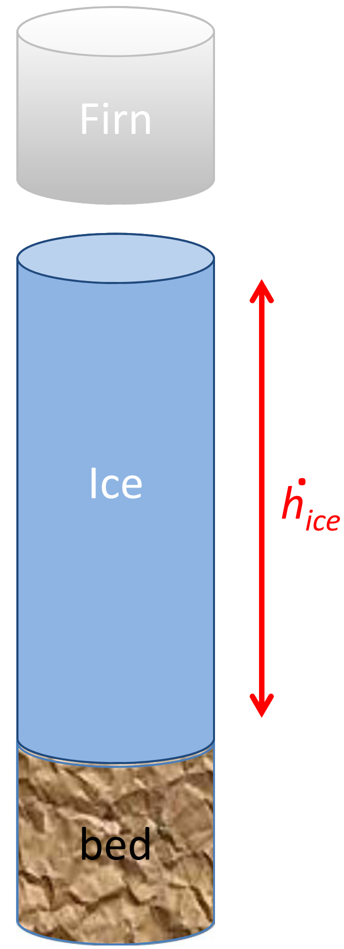

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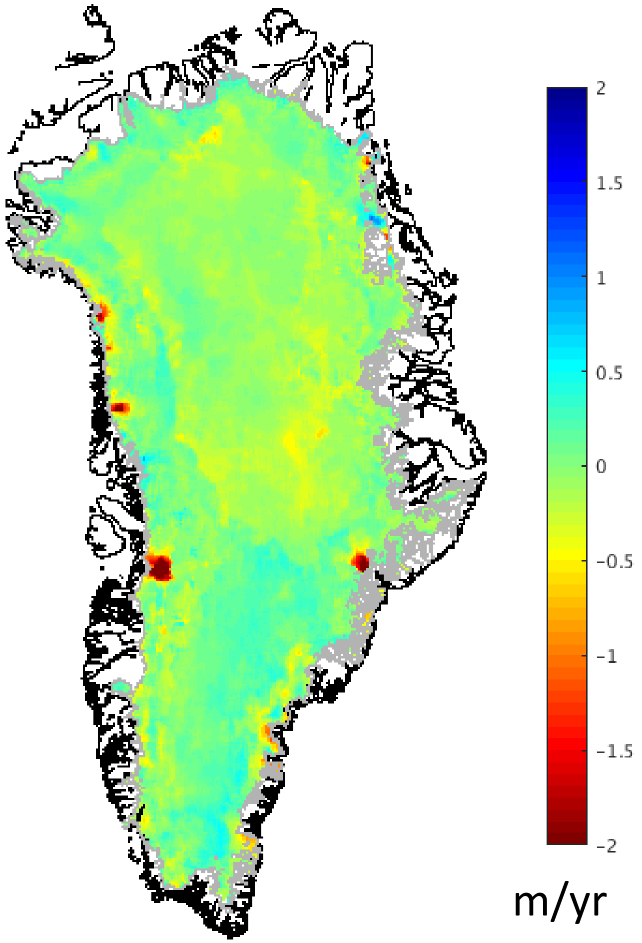

Ice column thickness change, 2011-2014.

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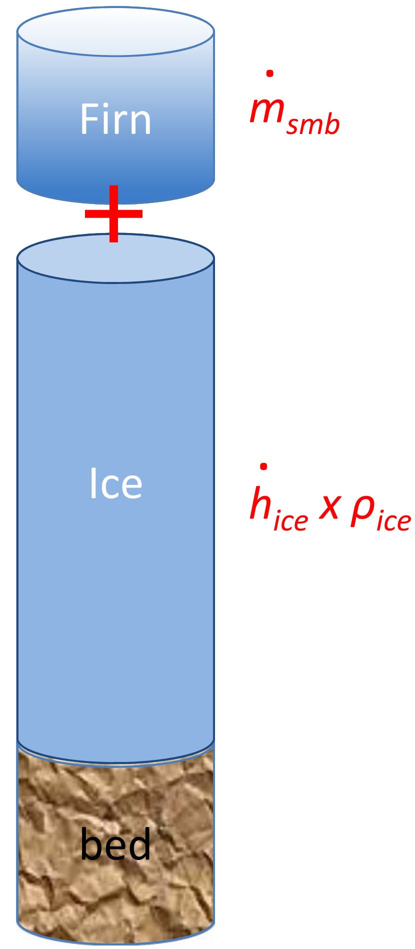

1. Use an empirical model to define regions undergoing dynamic and SMB driven changes.

Advantages

- Avoids observational and model errors being interpreted as ice imbalance across the ice sheet interior.
- For example:

small elevation rate errors x high density x large area

can accumulate into relatively large mass balance signals.

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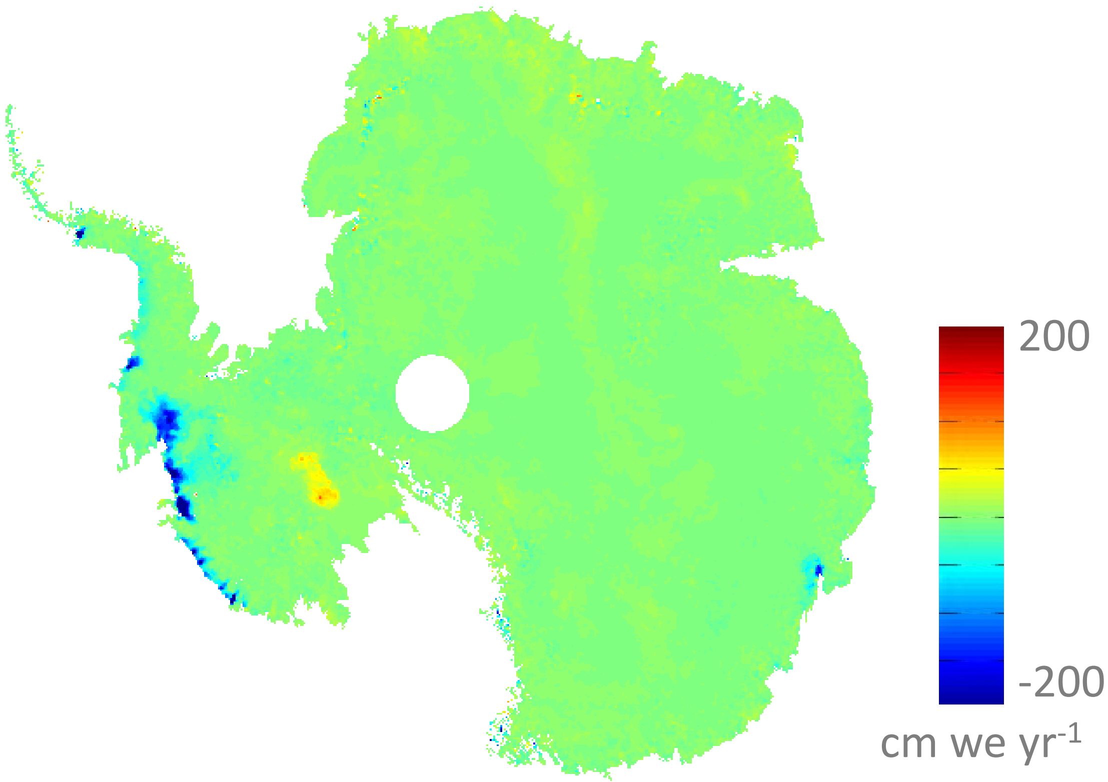
2. Use a firn model to simulate SMB driven changes and isolate the underlying ice dynamic imbalance.

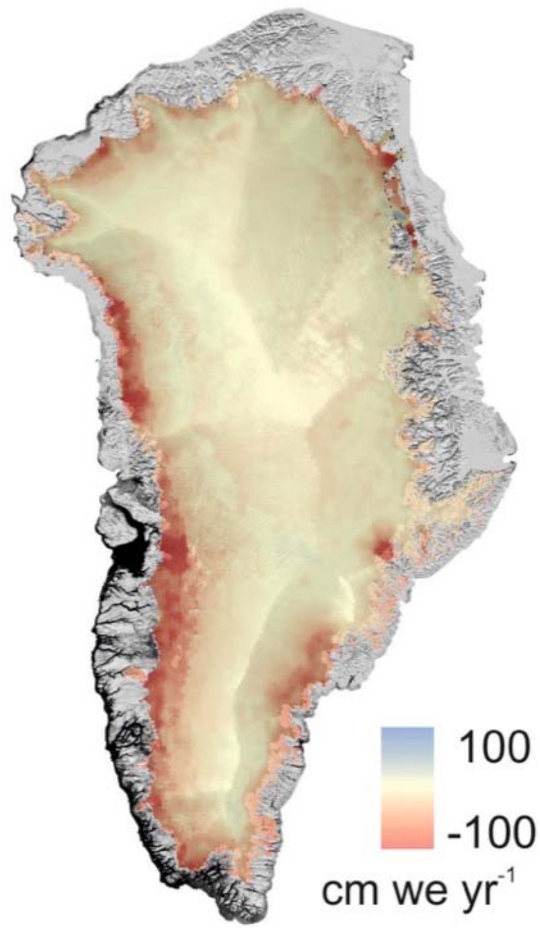
Advantages

- Avoids relying on an *a priori* model for where ice dynamic imbalance is occurring.
- For example, allows for the possibility that dynamic imbalance is occurring across the ice sheet interior.

Ice sheet specific mass balance

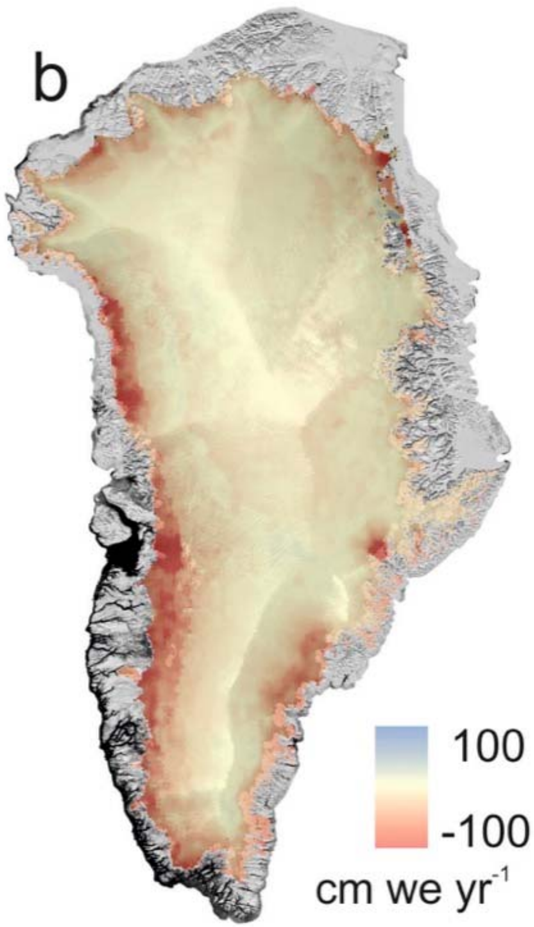


Antarctic rate of mass change, from CryoSat-2.

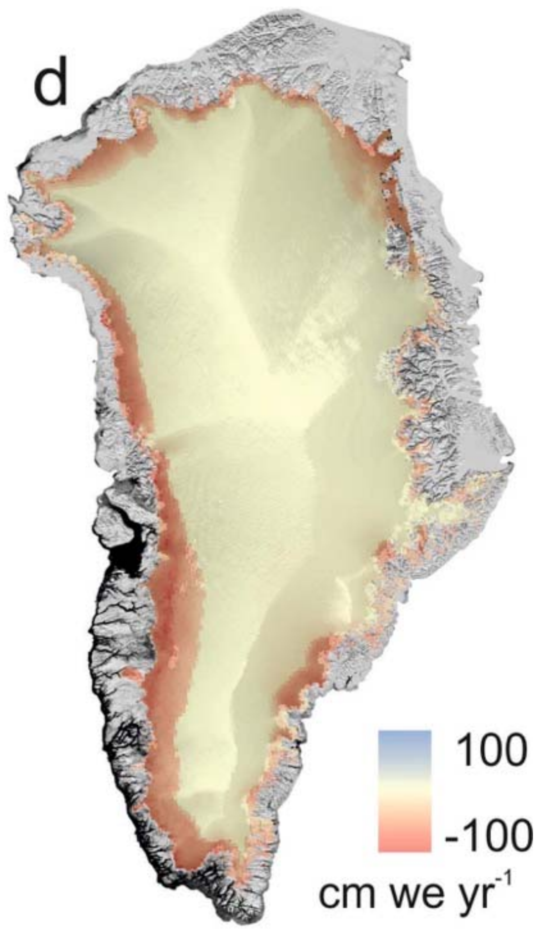


Greenland rate of mass change, from CryoSat-2.

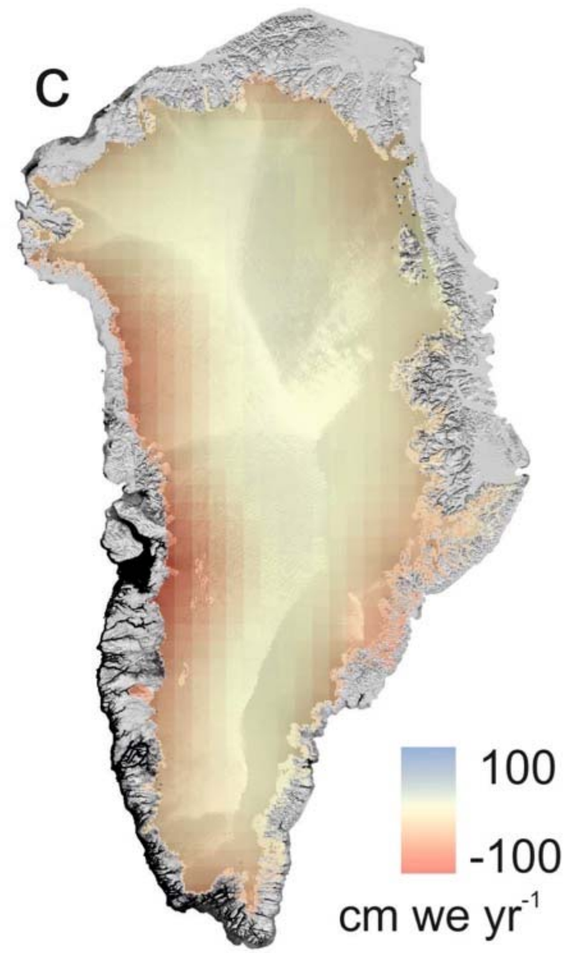
Ice sheet specific mass balance - comparisons



Rate of mass change
from CryoSat-2.

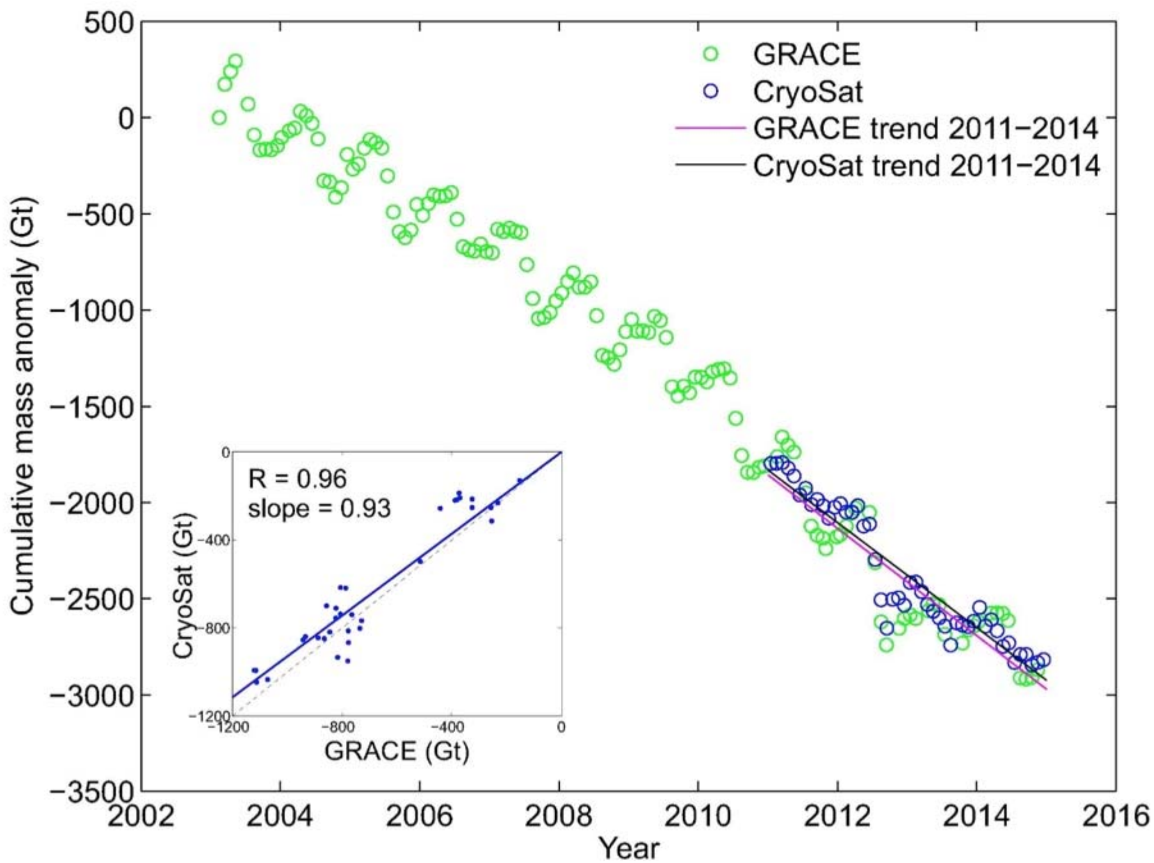


Rate of mass change
from RACMO2.3
(SMB only).



Rate of mass change
from GRACE.

Time series of mass evolution



Monthly time series of Greenland mass evolution
from GRACE (green) and CryoSat-2 (blue).

Principle Sources of Uncertainty*

1. Rates of elevation change
2. Density model used for volume to mass conversion
3. Accounting for omission areas
4. Correction for mass conserving processes

* Lots of approaches exist. This is one example based on a density model approach for the volume to mass conversion in Greenland.

Principle Sources of Uncertainty

1. Rates of elevation change.
    - Instrument effects (e.g. radar speckle).
    - Processing effects (e.g. retracking).
    - Elevation rate model limitations (i.e. how well does the functional form of the model reflect reality).
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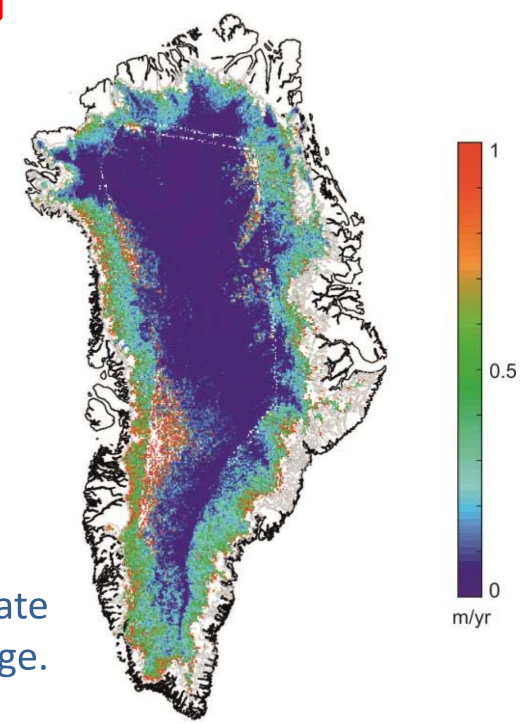
Estimated during model fit.



1-sigma uncertainty on rate of elevation change.

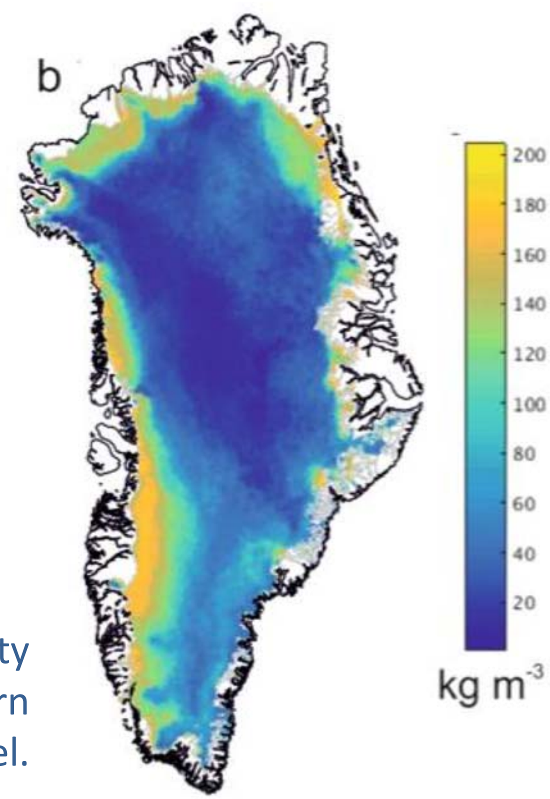
Principle Sources of Uncertainty

1. Rates of elevation change.
   - Instrument effects (e.g. radar speckle).
   - Processing effects (e.g.retracking).
   - Elevation rate model limitations (i.e. how well does the functional form of the model reflect reality).
   - Snowpack effects (e.g. changes in the depth distribution of backscattered energy).
     - Mitigate using a backscatter correction.
     - Estimate empirically, e.g. based on Greenland 2012 melt event.
     - Area of ongoing research.

Principle Sources of Uncertainty

1. Rates of elevation change.

2. Density model used for volume to mass conversion.
   - Estimate uncertainty based on model simulations..



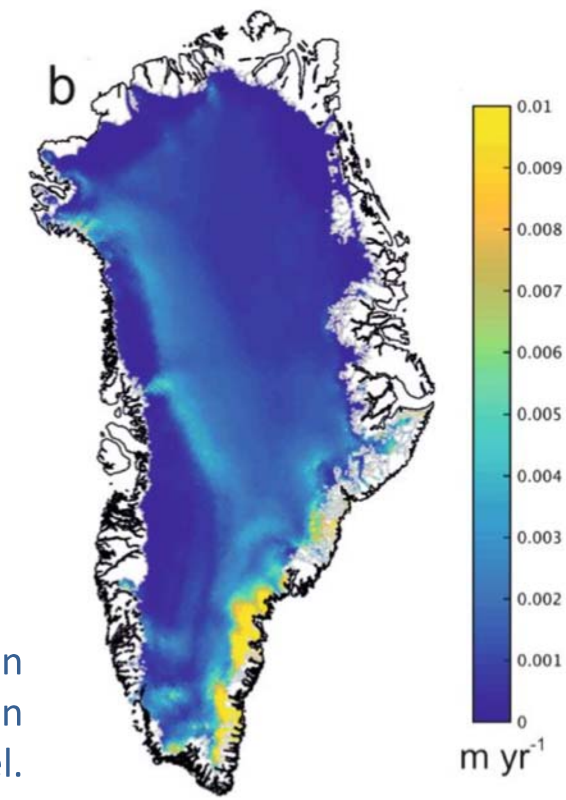
Estimate of density uncertainty based upon the IMAU firn densification model.

Principle Sources of Uncertainty

1. Rates of elevation change.
2. Density model used for volume to mass conversion.
3. Accounting for omission areas.
    - Statistical uncertainty from interpolation scheme or regression model.

Principle Sources of Uncertainty

1. Rates of elevation change.
2. Density model used for volume to mass conversion.
3. Accounting for omission areas.
4. Correction for mass conserving processes.
   - Estimate firn compaction correction uncertainty based upon model simulations.
   - Estimate magnitude of bed elevation change from GIA model.



Estimate of firn compaction correction uncertainty based upon the IMAU firn densification model.

Current Frontiers for Radar Altimetry

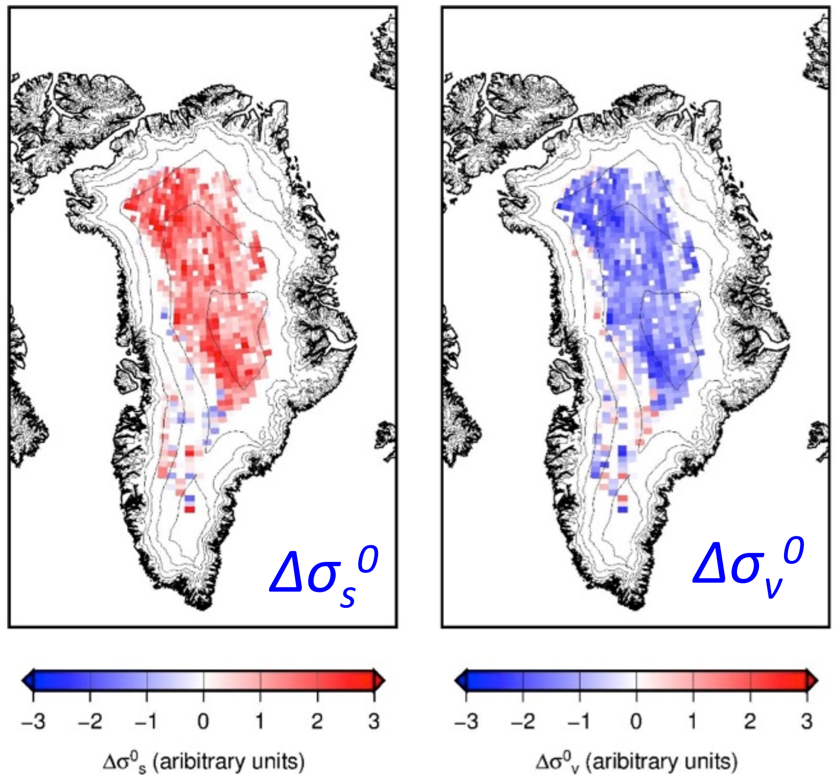
1. Improving understanding of radar wave interaction with the snowpack.

2. Inter-mission cross-calibration for continuous time series generation.

3. Managing the transition from low to high resolution measurements.

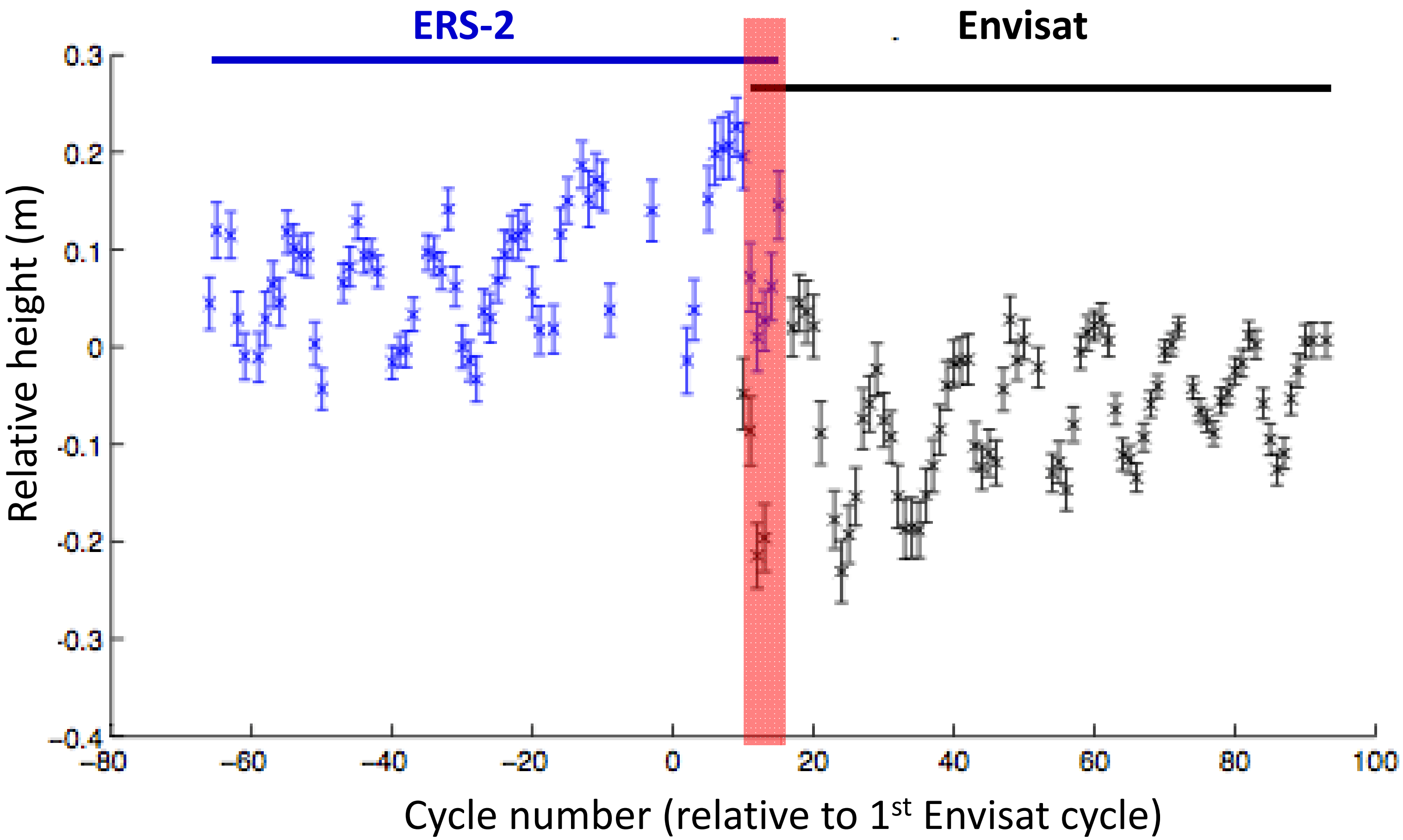
1. Improving understanding of radar wave interaction with the snowpack.

Change in scattering characteristics during summer 2012 melt event.



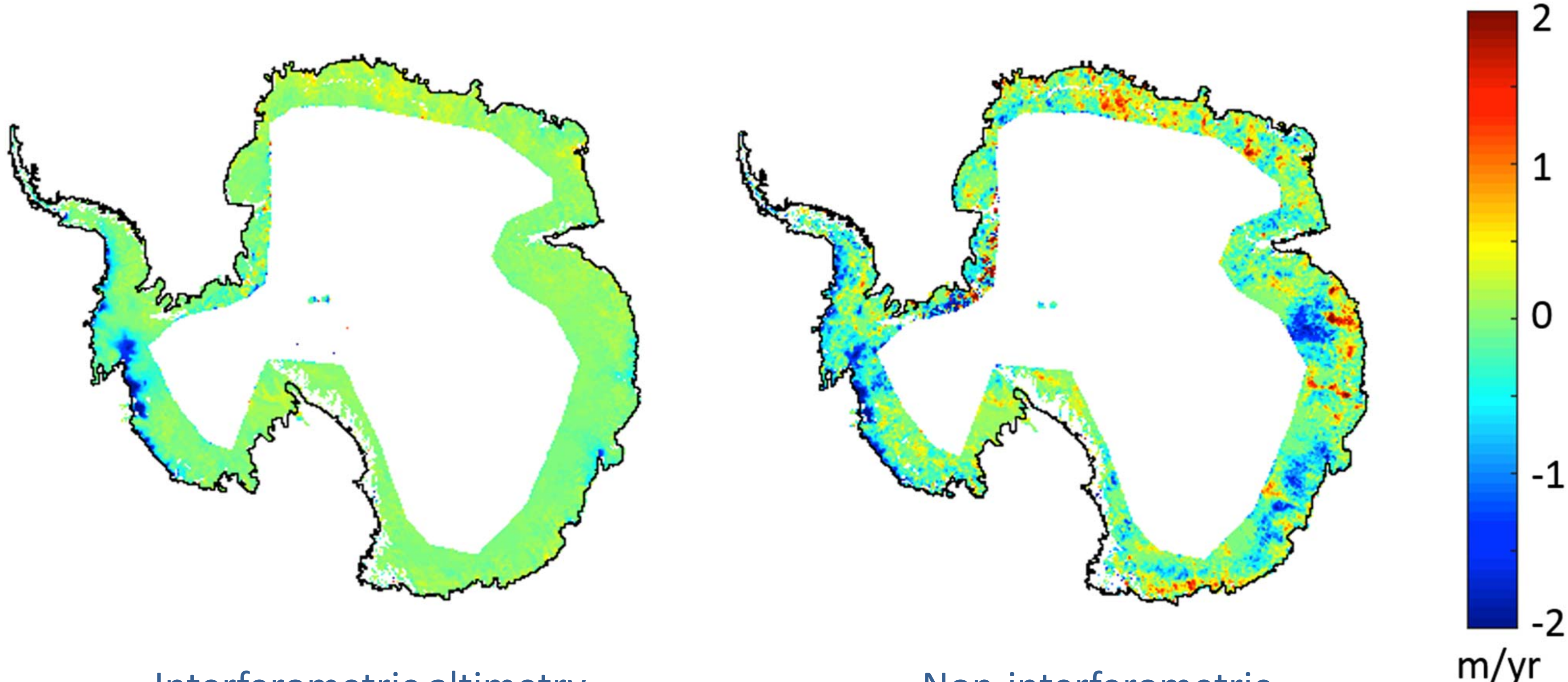
- Retrieval of scattering properties from the radar echo.
- Use to investigate snowpack related artifacts.

2. Inter-mission cross-calibration for continuous time series generation.



3. Managing the transition from low to high resolution measurements.

- Comparisons between interferometric and non-interferometric high resolution altimetry

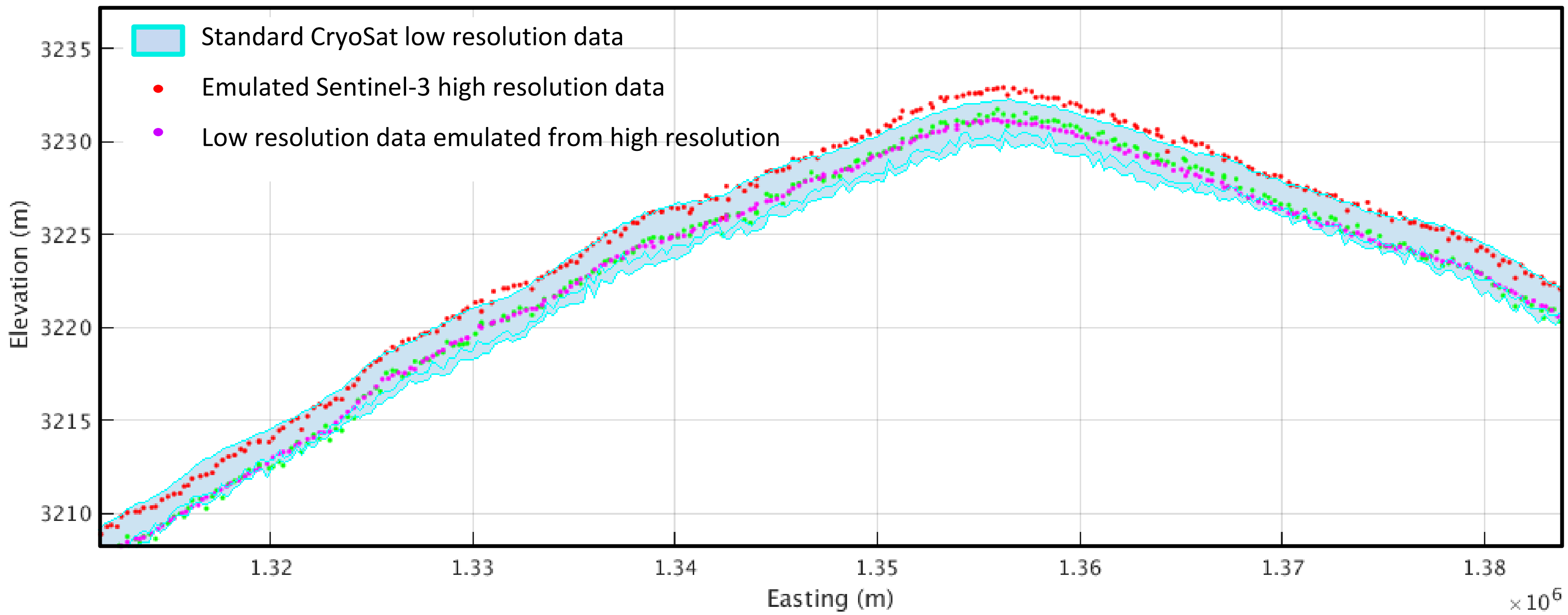


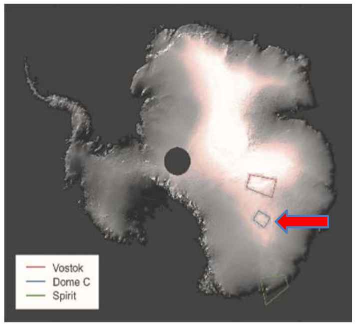
Interferometric altimetry elevation rates

Non-interferometric altimetry elevation rates

3. Managing the transition from low to high resolution measurements.

- Comparison between high and low resolution altimetry.
- Assessment of whether the latter can be simulated from the former.





Comparison of high and low resolution data over Dome C in East Antarctica, and capability to generate a pseudo low resolution product to facilitate merging of full altimeter record.

Summary and Outlook

- 25 year record of ice sheet elevation change from radar altimetry.
- Longest continuous record of all geodetic techniques.
- Unlike GRACE doesn’t measure mass change directly, and so additional processing steps and assumptions are required to convert to mass.
- Able to provide high resolution measurements of mass balance, at the basin scale and with monthly temporal sampling.
- Observations can be combined with regional climate and firn model simulations to investigate processes driving change.

Summary and Outlook

- Provision of future measurements with the Sentinel-3 and ICESat-2 satellites, allowing the continuation of long-term, systematic monitoring programmes.