

A satellite altimetry map of the Southern Ocean, showing bathymetry and ice sheet mass balance. The map features a color gradient from dark blue (deep ocean) to light blue/green (shallow ocean). A circular inset in the upper left shows a detailed view of the ice sheet. The text "Ice sheet mass balance from satellite altimetry" is centered in the upper half. The text "Kate Briggs (Mal McMillan)" is centered below the title. The "cpom" logo is in the bottom right corner.

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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- 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



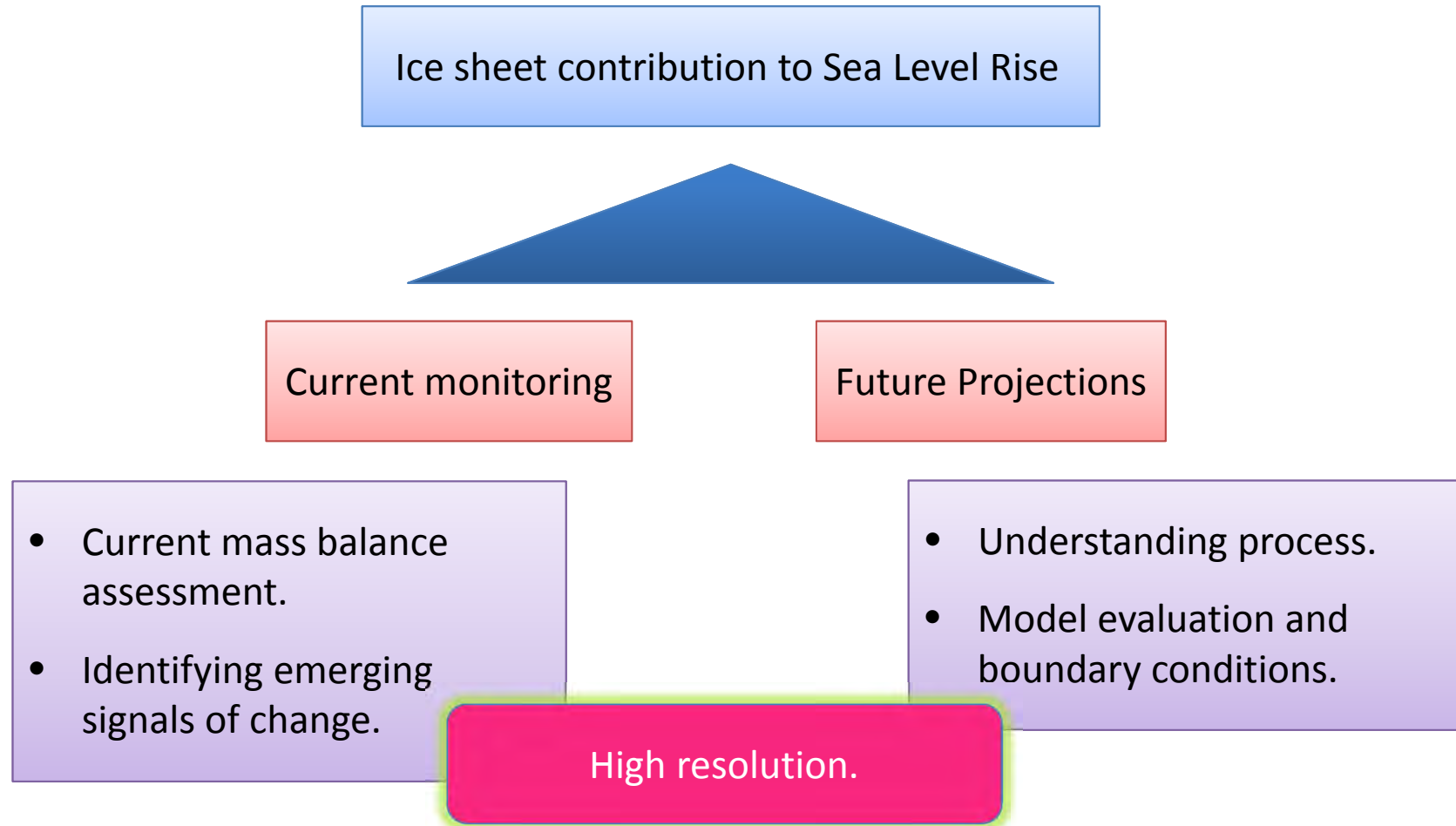
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graph TD; A[Ice sheet contribution to Sea Level Rise] --> B[Current monitoring]; A --> C[Future Projections]; B --> D["• Current mass balance assessment.  
• Identifying emerging signals of change."]; C --> E["• Understanding process.  
• Model evaluation and boundary conditions."];
```

Current monitoring

- Current mass balance assessment.
- Identifying emerging signals of change.

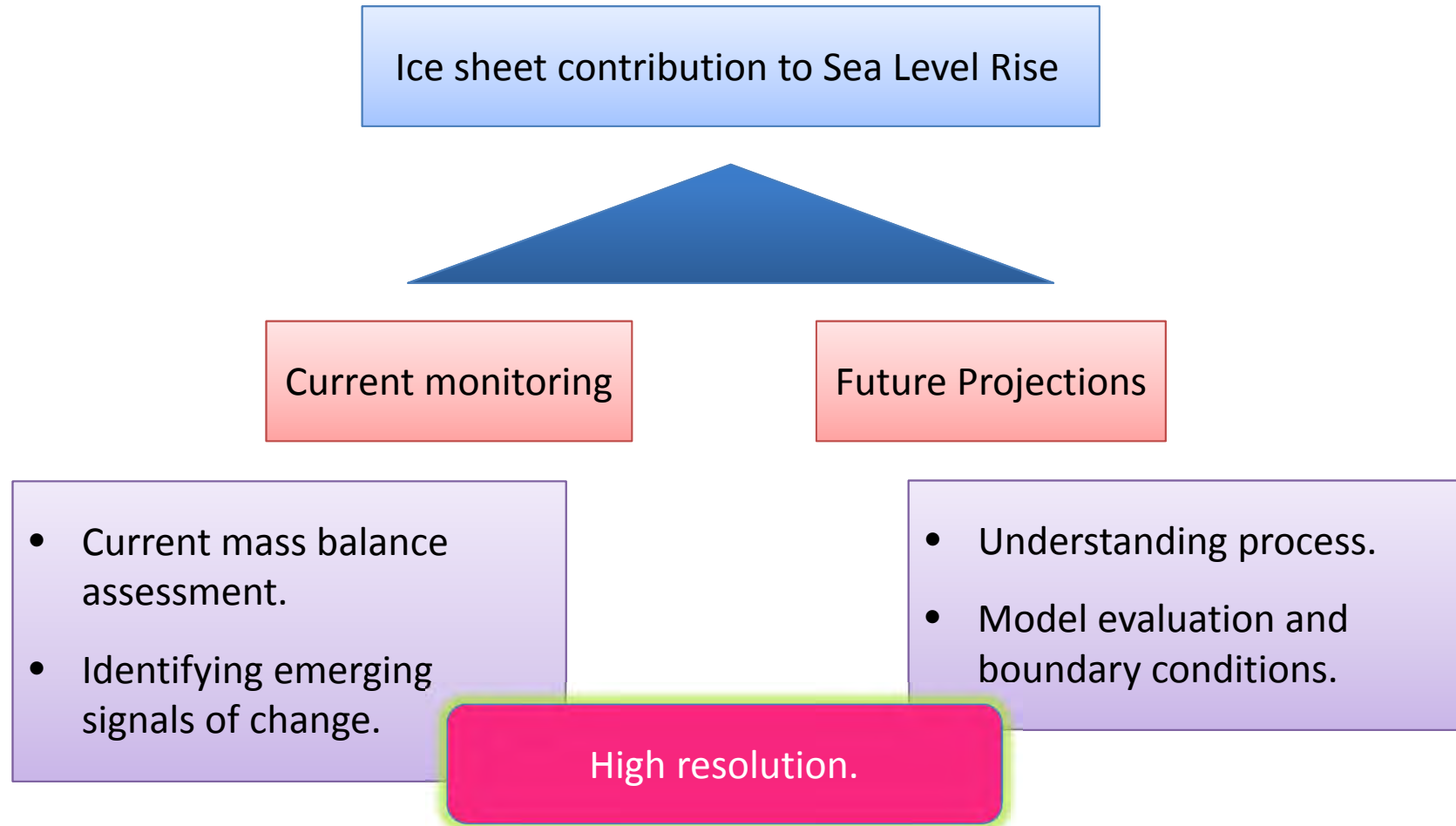
Future Projections

- 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

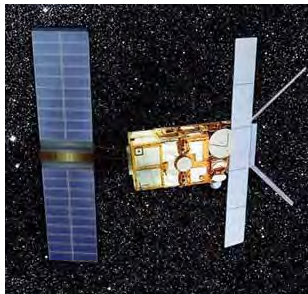
* Focus here on radar altimetry but large overlap with laser altimetry *

Polar orbiting radar altimeter missions

ERS-1



ERS-2



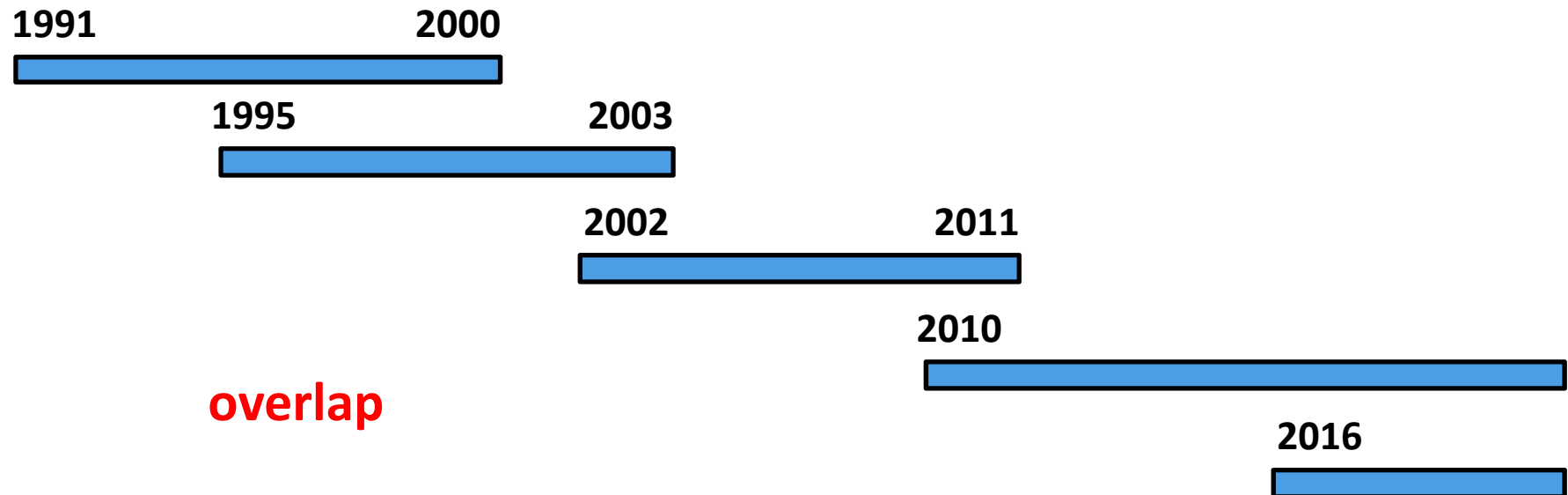
ENVISAT



CryoSat-2



Sentinel-3

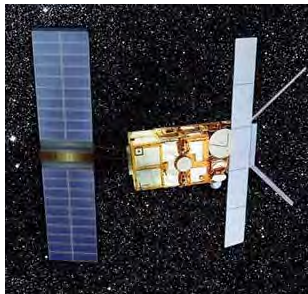


Polar orbiting radar altimeter missions

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Repeat measurement every ~ 35 days



369 day repeat



(30 day subcycle)

27 day repeat

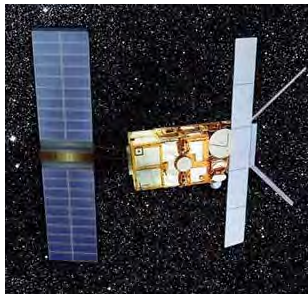


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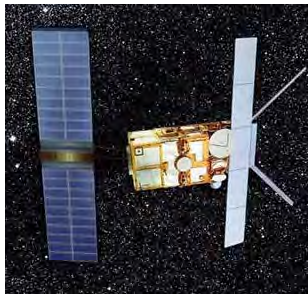
Regular, near continuous record of surface elevation change

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

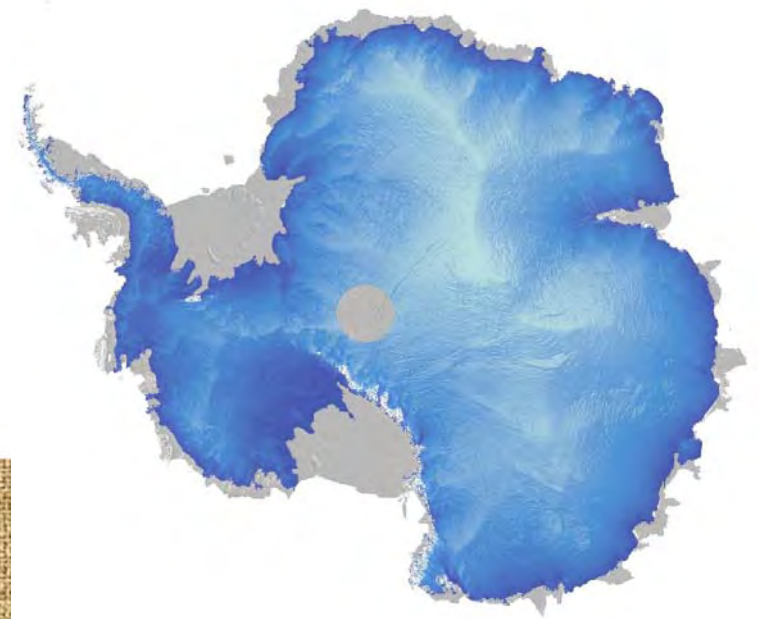
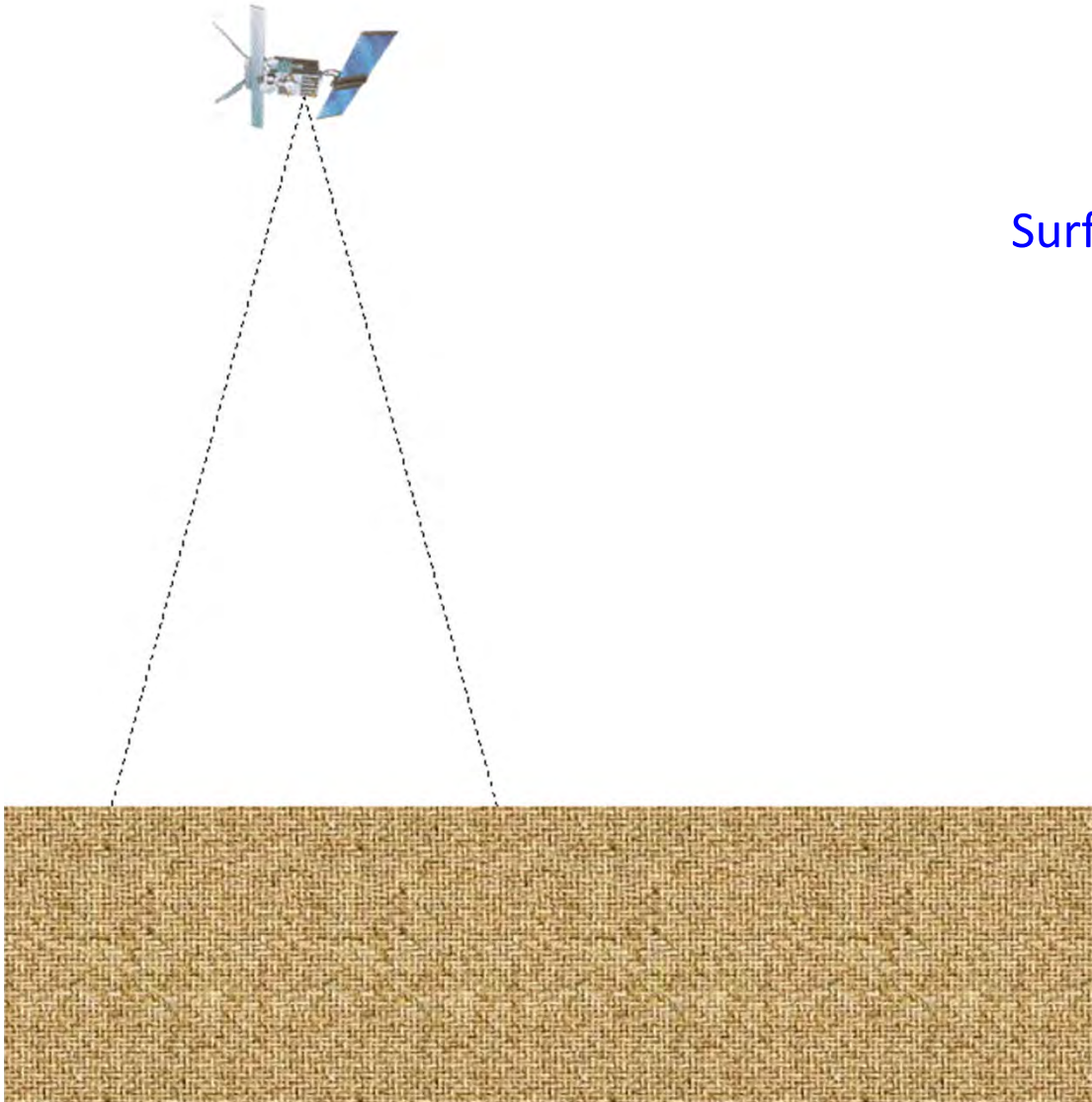
Measures time taken for
electromagnetic pulse to be
reflected back from Earth's surface.

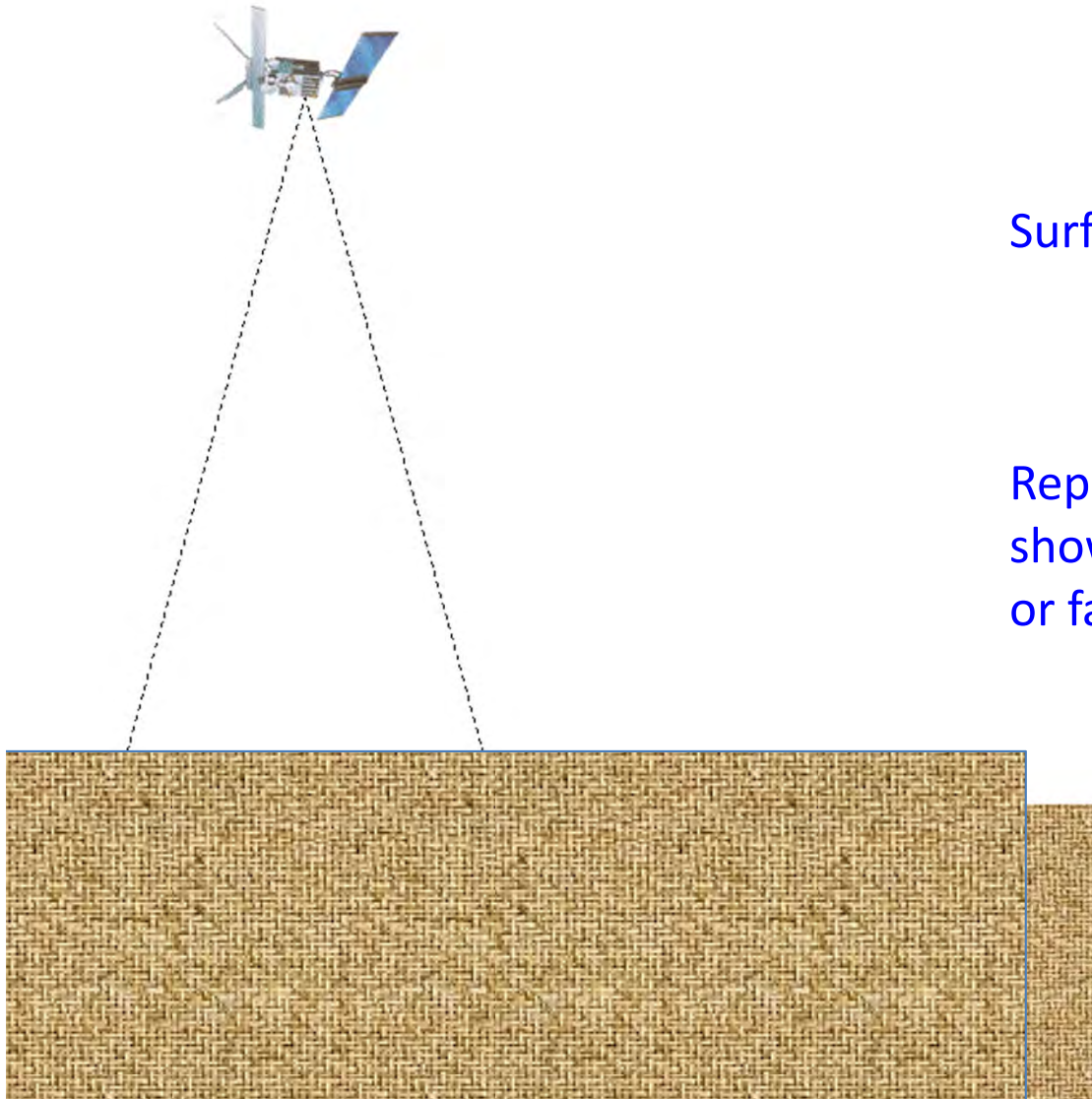


Measures time taken for
electromagnetic pulse to be
reflected back from Earth's surface.



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.



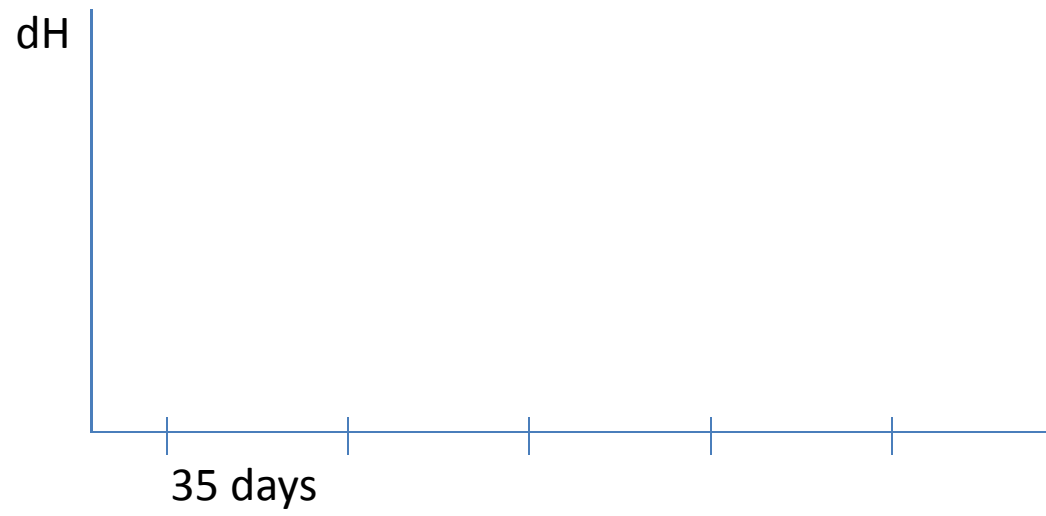
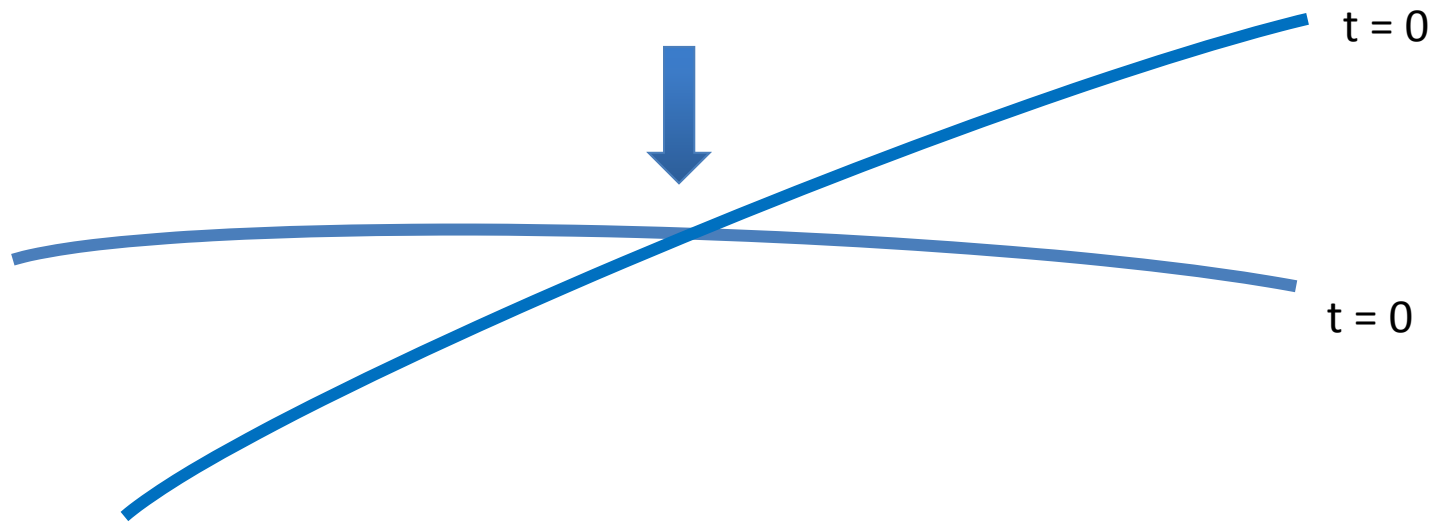
Measuring surface elevation change

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

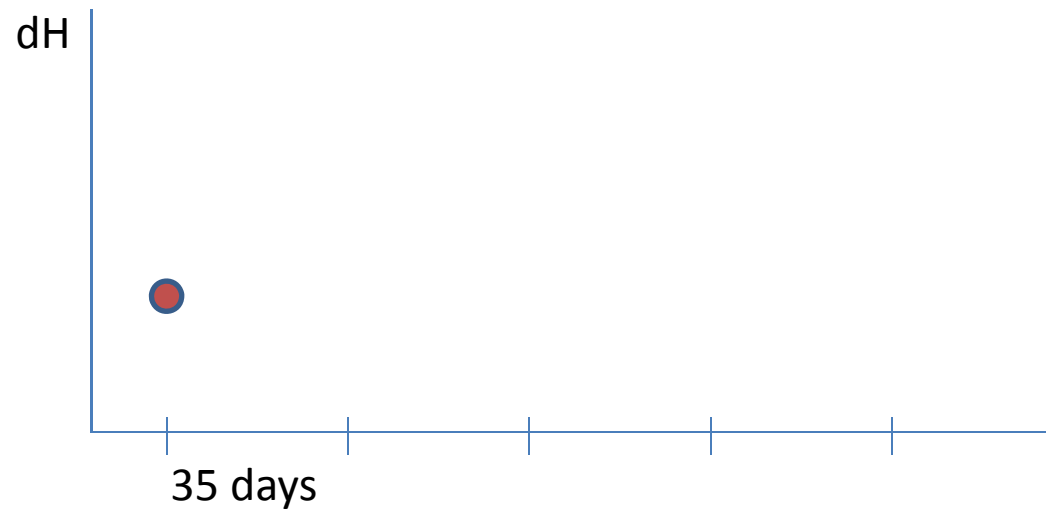
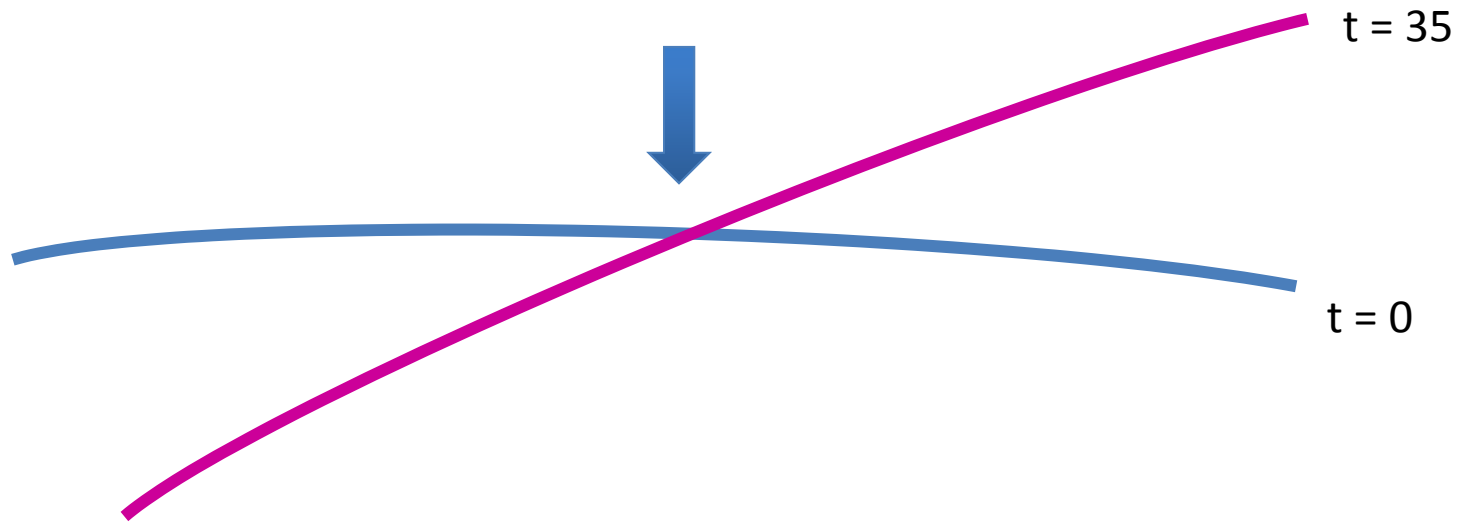
Cross-over Method

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

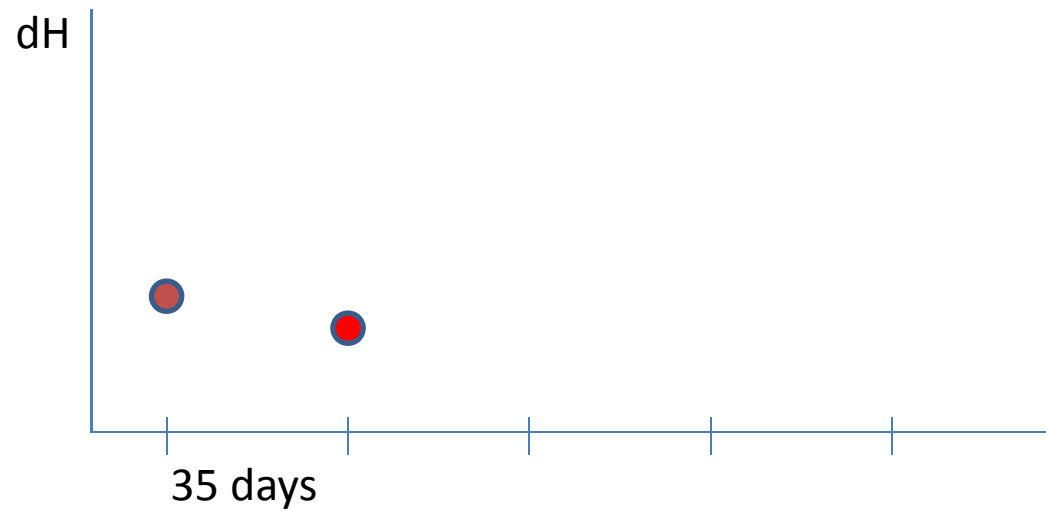
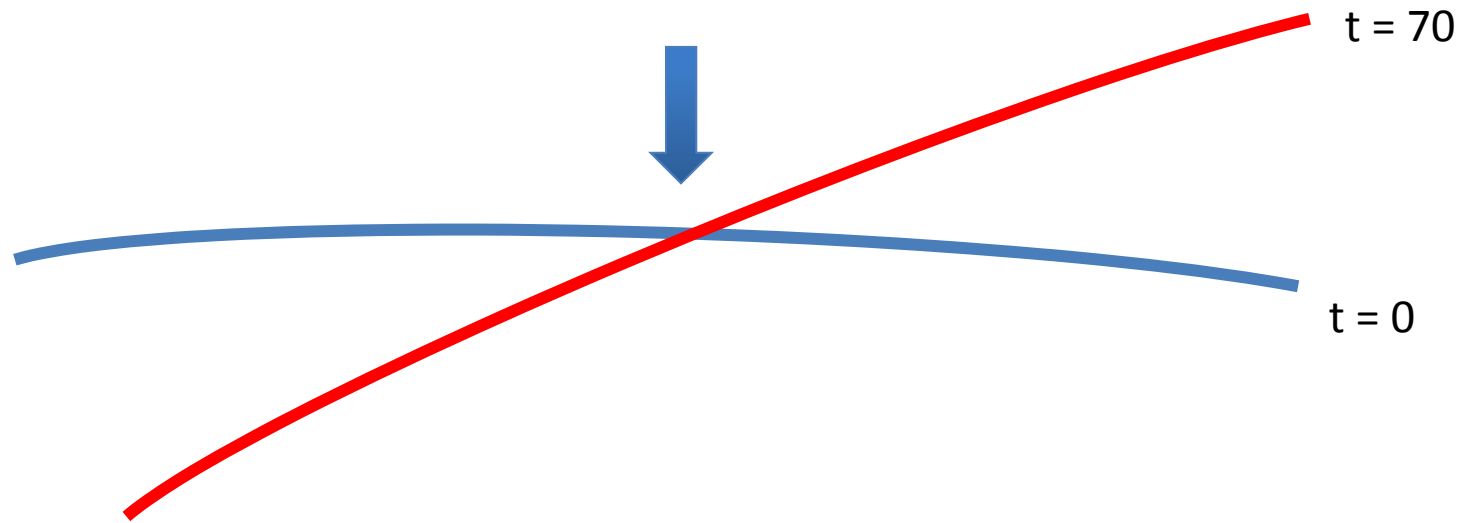
Cross-over Method



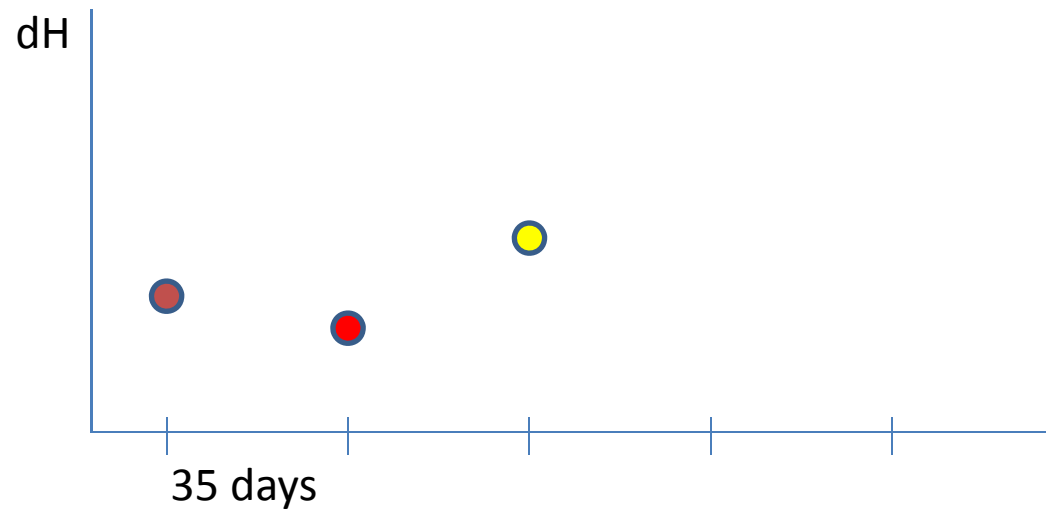
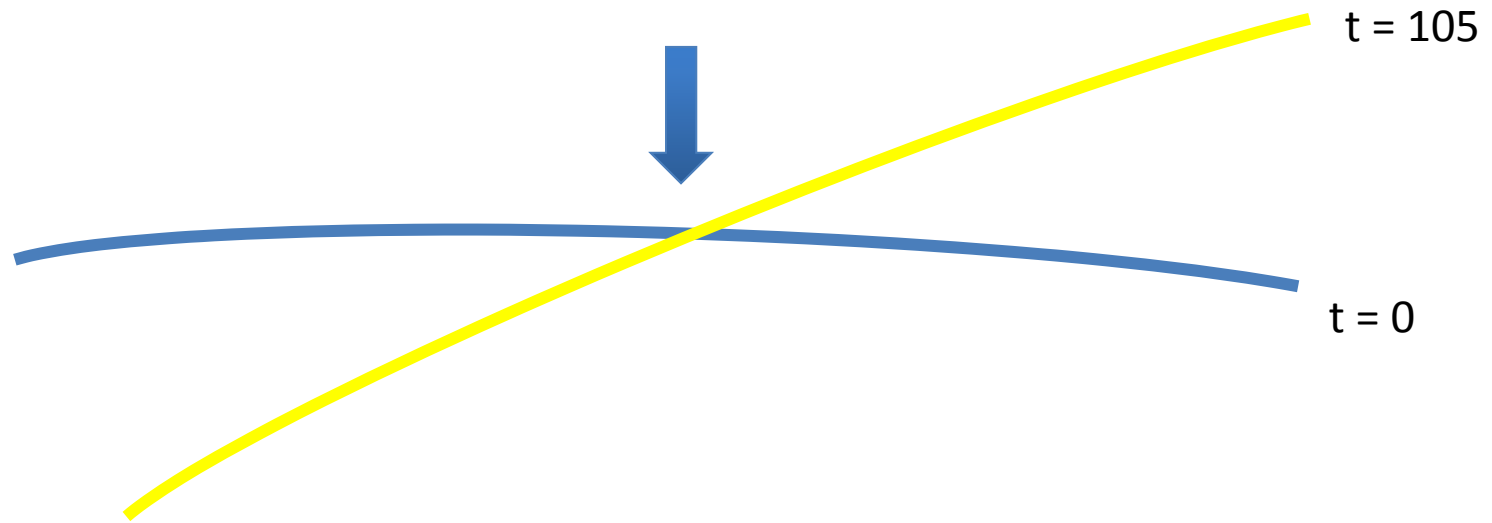
Cross-over Method



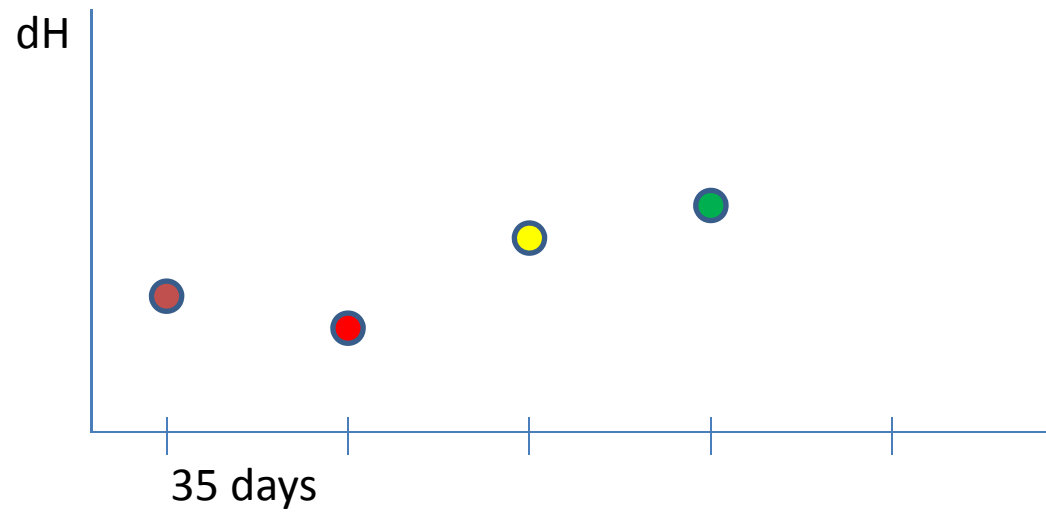
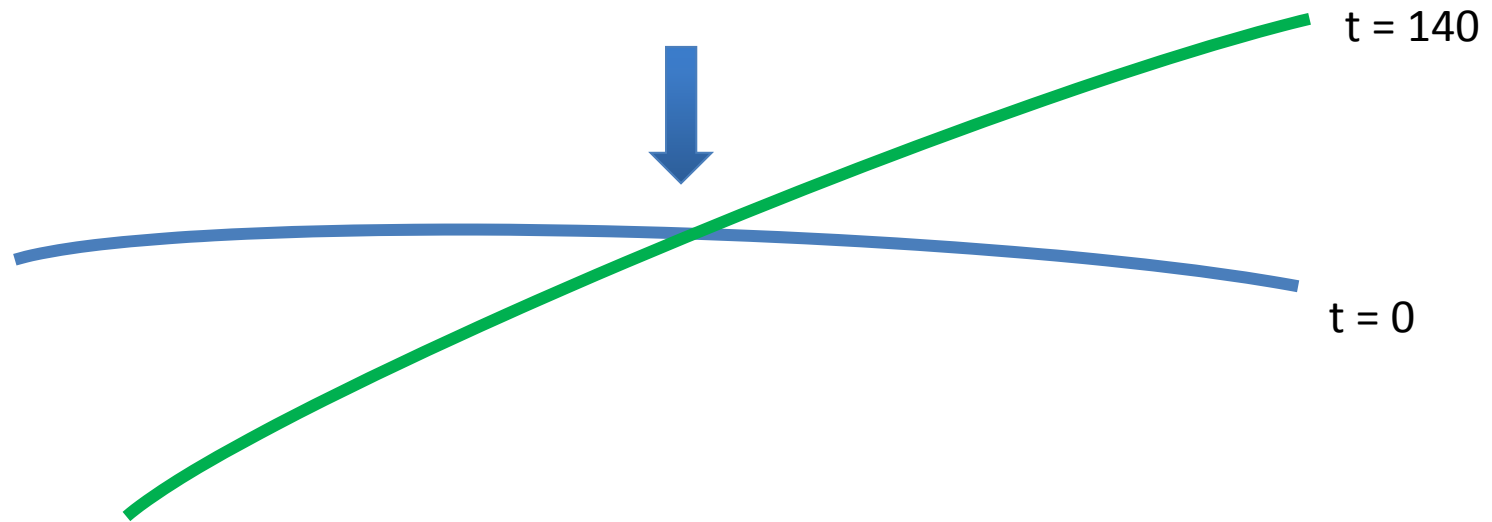
Cross-over Method



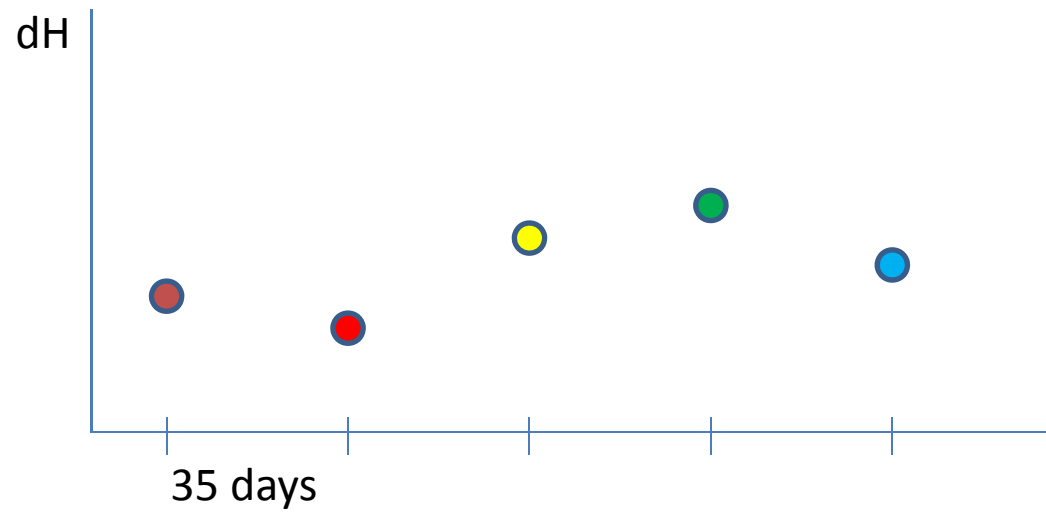
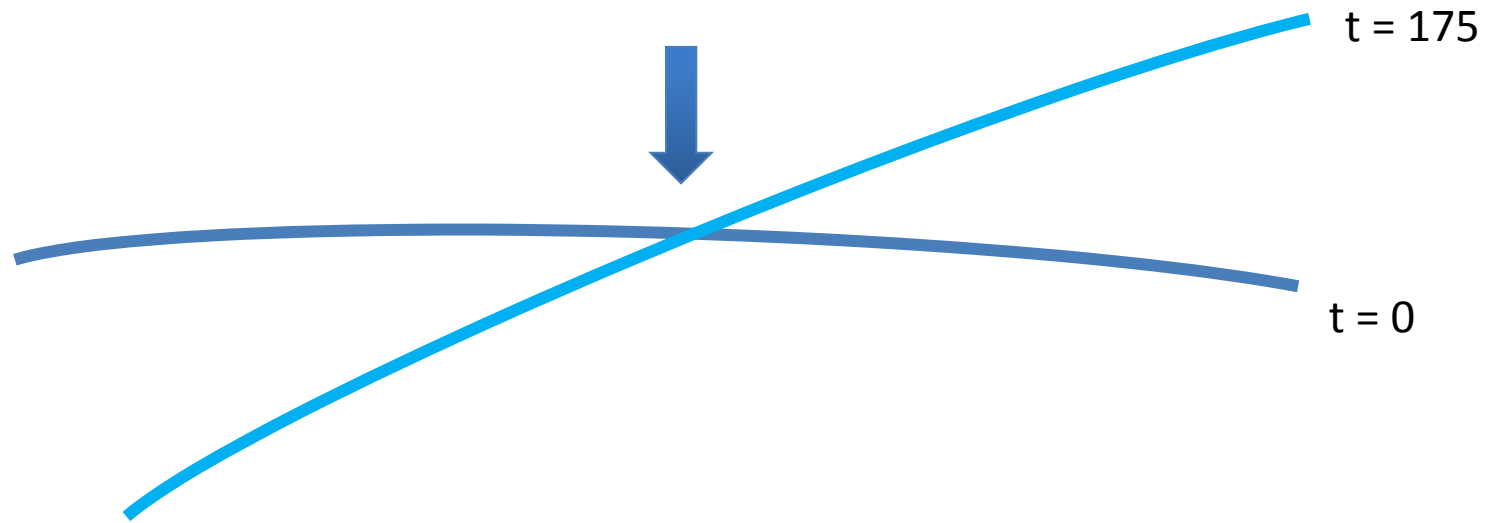
Cross-over Method



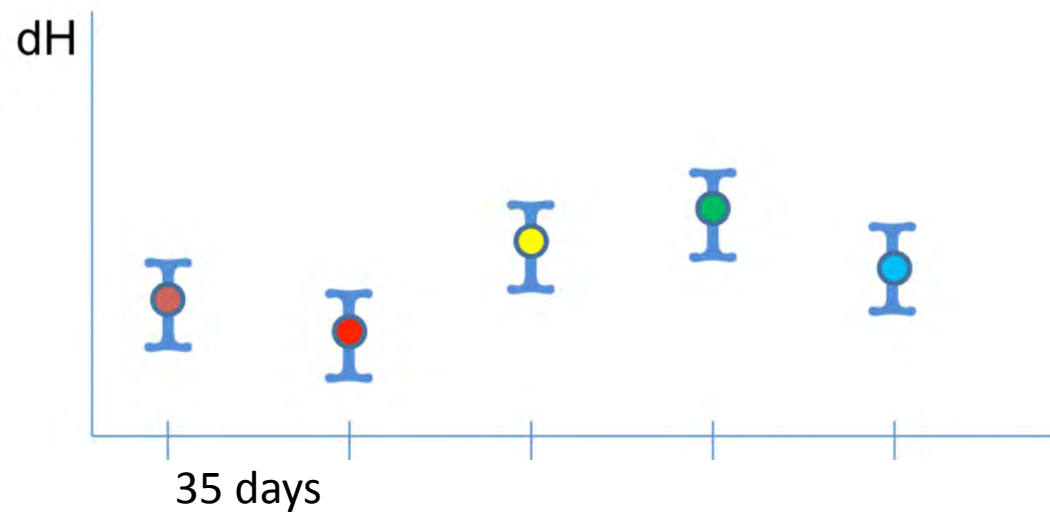
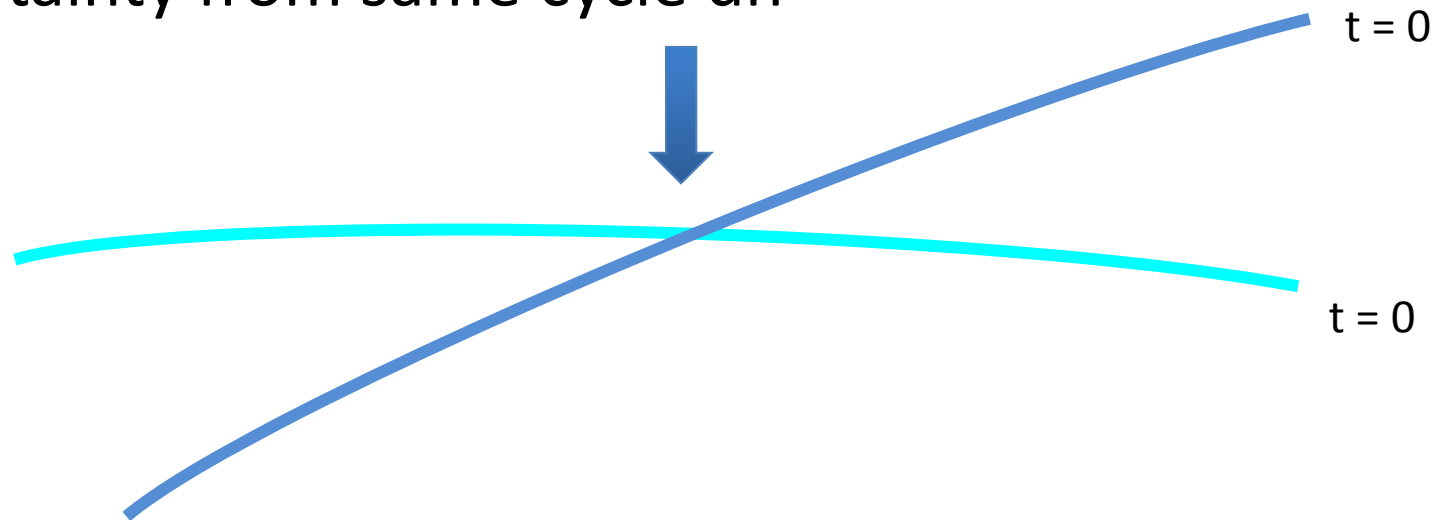
Cross-over Method



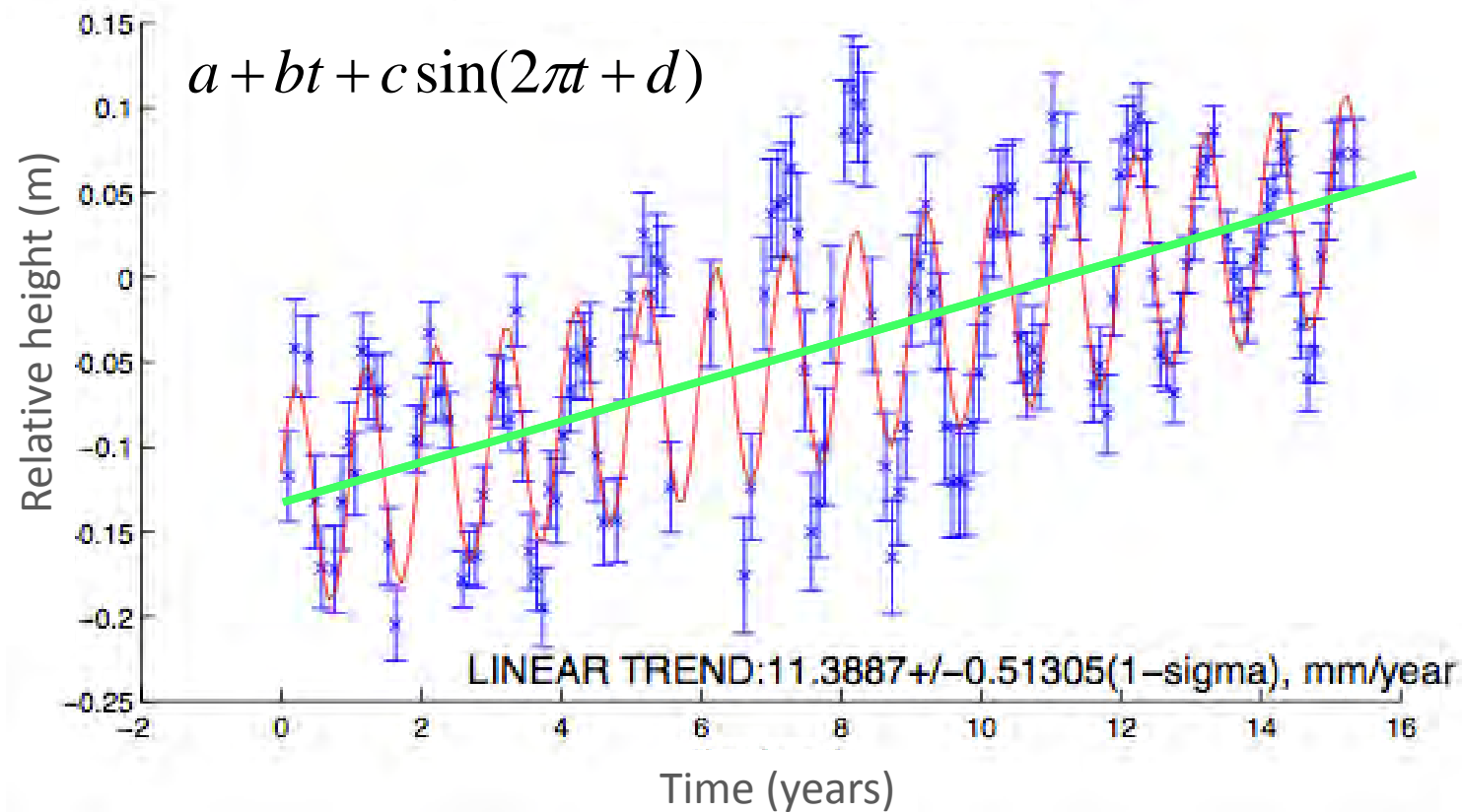
Cross-over Method



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.

Alternative:
External
DEM

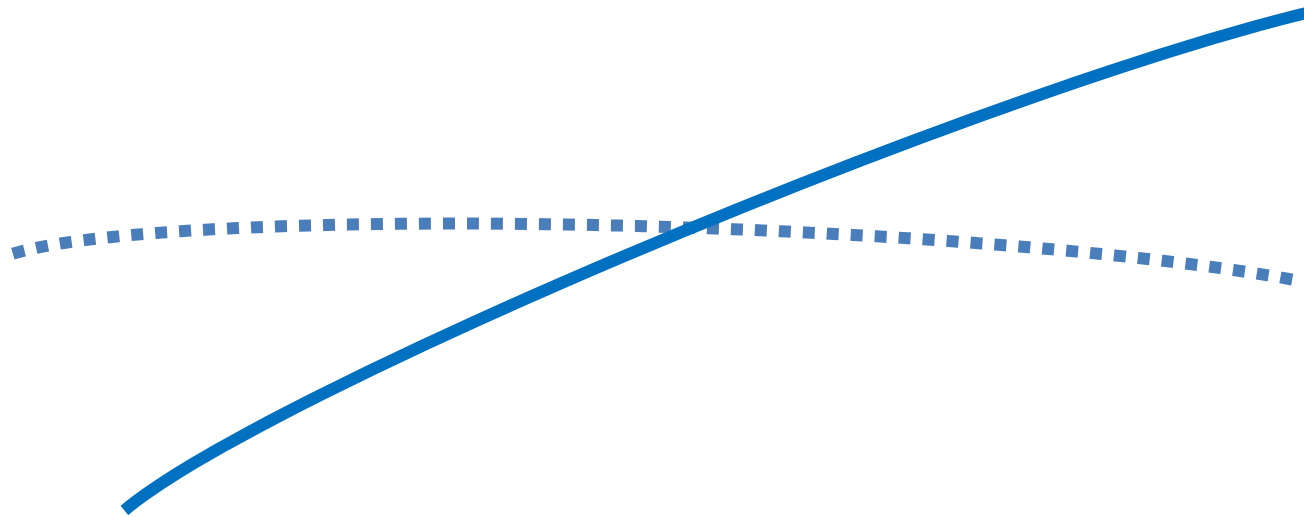
2. Define a model for elevation fluctuations within each segment.
Least squares fit of model to data within each segment.
Retrieve model parameters and associated uncertainty (includes elevation rate).

5. Remove poorly constrained solutions.

6. Retrieve elevation time series using model fit.

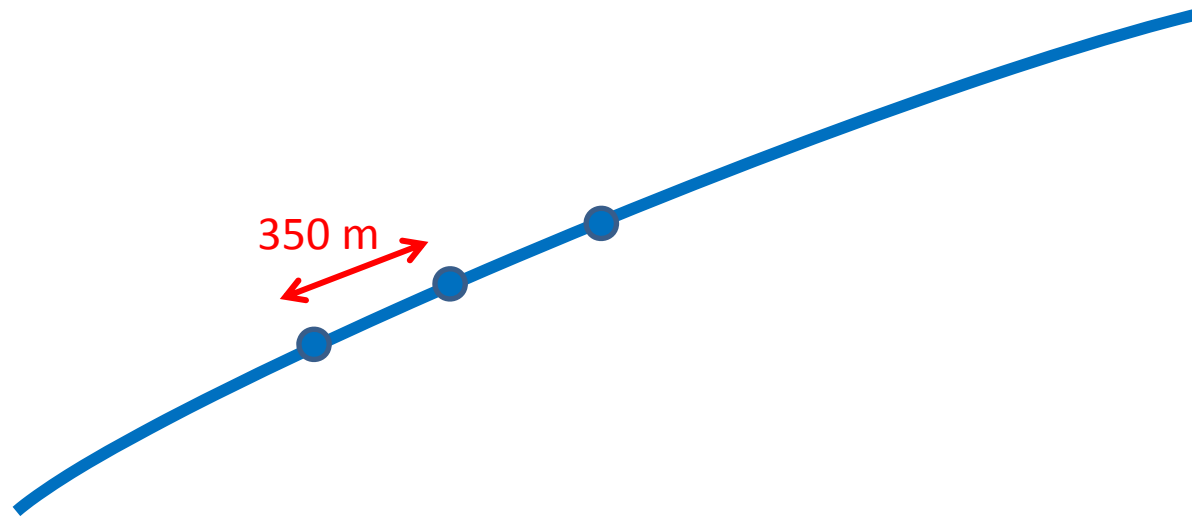
7. Account for omission areas.

Repeat track method



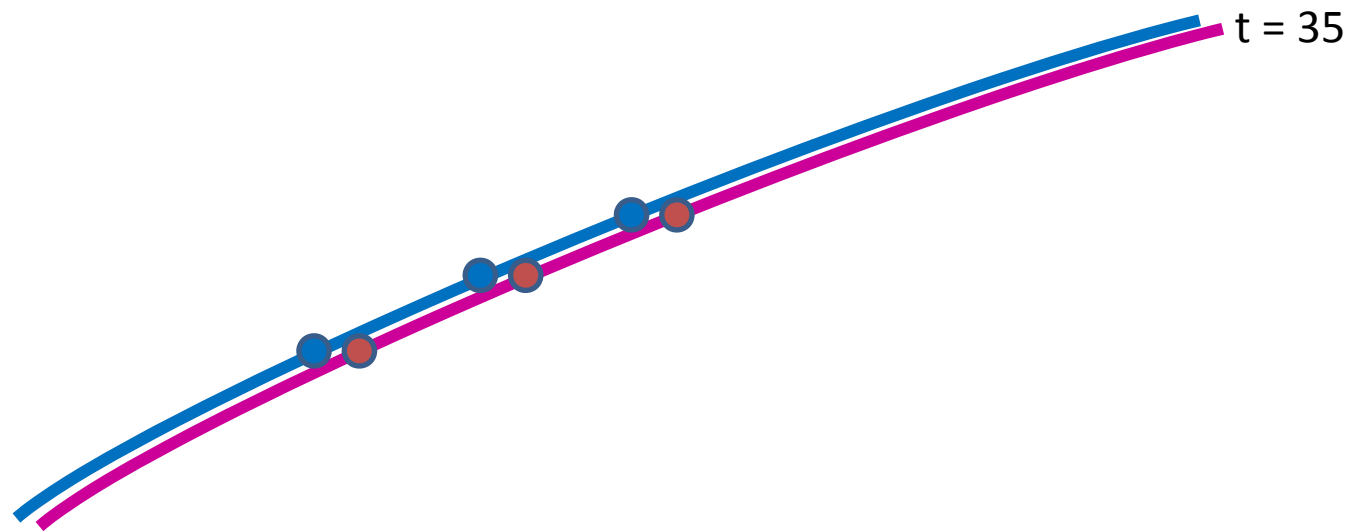
Don't just utilise data at orbit crossing point....

Repeat track method

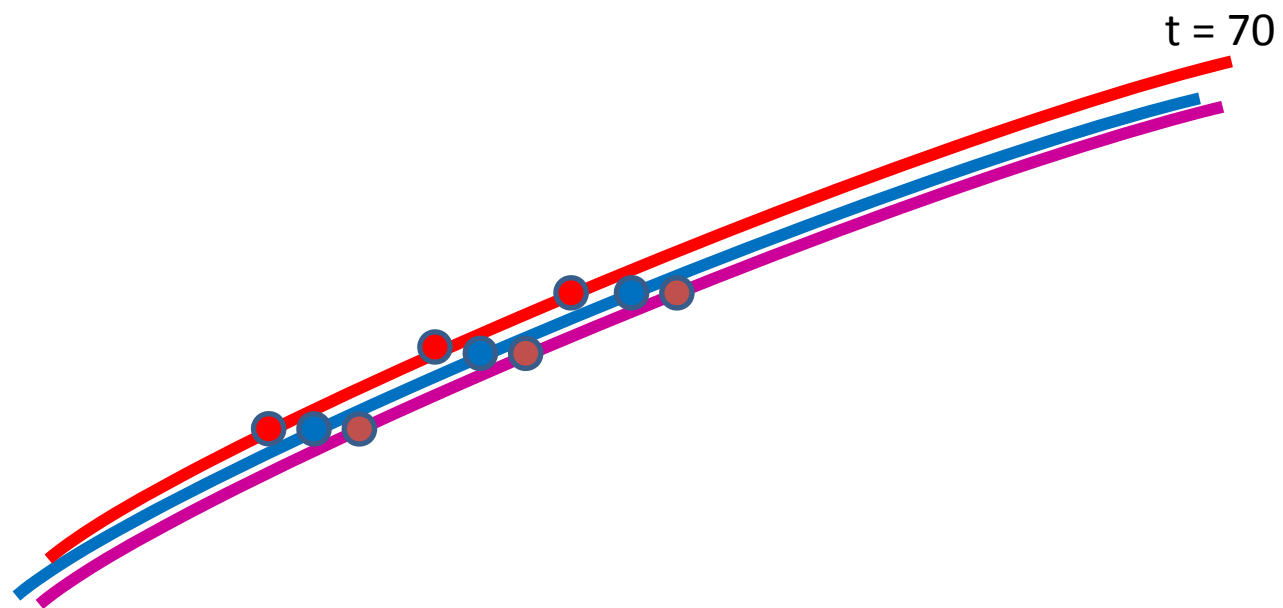


.... use all data along the satellite track.

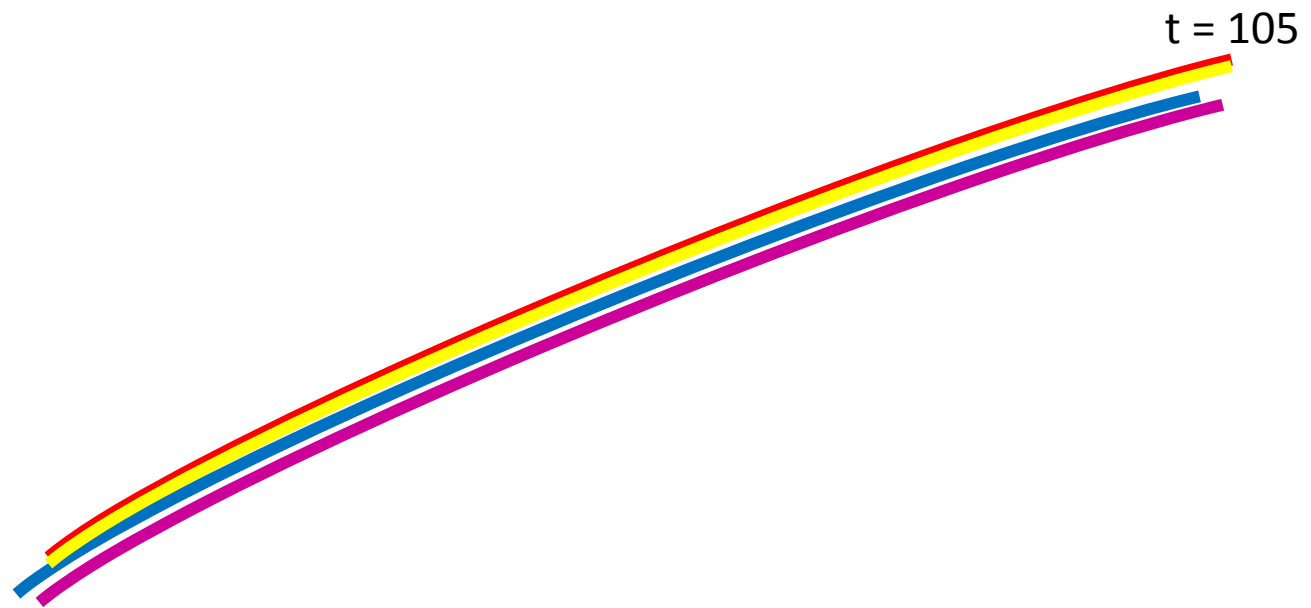
Accumulate data from repeat tracks



Accumulate data from repeat tracks



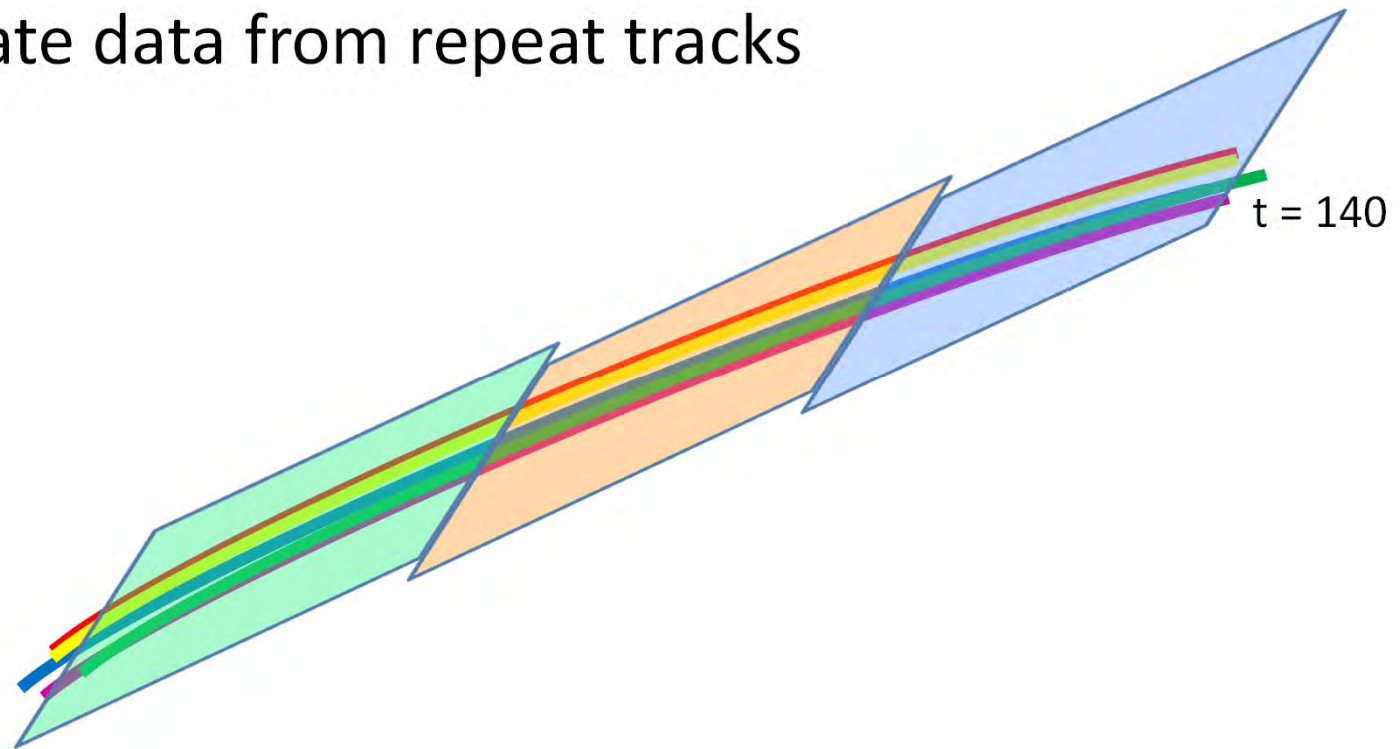
Accumulate data from repeat tracks



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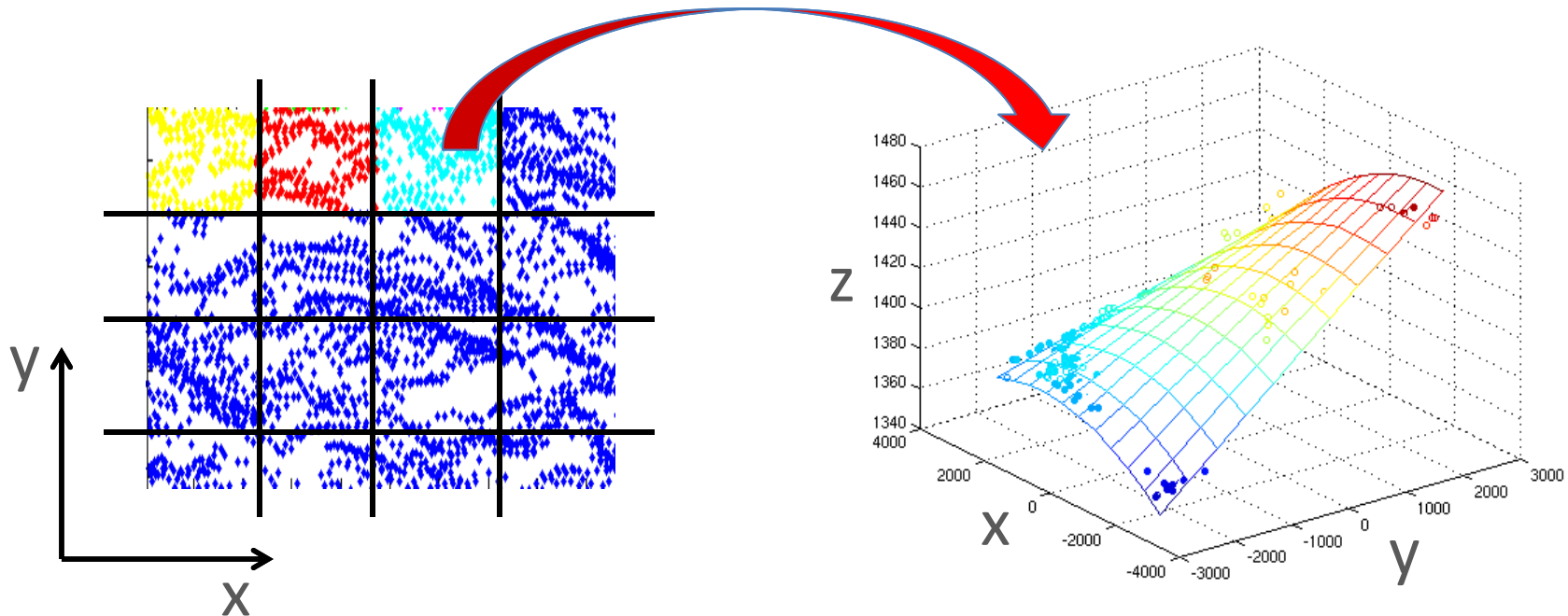
Accumulate data from repeat tracks



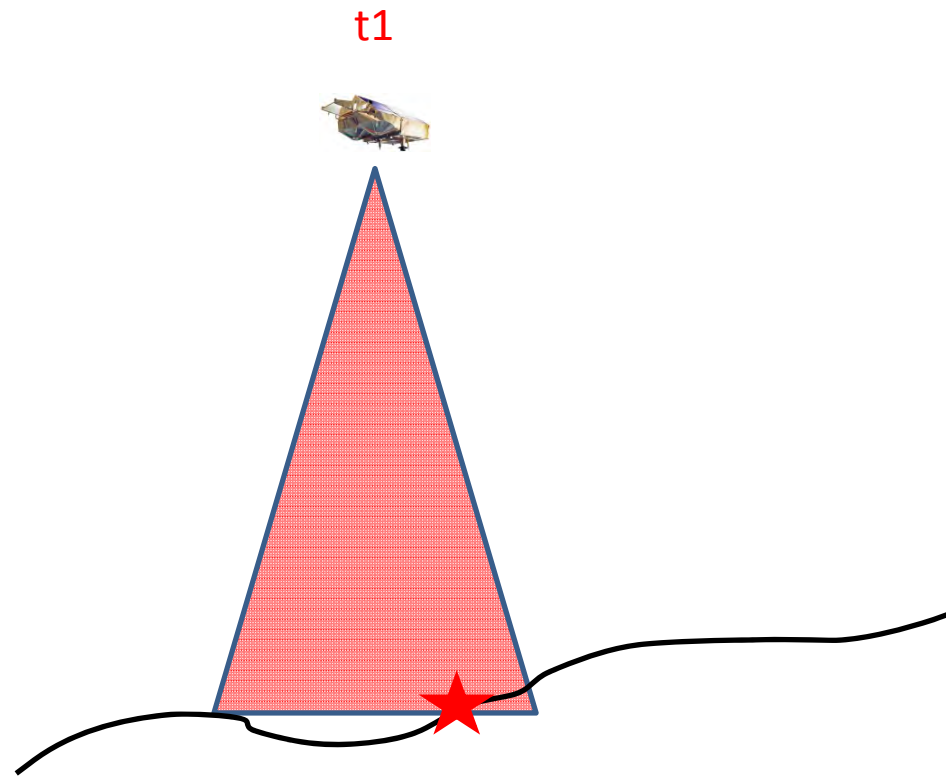
- Cut data up into segments along track.
- Data within each track segment are dispersed in space and time, and so solve simultaneously for both spatial and temporal components.
- Retrieve elevation rate.

Plane fit method

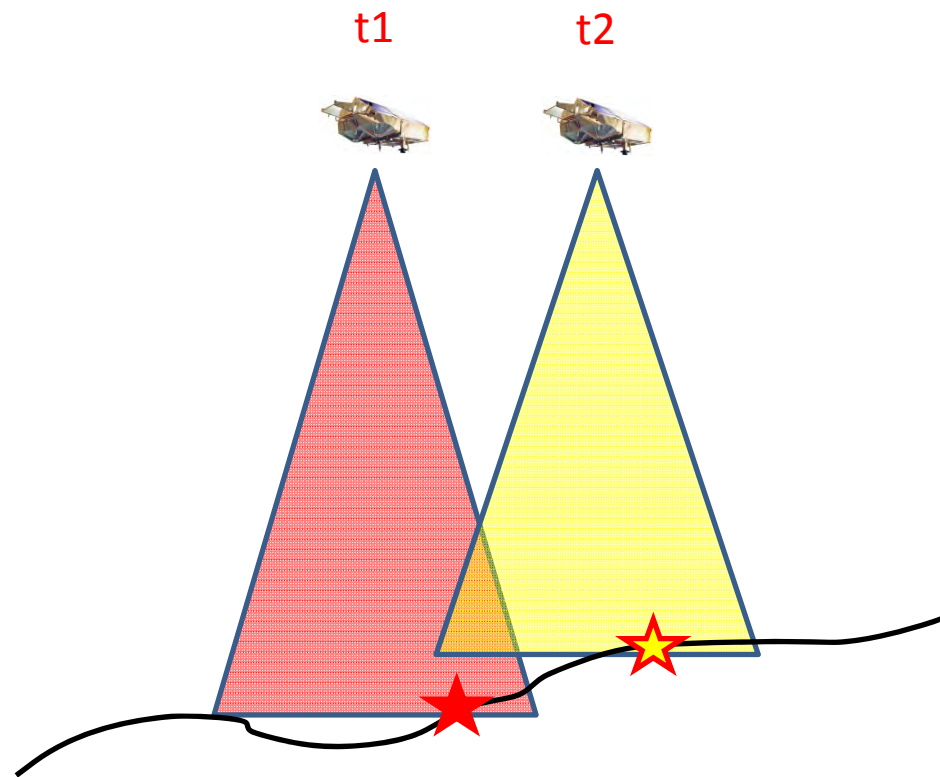
- Modification of repeat track approach.
- Well suited to more homogeneous data sampling (e.g. CryoSat), rather than where data clustered along distinct tracks (e.g. ICESat).
- Group data based on spatial proximity, don't distinguish between tracks.



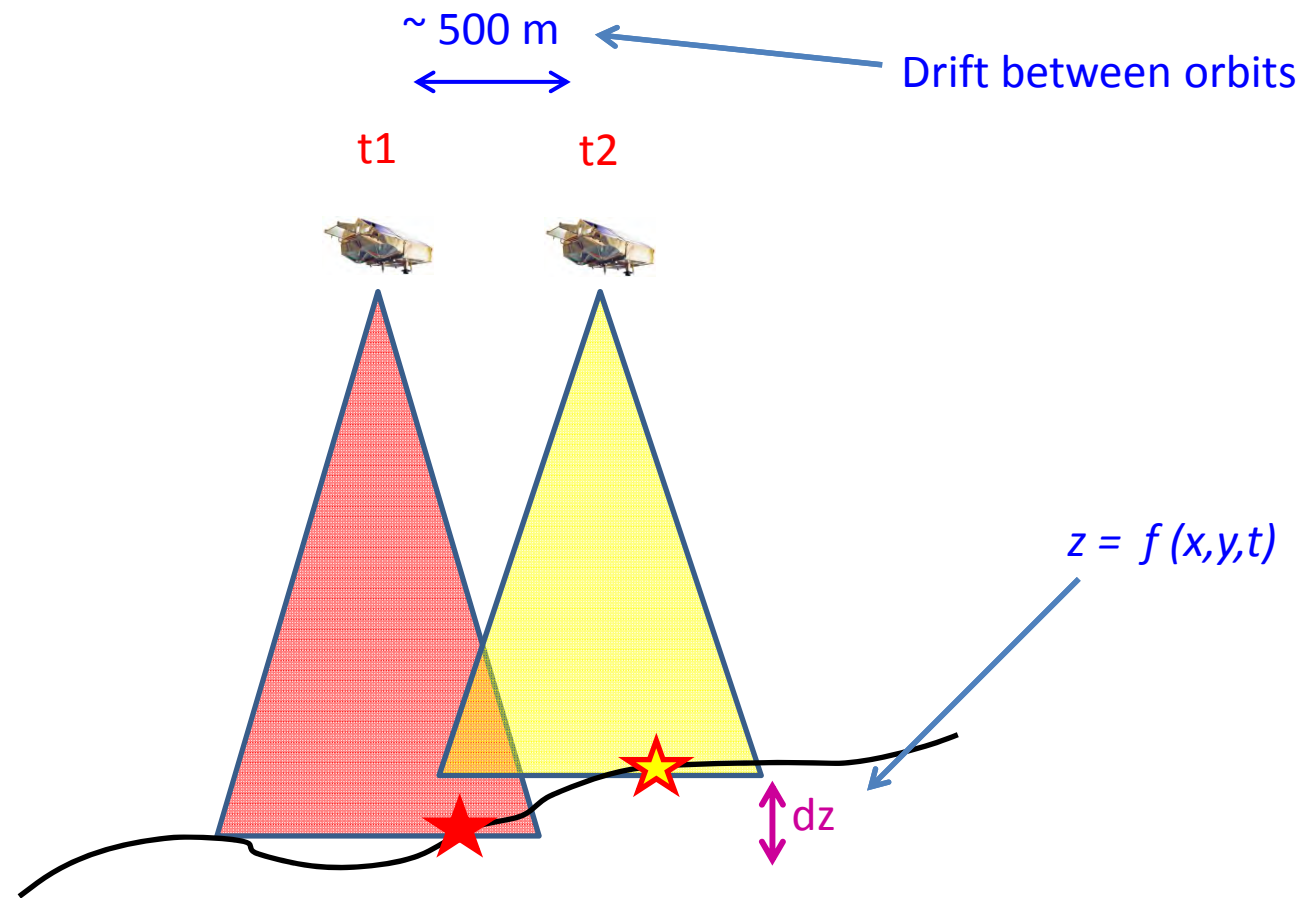
Influence of surface slope – affects repeat track and model fit



Influence of surface slope – affects repeat track and model fit

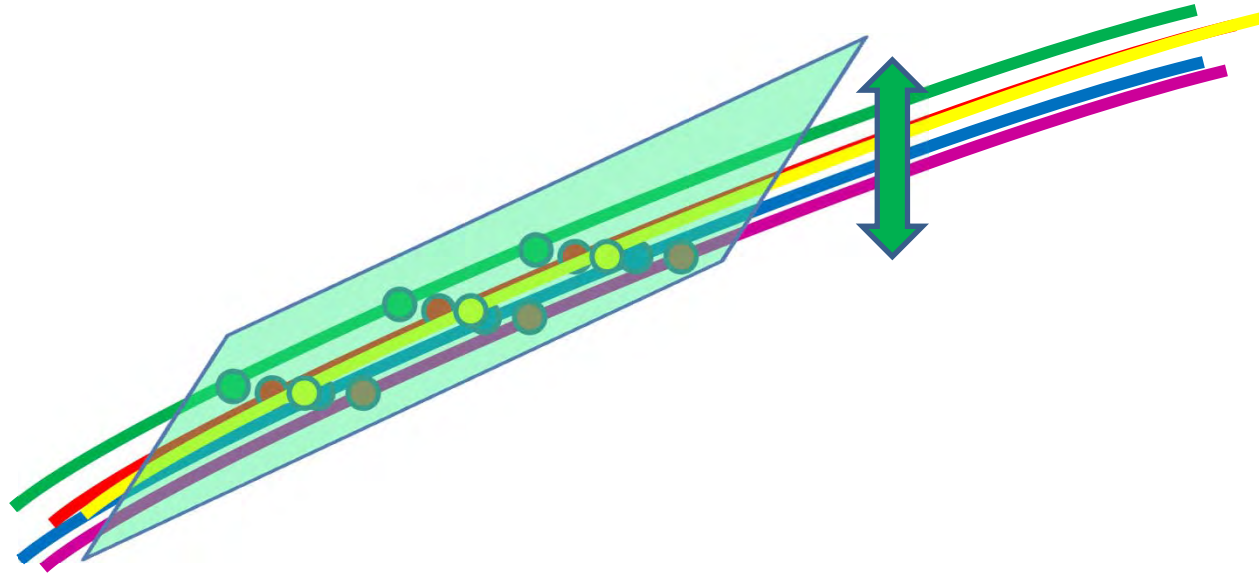


Influence of surface slope – affects repeat track and model fit



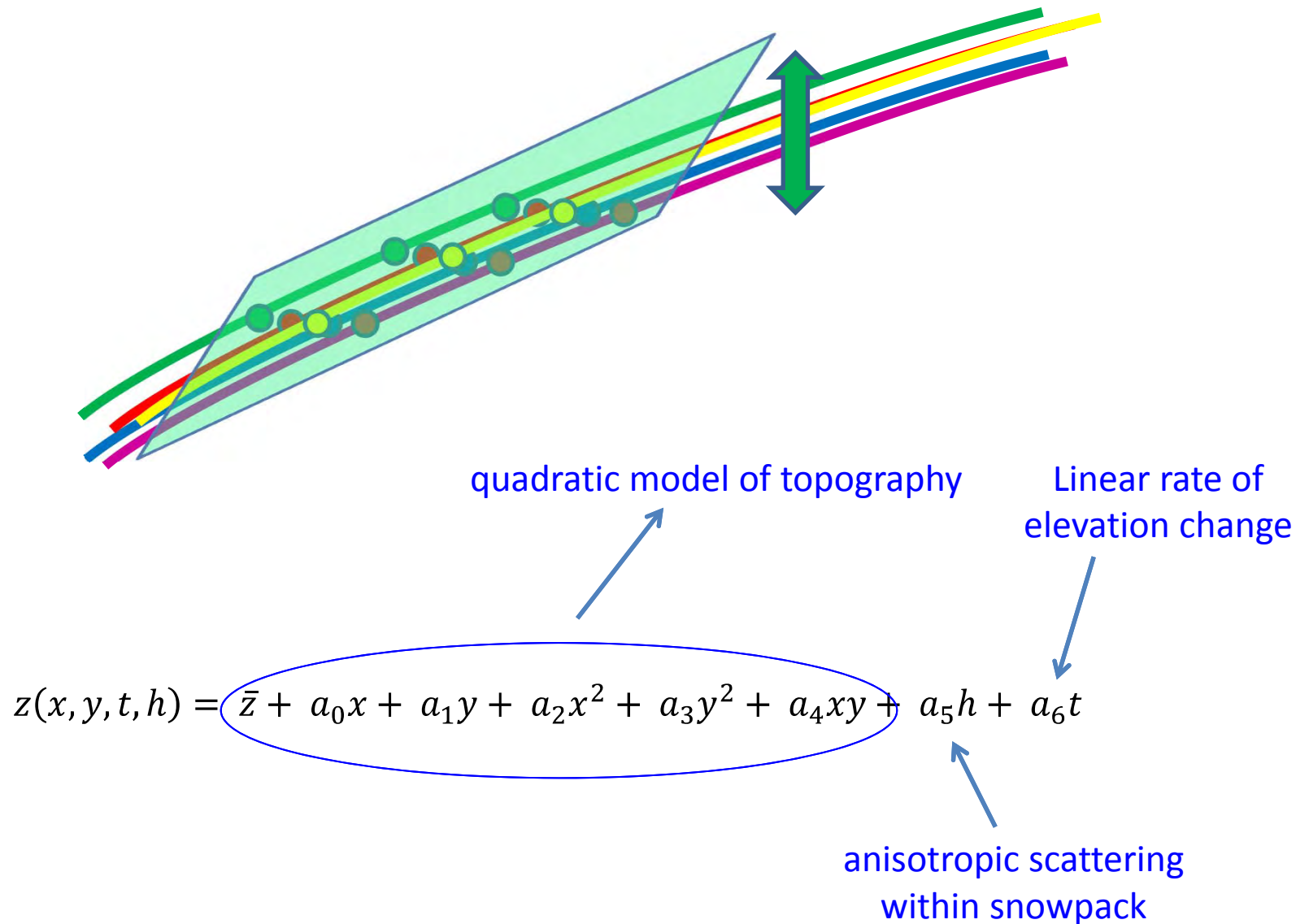
Strategy required to separate elevation changes into spatial and temporal components.

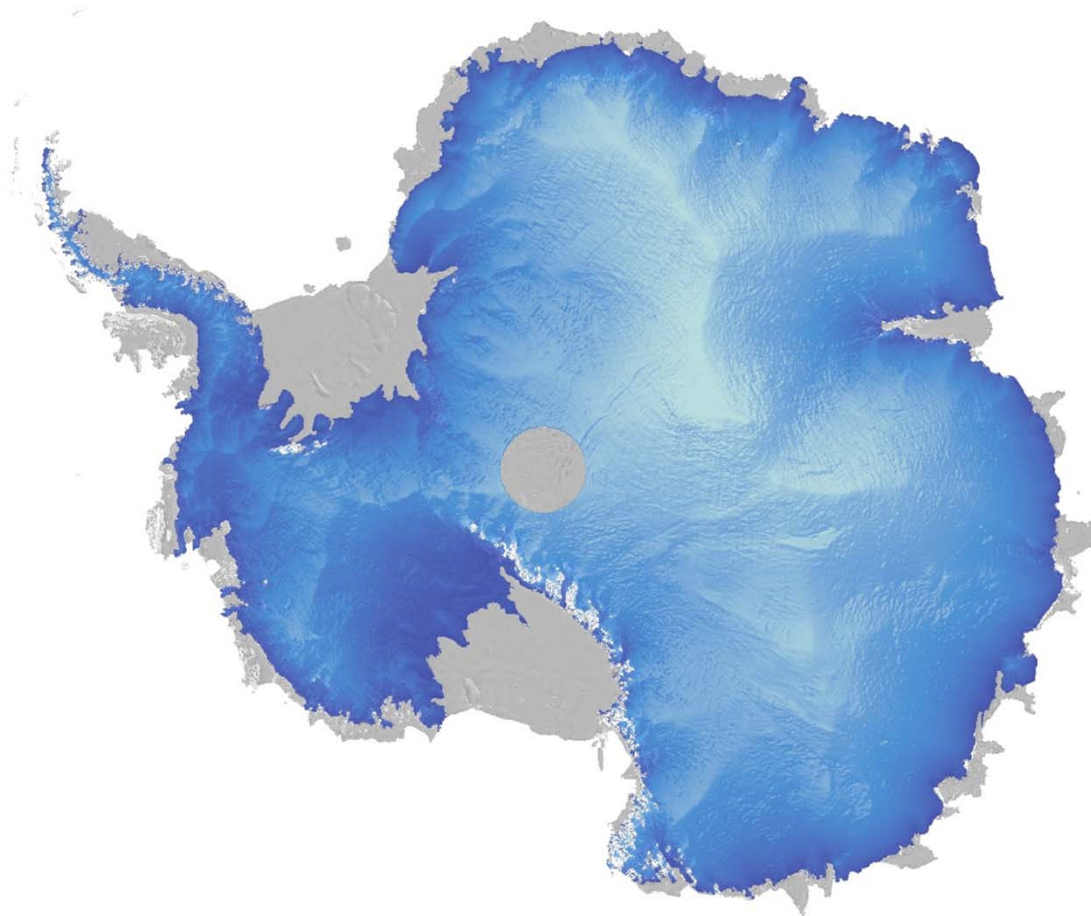
Fit model to data segment and retrieve elevation rate



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

Fit model to data segment and retrieve elevation rate

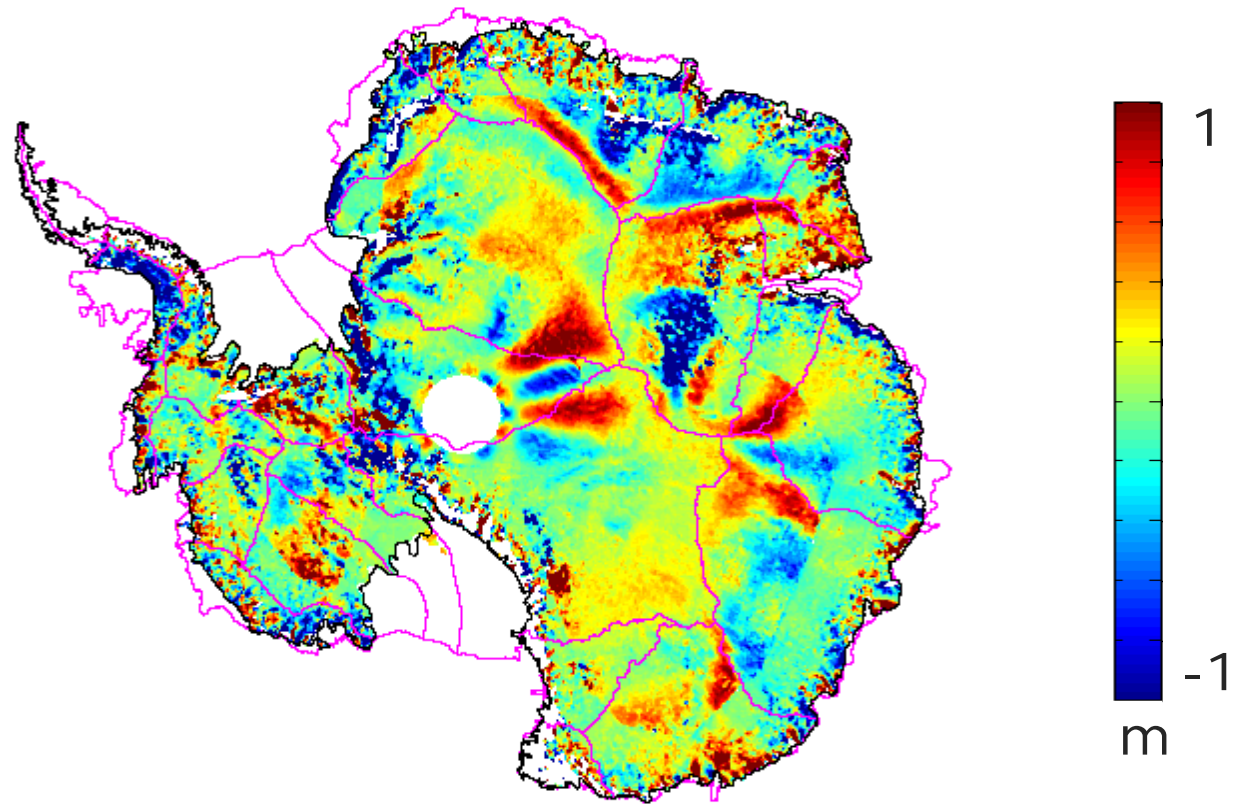




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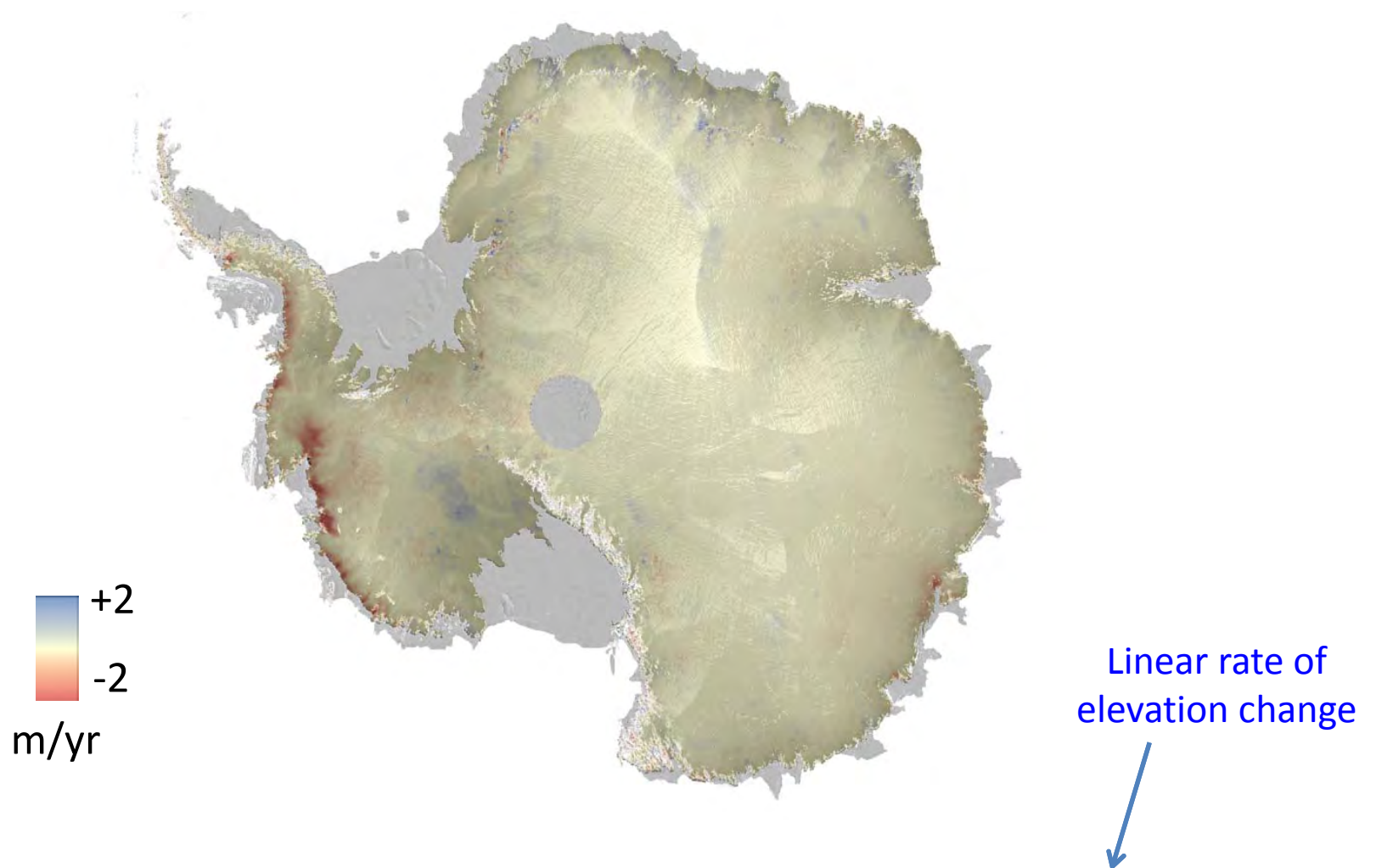
mean elevation



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

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

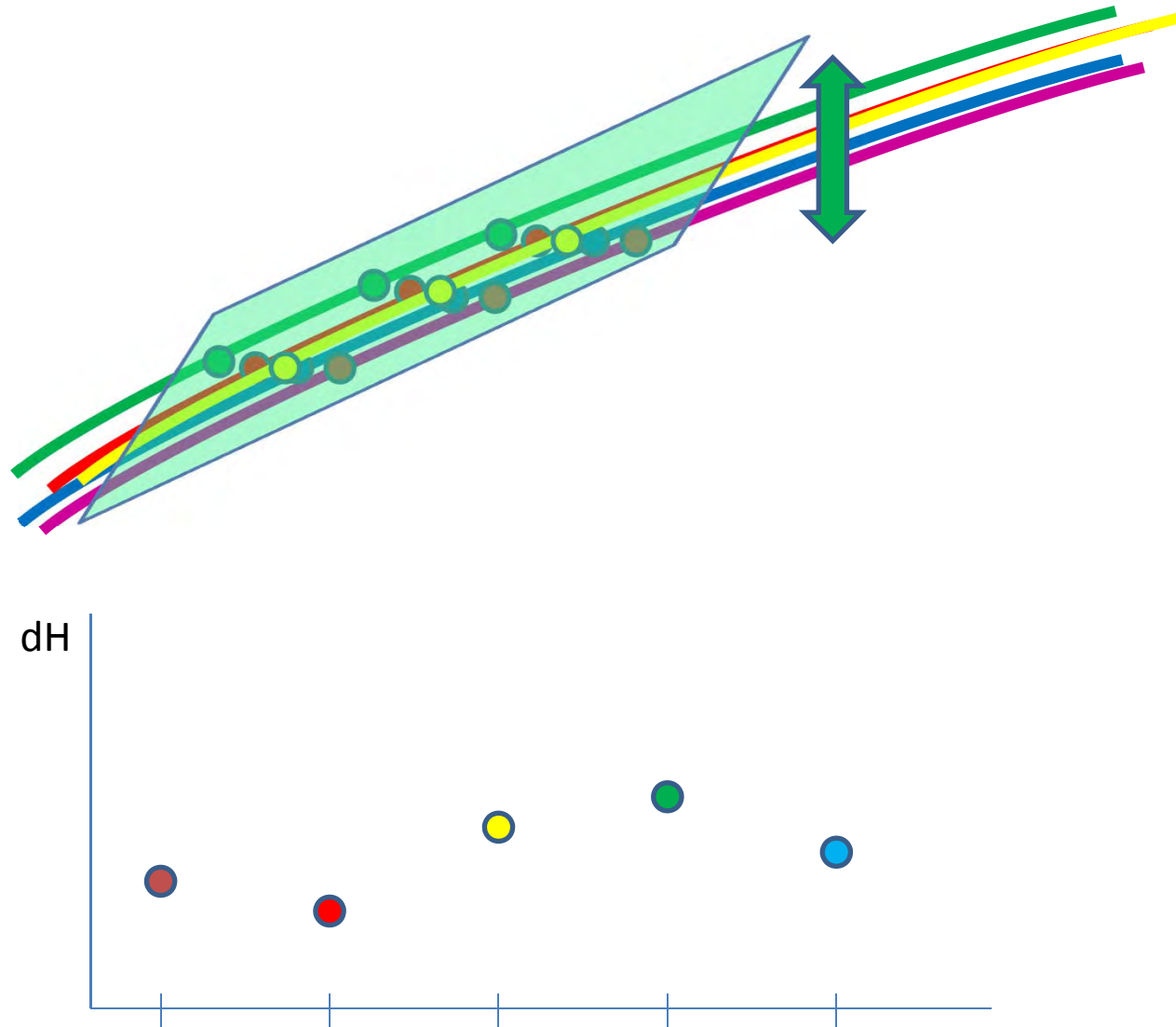
anisotropic scattering
within snowpack



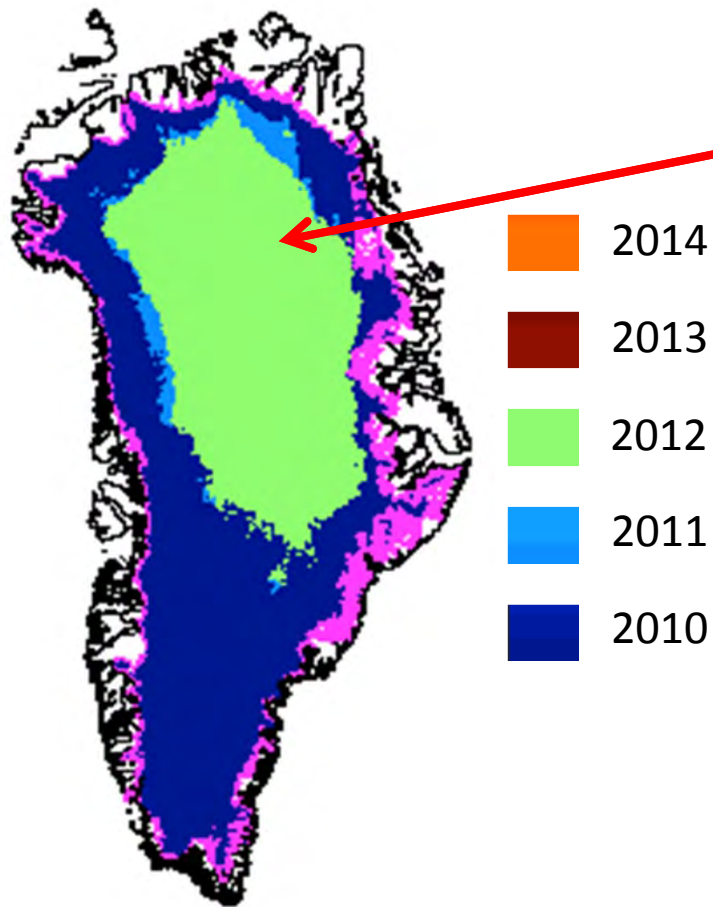
+2
-2
m/yr

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

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.

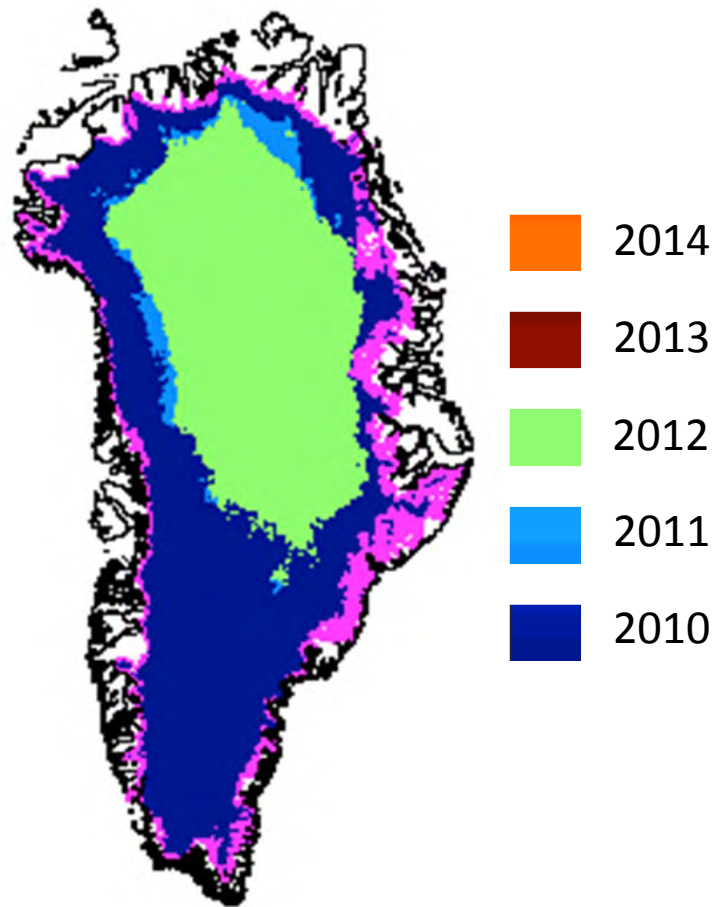


Transition from dry to wet snowpack and ice lens formation.

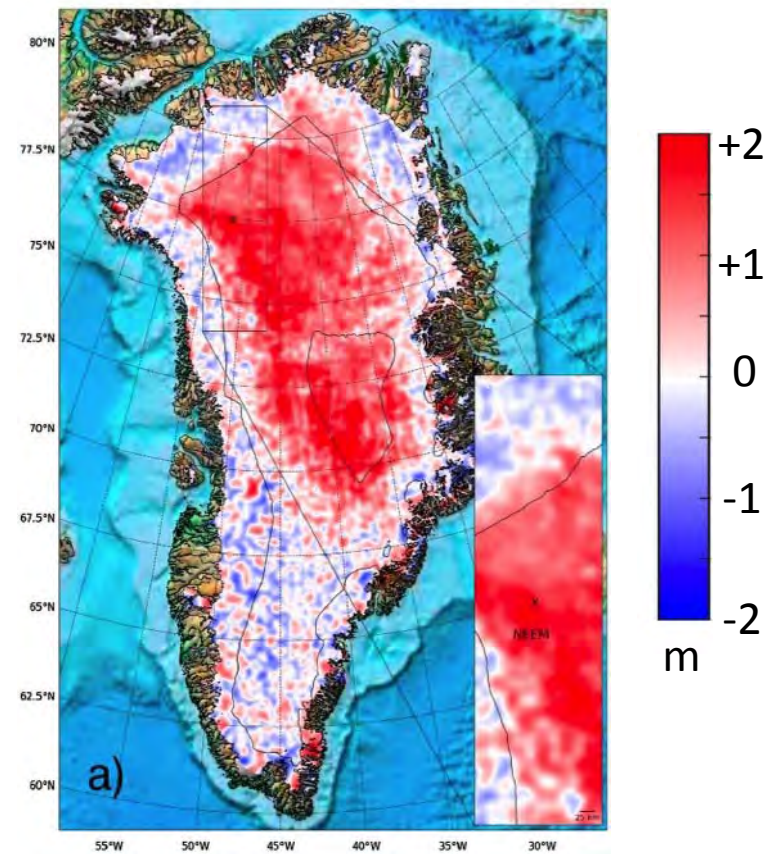


Affected the depth distribution of backscattered energy.

Model fit - Greenland model refinements

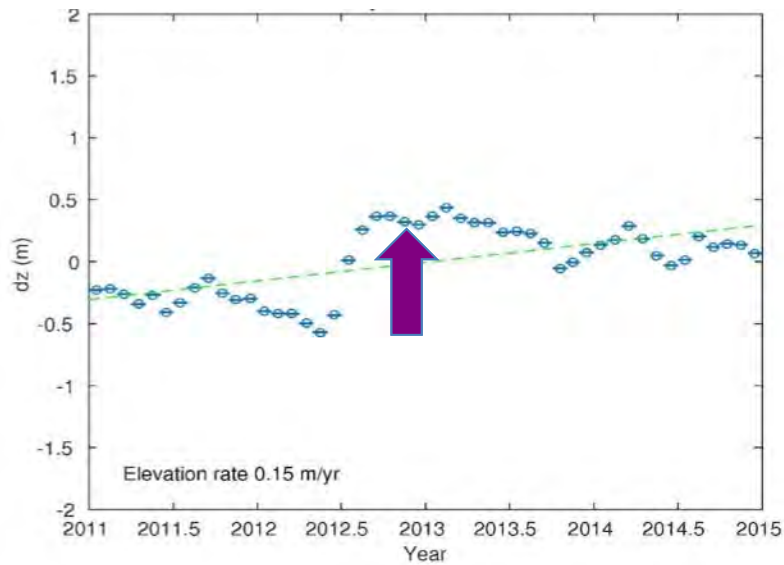


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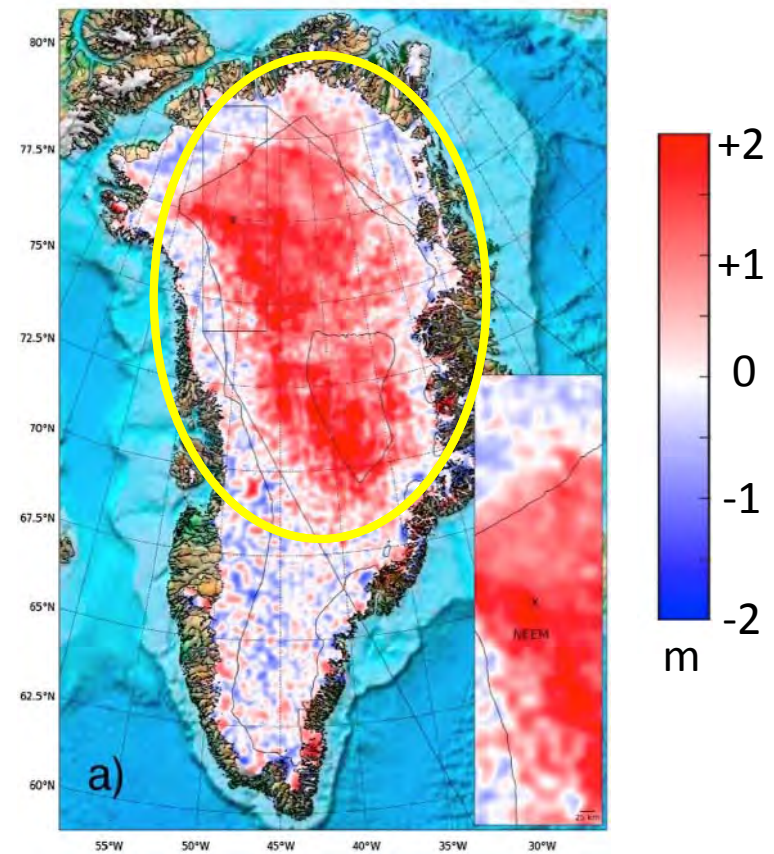


Surface elevation change recorded by CryoSat-2 during summer 2012.

Model fit - Greenland model refinements



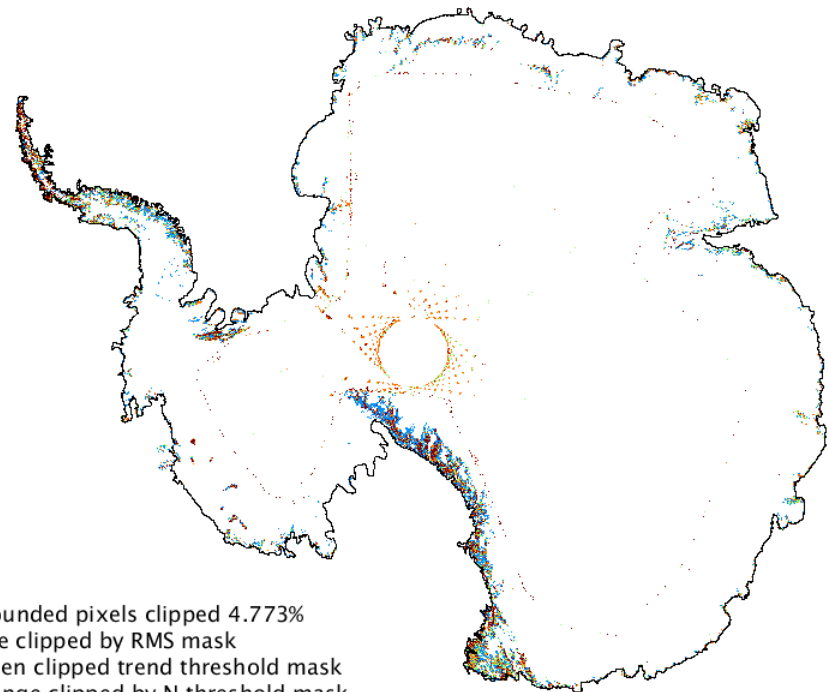
Additional term introduced into the model fit to account for changes in depth distribution of backscattered energy.



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

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.

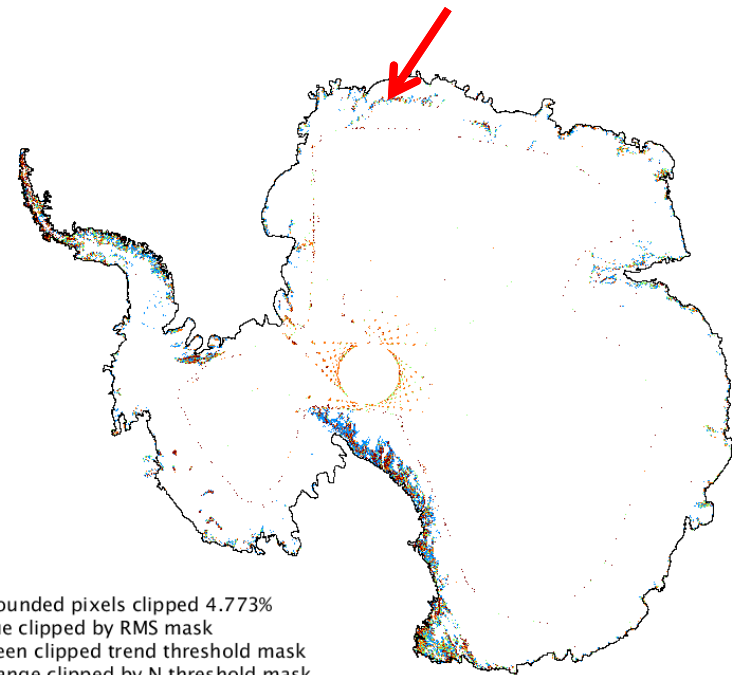
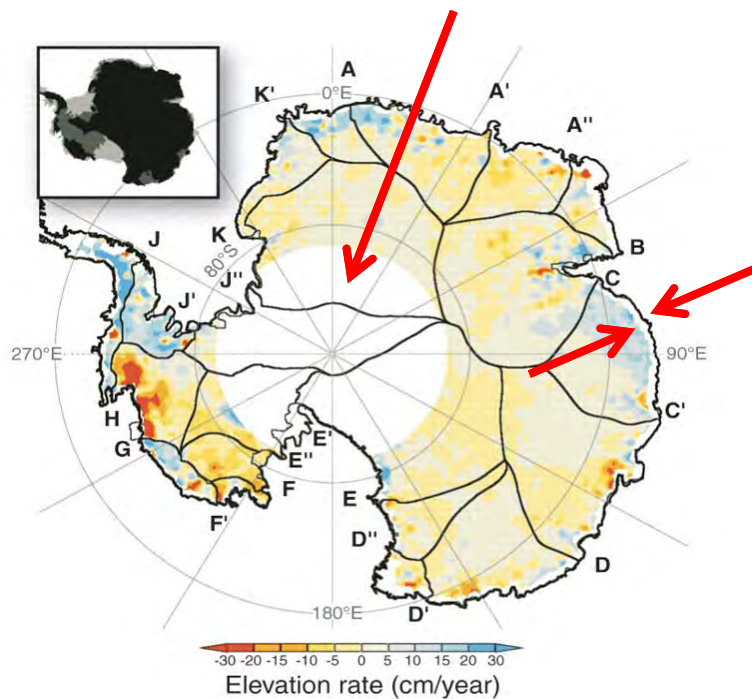


Grounded pixels clipped 4.773%
Blue clipped by RMS mask
Green clipped trend threshold mask
Orange clipped by N threshold mask
Red clipped by slope threshold mask

Failure of CryoSat-2 interferometric model fits

Account for omission areas

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



Grounded pixels clipped 4.773%
Blue clipped by RMS mask
Green clipped trend threshold mask
Orange clipped by N threshold mask
Red clipped by slope threshold mask

Account for omission areas

1. Statistical approaches:

- apply the mean elevation rate of each basin to unobserved regions.
- interpolation, e.g. Delaunay triangulation, ordinary Kriging.

Account for omission areas

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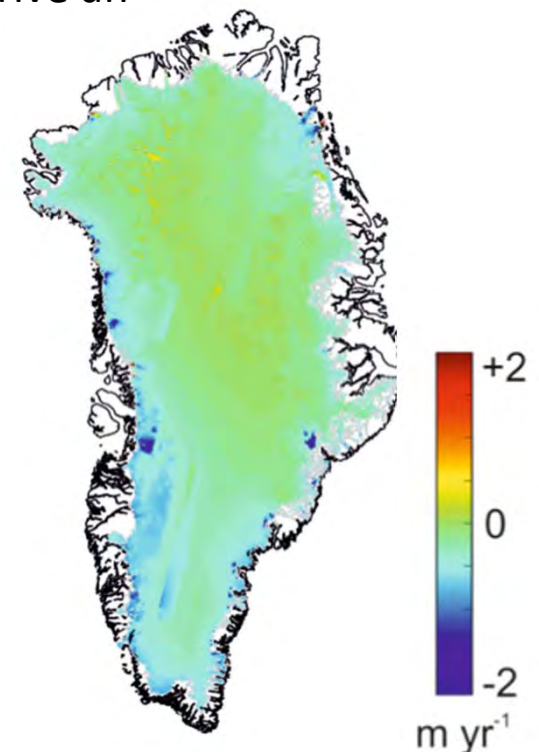
- apply the mean elevation rate of each basin to unobserved regions.
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2. Model based approaches:

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

$$\frac{dz}{dt} = al + bz + c \Delta v + d$$

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



Account for omission areas

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

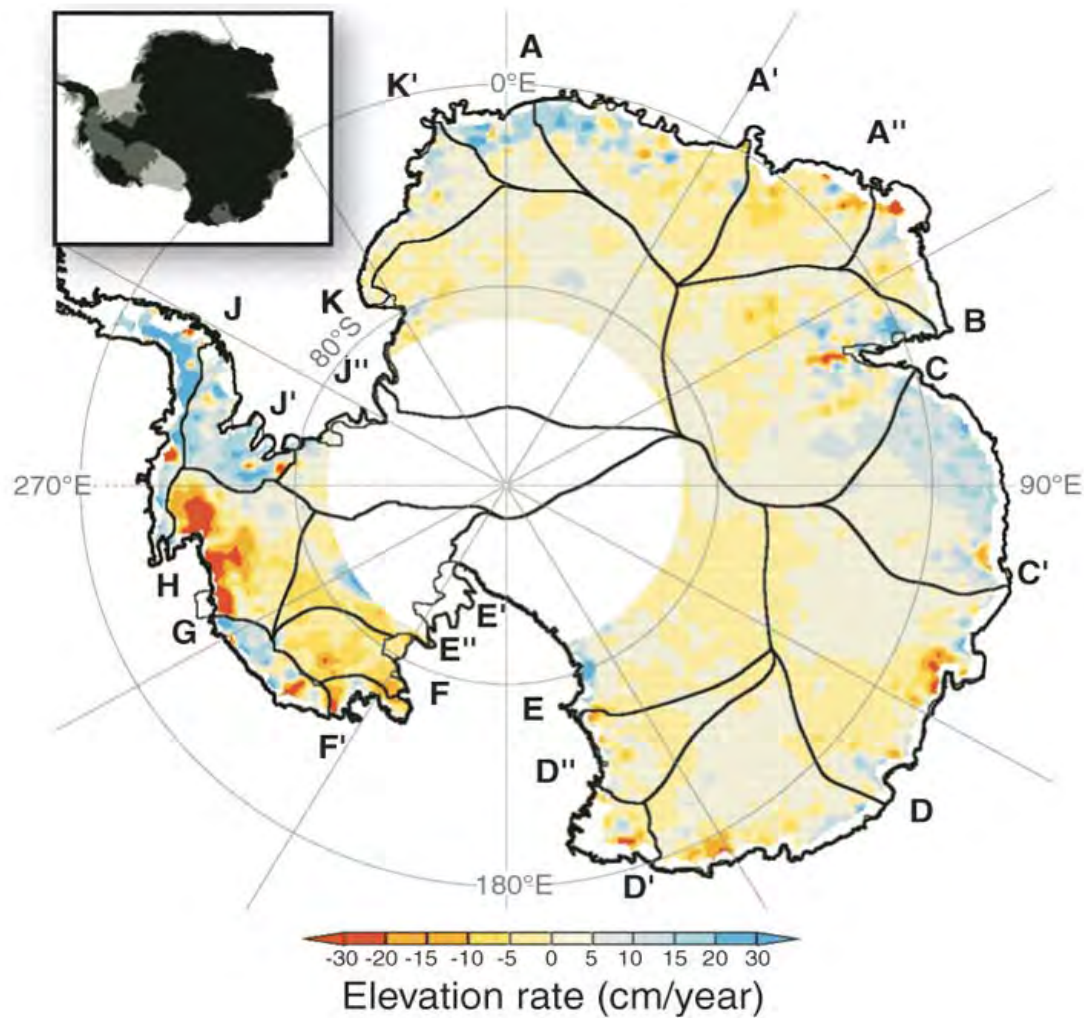
2. Model based approaches:

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3. Combined approaches:

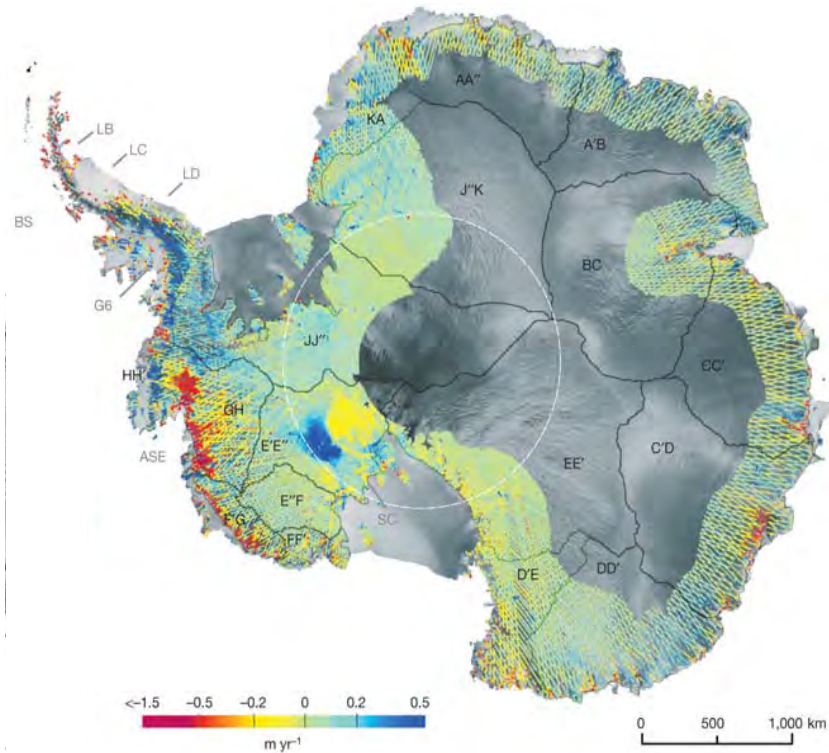
- e.g. Kriging with external drift.
- supplements Kriging with a background field, e.g. velocity, to guide interpolation in data sparse areas.

Cross-over solution - Antarctica

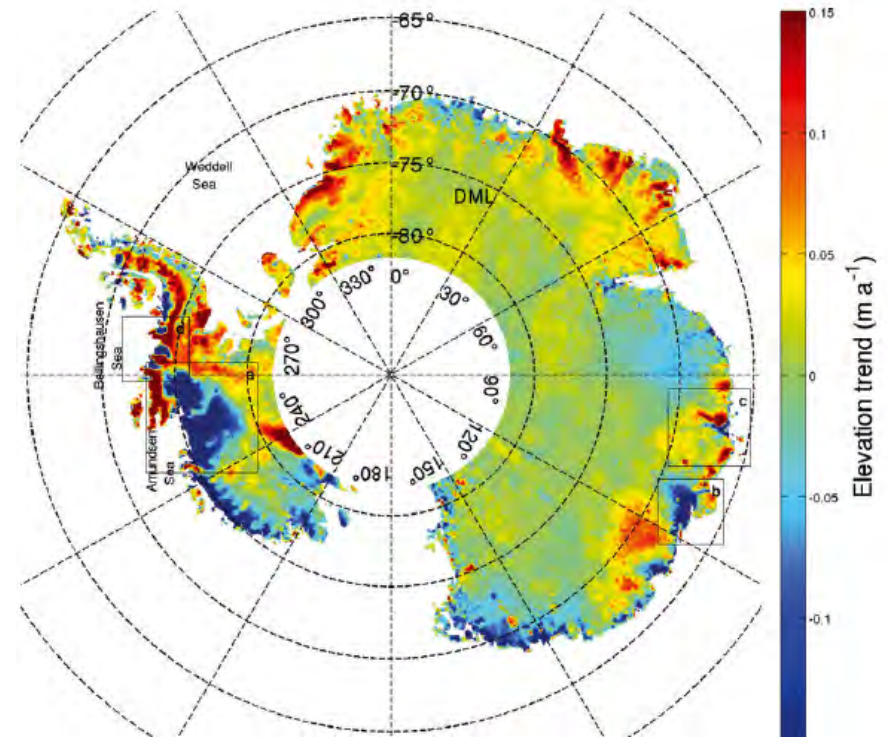


1992-2003 elevation change (Shepherd and Wingham, 2007)

Repeat track solutions - Antarctica

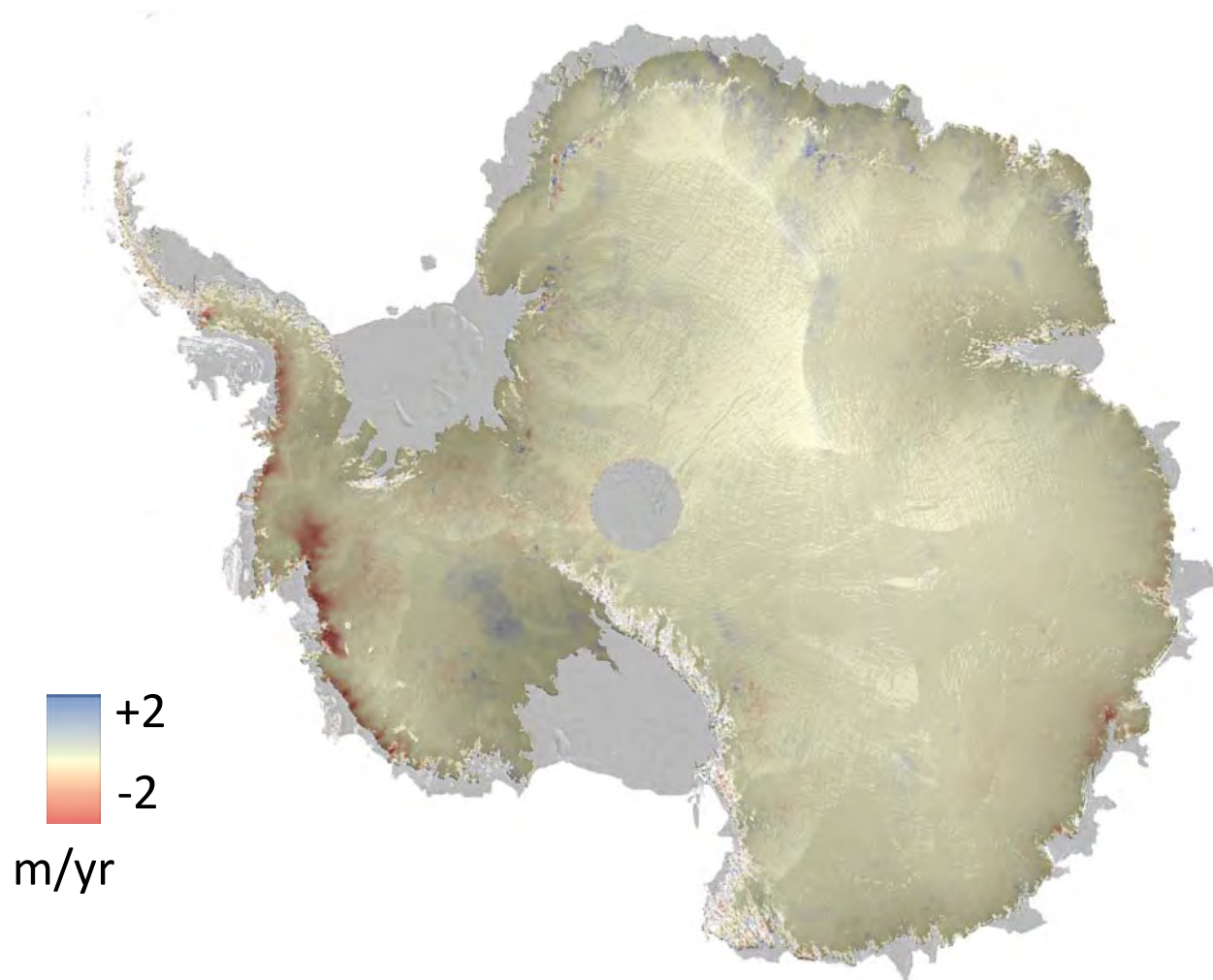


ICESat laser altimetry, 2003-2008



Envisat radar altimetry, 2002-2010

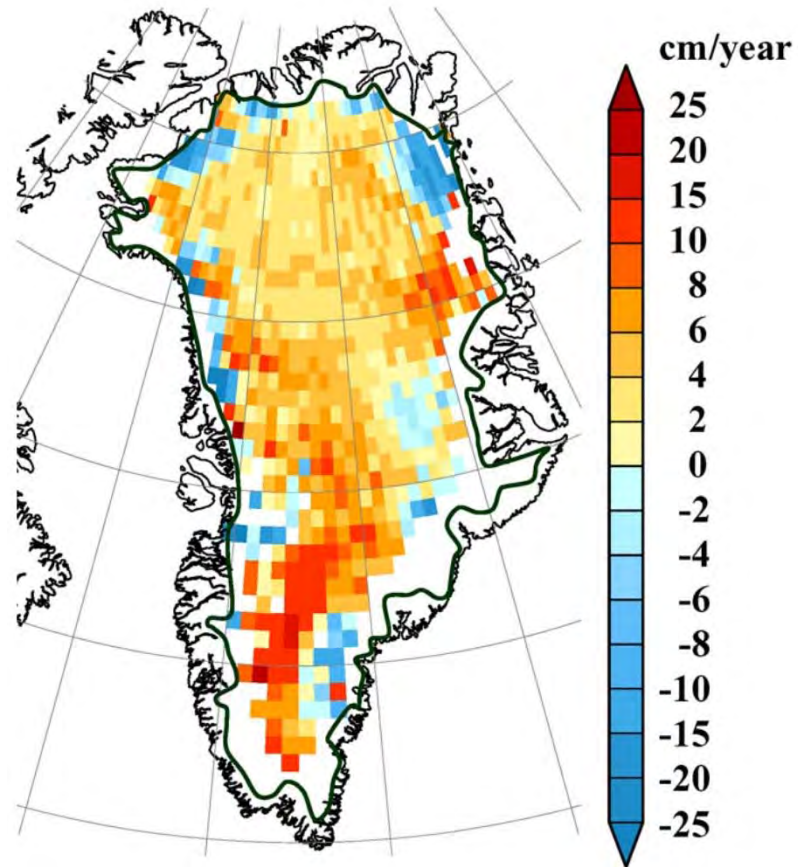
Model fit solution - Antarctica



+2
-2
m/yr

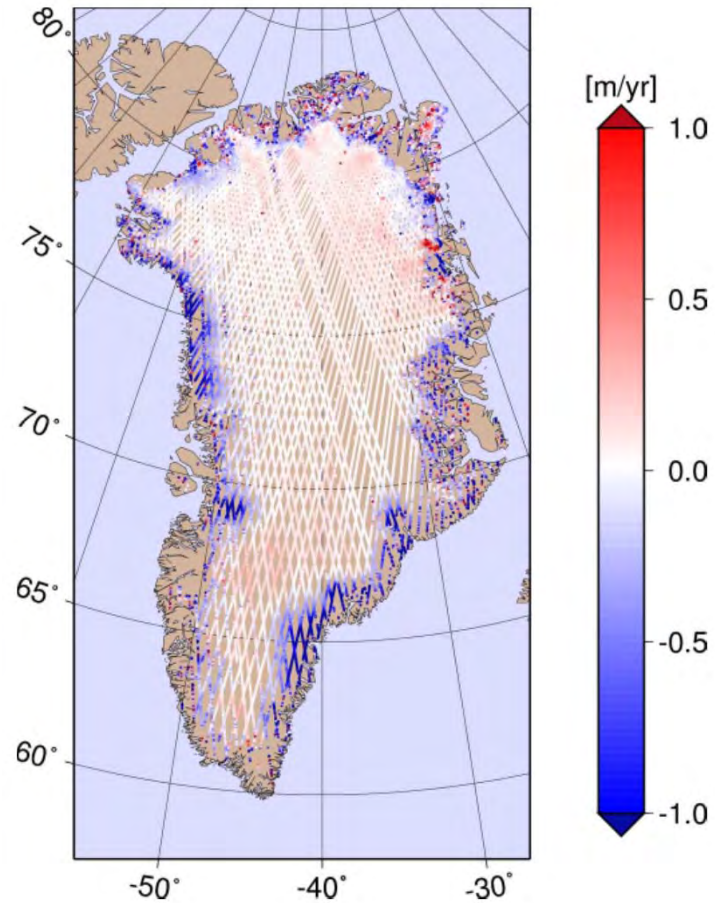
CryoSat-2 radar altimetry, 2010-2013

Cross-over solution - Greenland



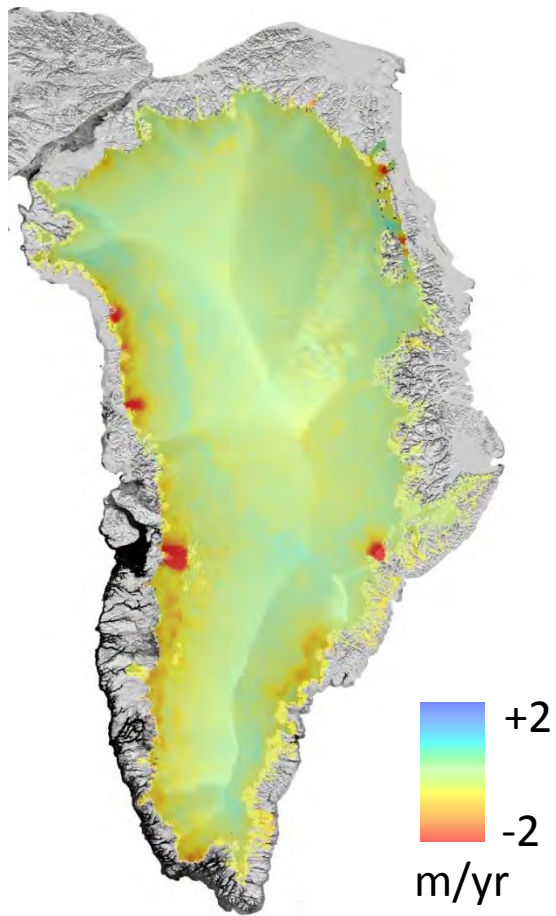
1992-2008 elevation change from radar altimetry
(Khvorostovsky, 2012)

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.

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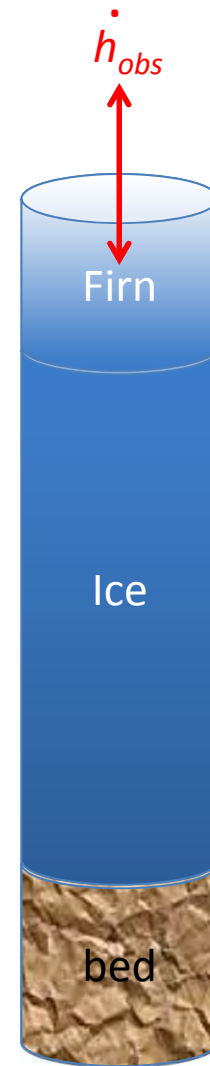
Repeat track / Model fit advantages

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

Determining ice sheet mass changes

Determining ice sheet mass changes

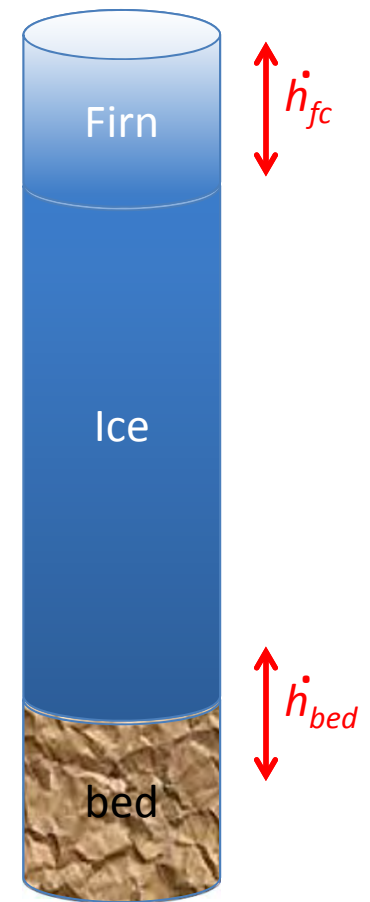
$$\dot{h}_{obs} = \dot{h}_{SMB} + \dot{h}_{dyn} + \dot{h}_{fc} + \dot{h}_{bed} + \dot{h}_{bmb}$$



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



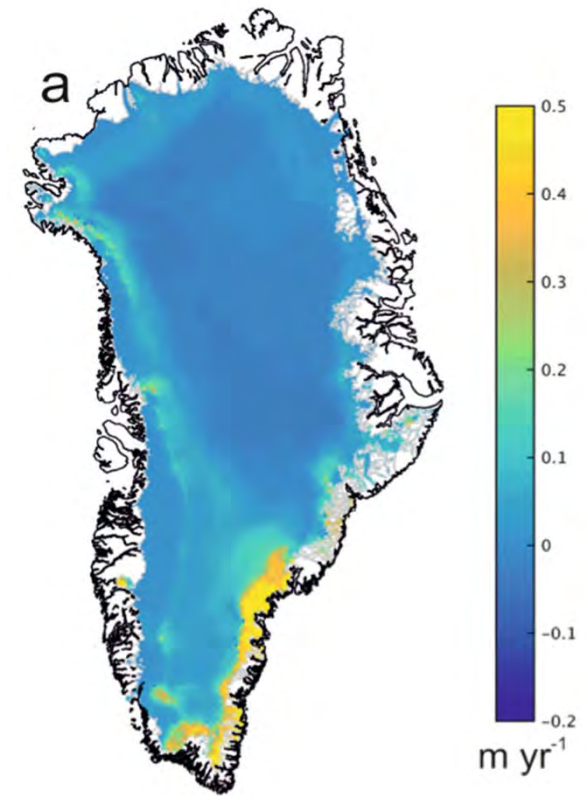
Elevation changes not associated with change in ice mass

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

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

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.

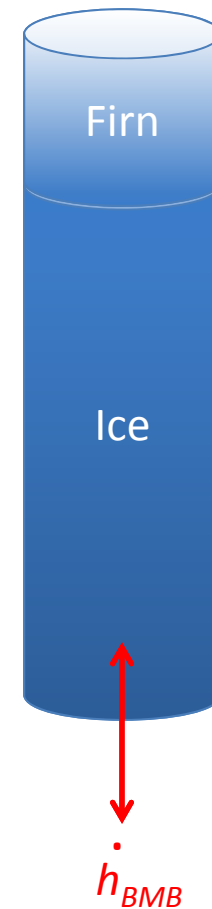


2011-2014 rate of elevation change,
due to anomalies in firn compaction,
from IMAU-FDM.

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

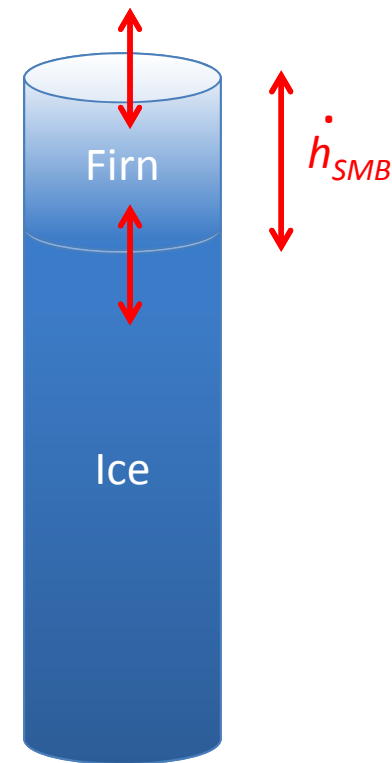
$$\dot{h}_{obs} = \dot{h}_{SMB} + \dot{h}_{dyn} + \dot{h}_{fc} + \dot{h}_{bed} + \dot{h}_{bmb}$$

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

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

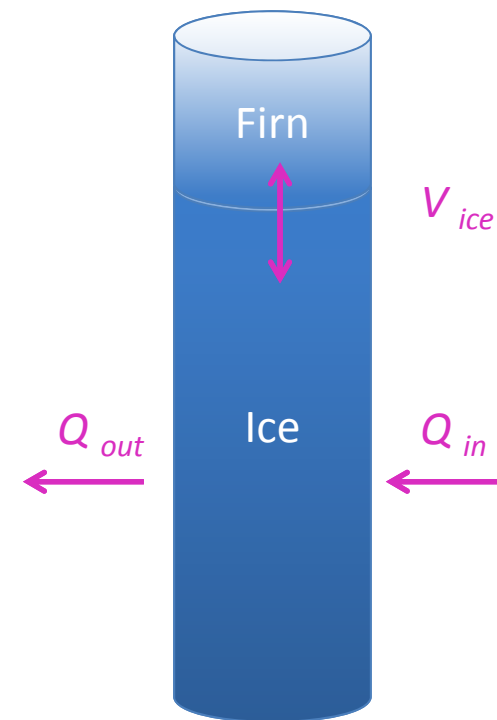
Leaves changes in the thickness of the **firn** and **ice** column, driven by mass loss or gain.

Ice

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

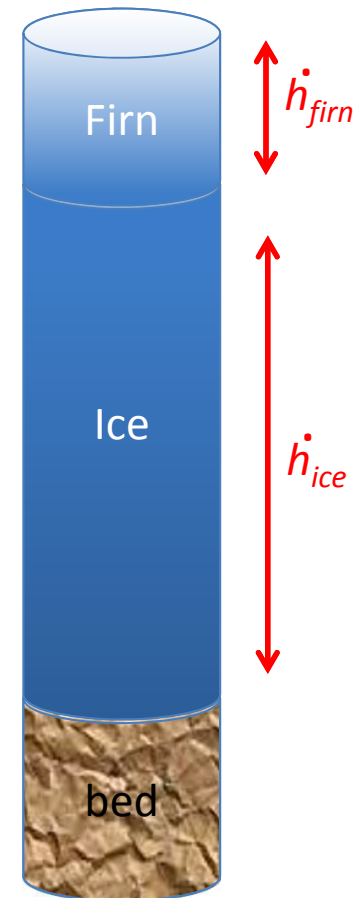
i.e. when mass exchange at the lateral and upper boundaries of the ice column are not in balance.

For example resulting from changes in ice dynamics.



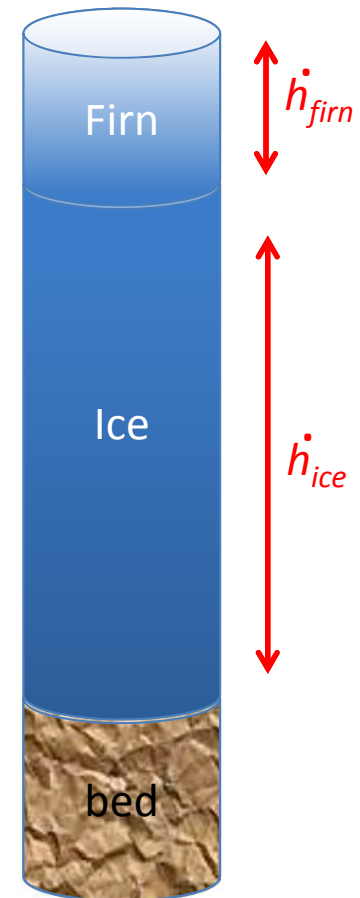
Determining ice sheet mass changes

- 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

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- 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

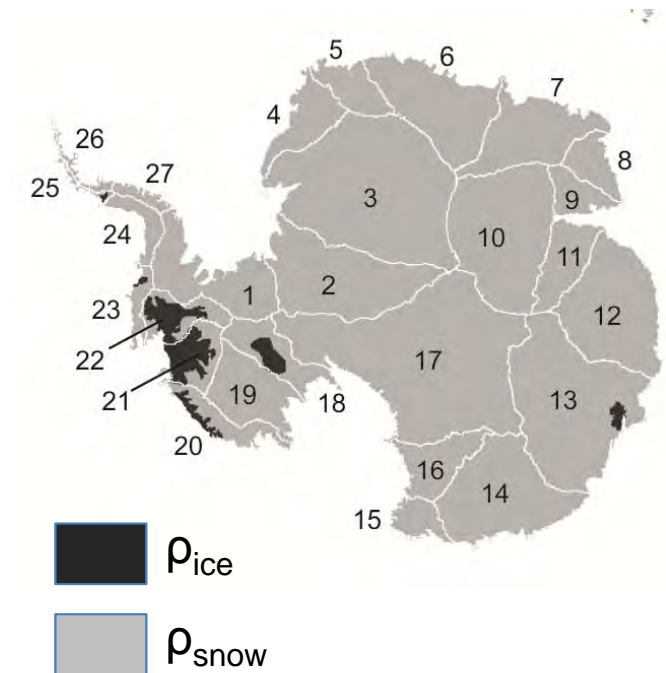
Binary model for Greenland:

- $\rho_{\text{snow}} > \text{ELA}$
- $\rho_{\text{ice}} < \text{ELA}$

Binary model for Antarctica:

- $\rho_{\text{snow}} < T_{\text{dyn}}$
- $\rho_{\text{ice}} > T_{\text{dyn}}$

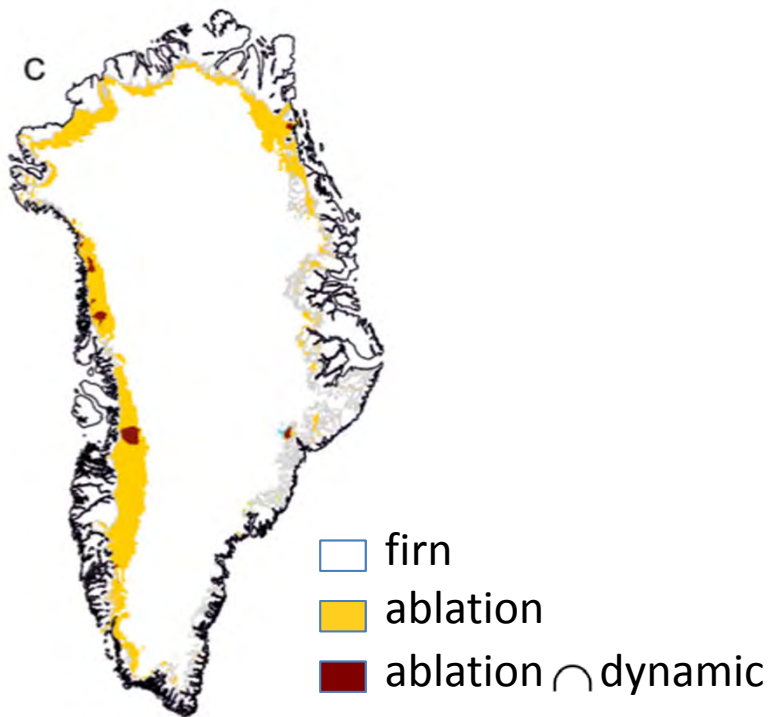
T_{dyn} is a threshold based on auxiliary data, for example elevation rate and velocity.



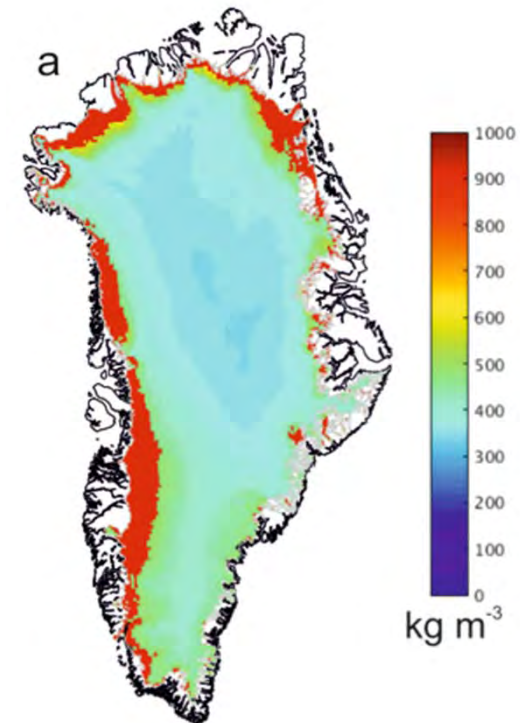
1. Use an empirical model to define regions undergoing dynamic and SMB driven changes.

Refined model

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



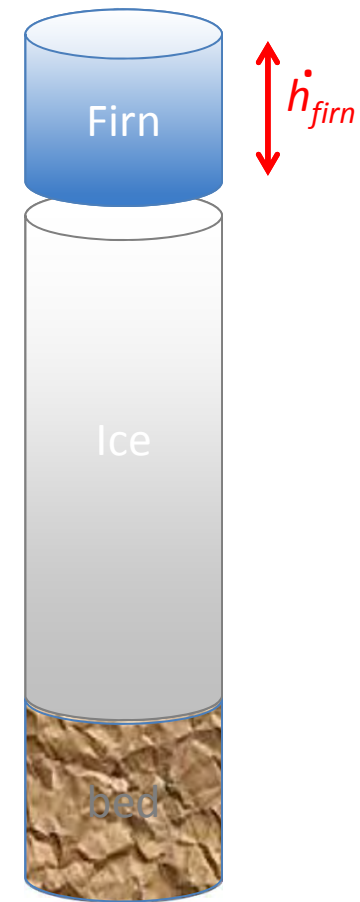
Greenland density model definition.



Greenland density model.

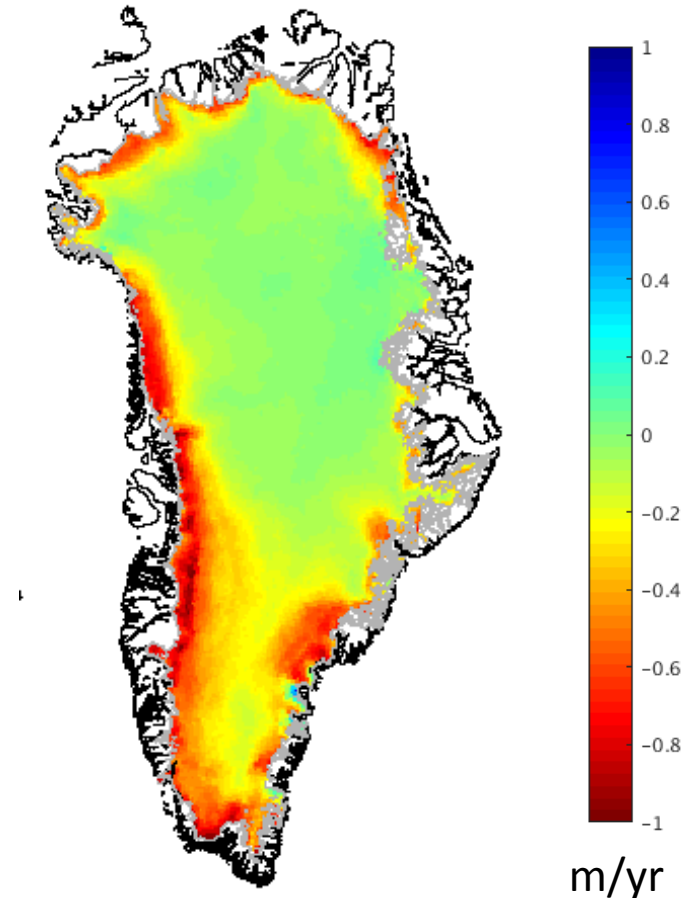
2. Use a firn model to simulate SMB driven changes and isolate the underlying ice dynamic imbalance.

- 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.



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

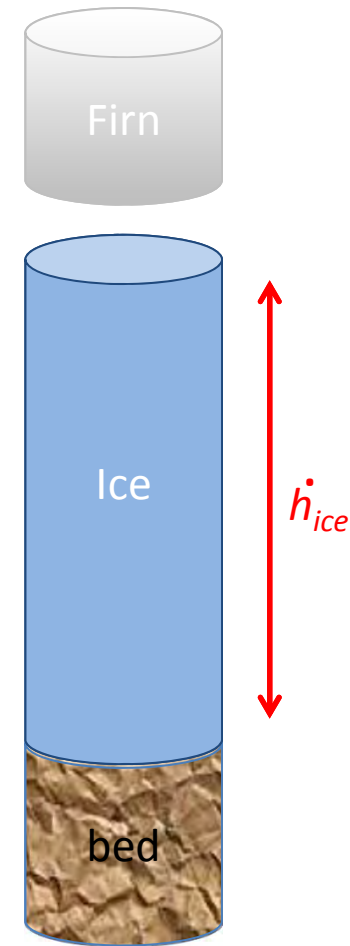
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IMAU-FDM rate of SMB driven thickness change, 2011-2014.

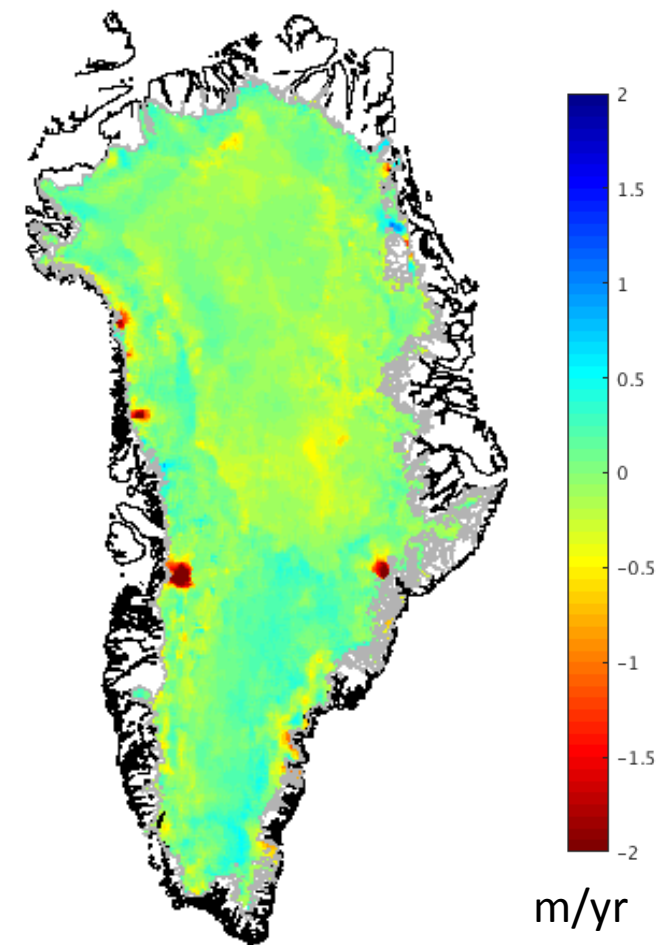
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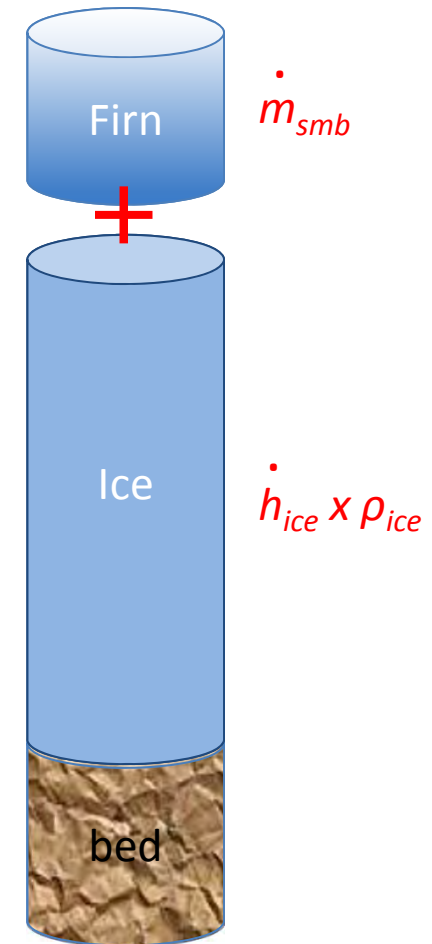
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Ice column thickness change,
2011-2014.

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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.

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

Advantages

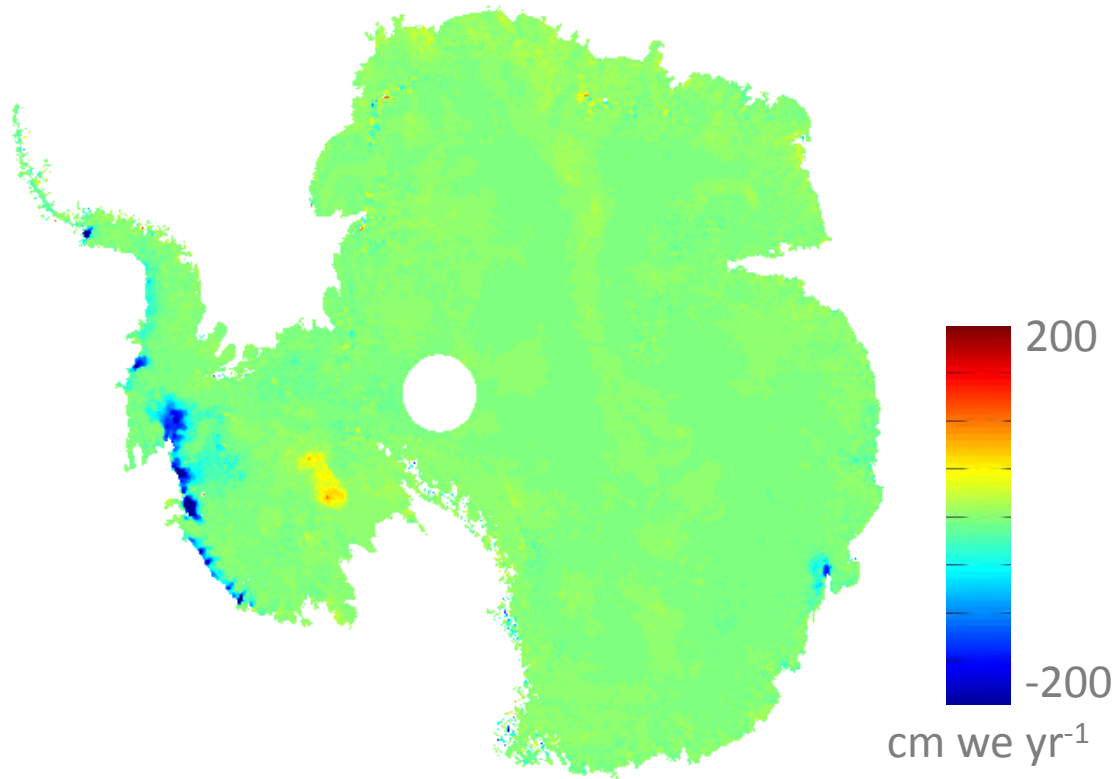
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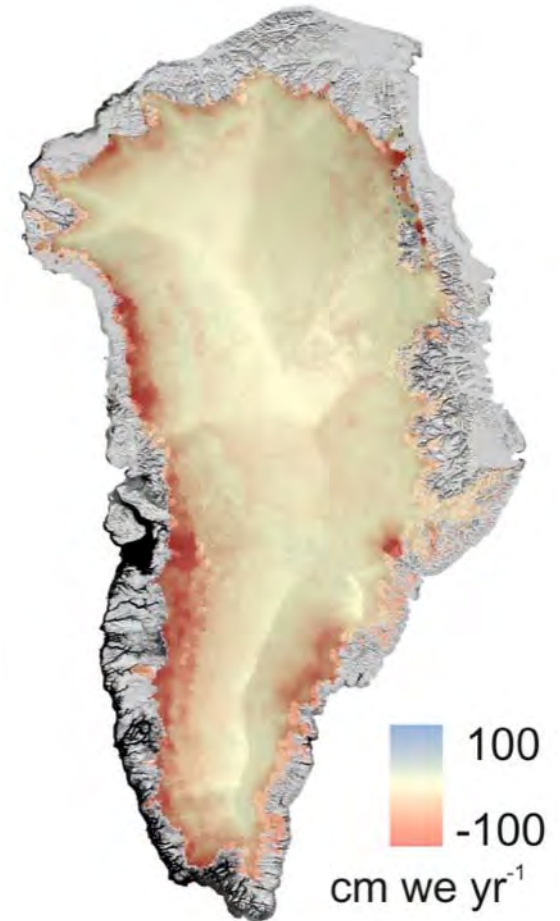
Advantages

- 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

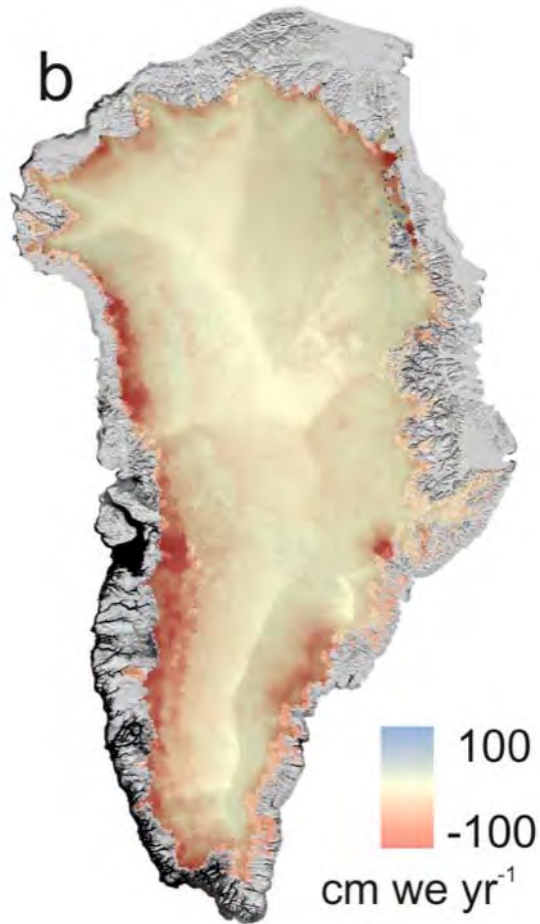


Antarctic rate of mass change,
from CryoSat-2.

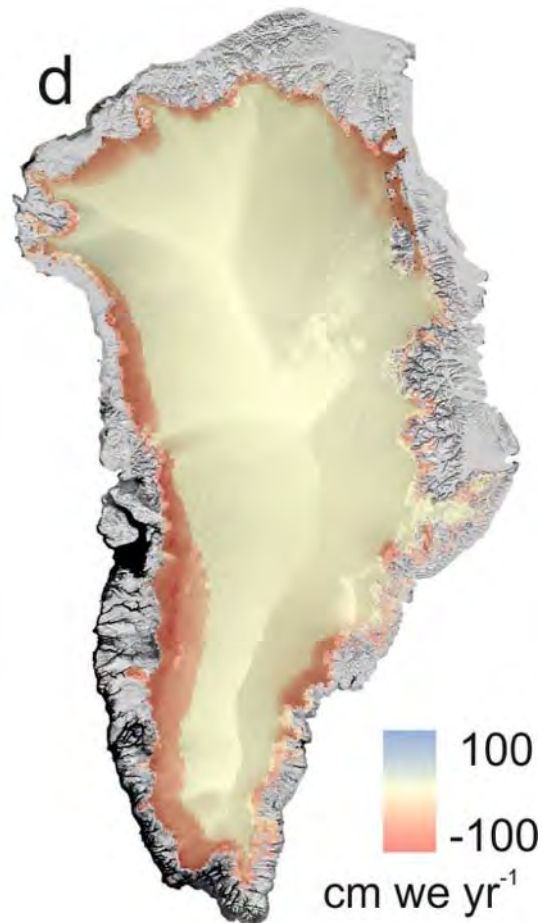


Greenland rate of mass change,
from CryoSat-2.

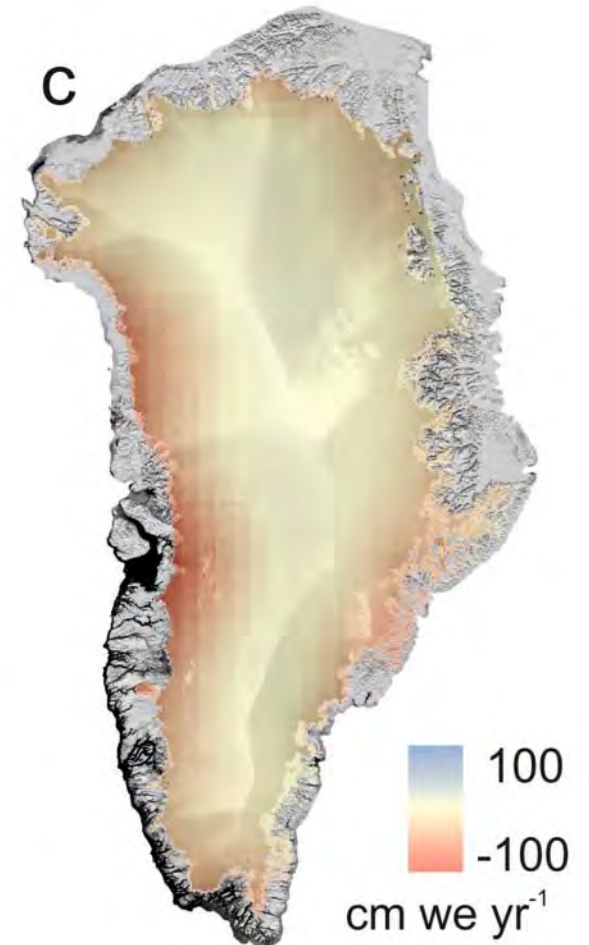
Ice sheet specific mass balance - comparisons



Rate of mass change
from CryoSat-2.

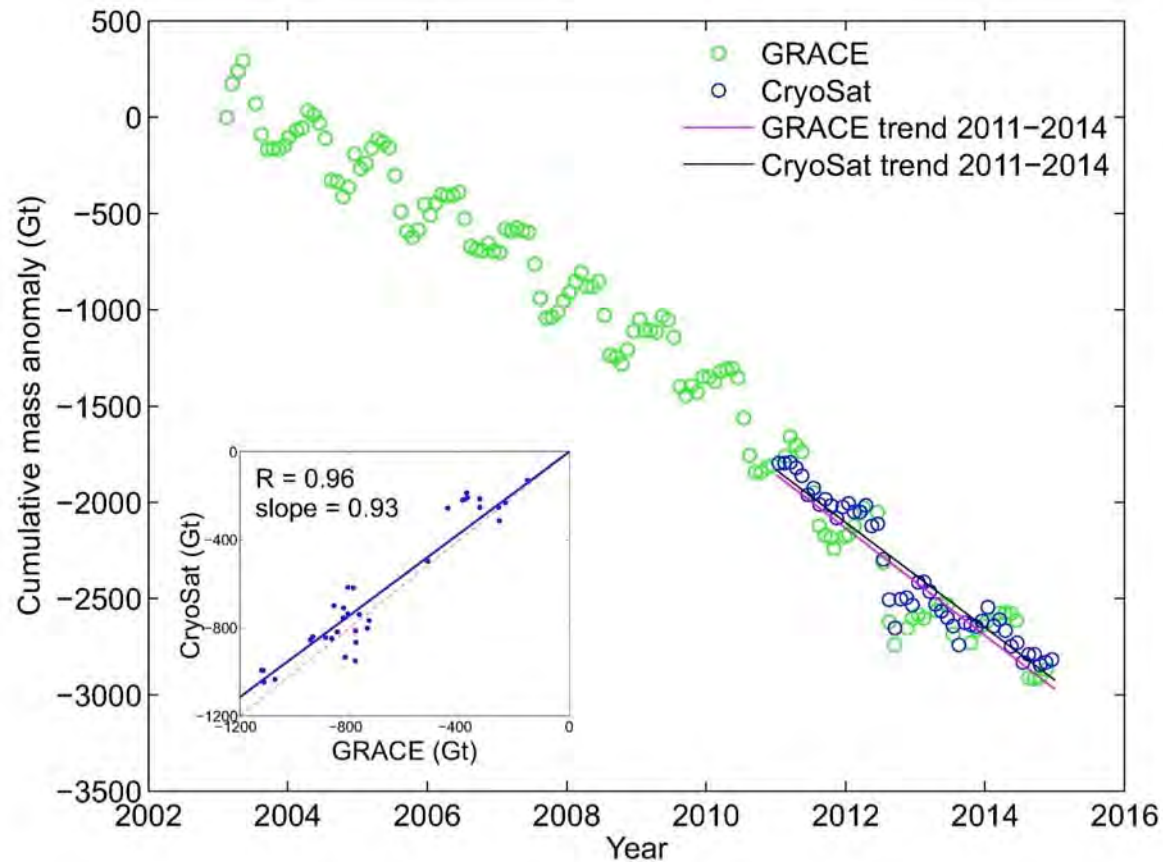


Rate of mass change
from RACMO2.3
(SMB only).



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.

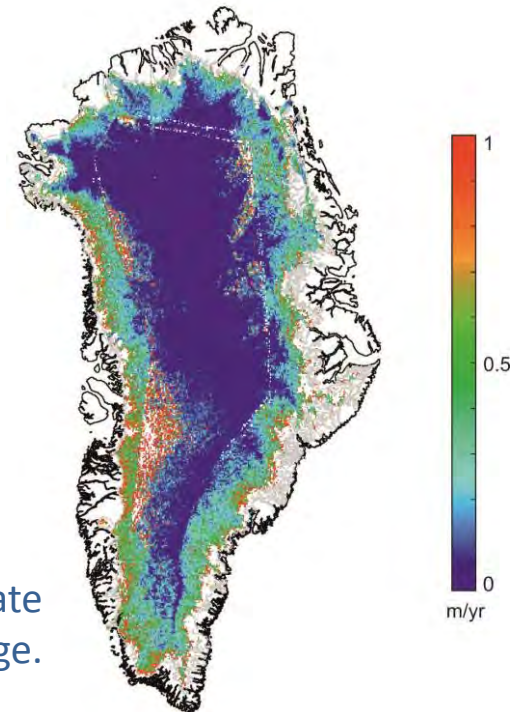
- Instrument effects (e.g. radar speckle).
- Processing effects (e.g. retracking).
- Elevation rate model limitations (i.e. how well does the functional form of the model reflect reality).
- Snowpack effects (e.g. changes in the depth distribution of backscattered energy).

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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.

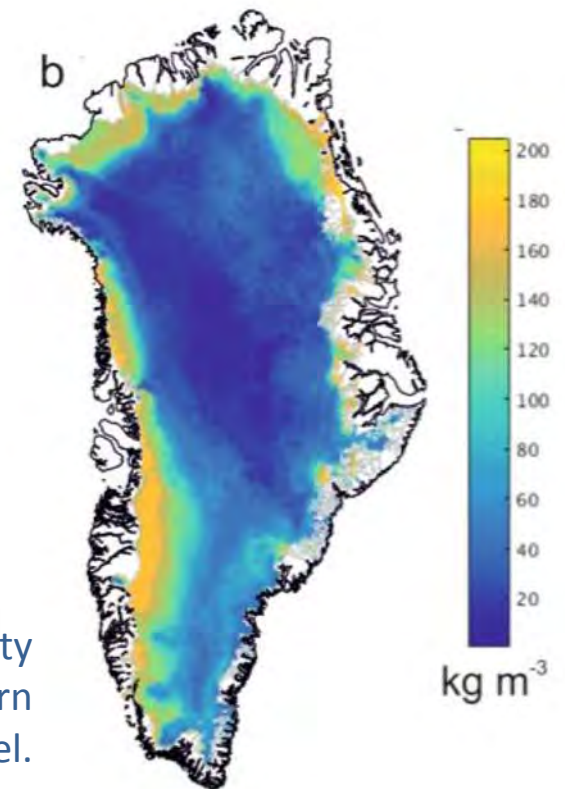
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- Mitigate using a backscatter correction.
- Estimate empirically, e.g. based on Greenland 2012 melt event.
- Area of ongoing research.

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.

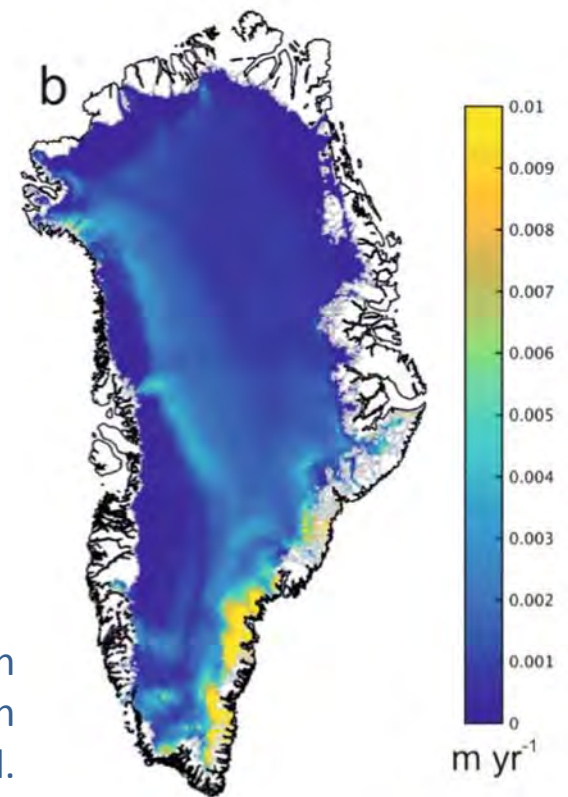
Principle Sources of Uncertainty

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.

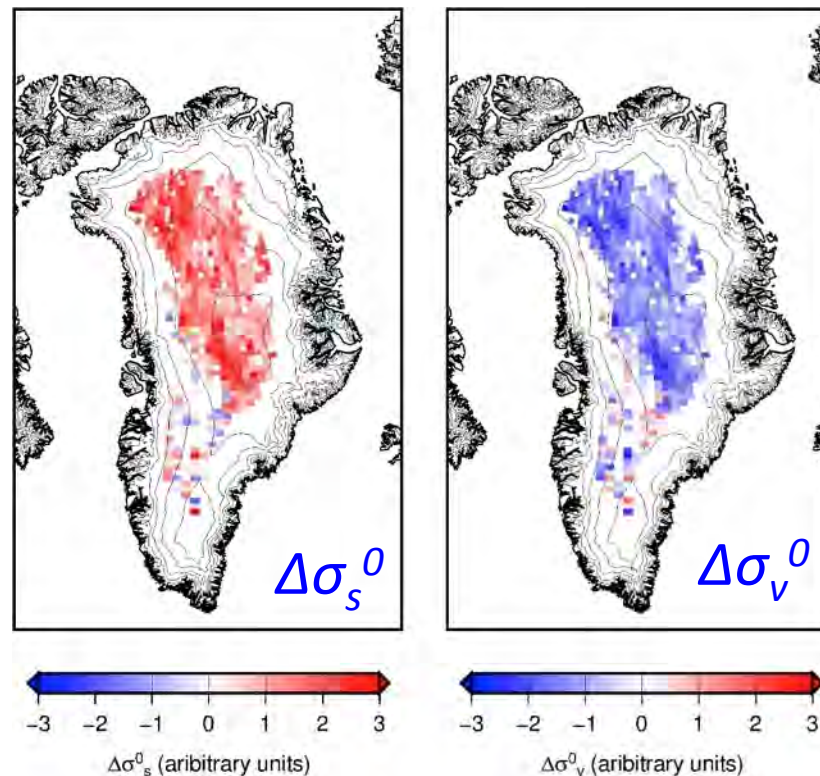


Current Frontiers for Radar Altimetry

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.

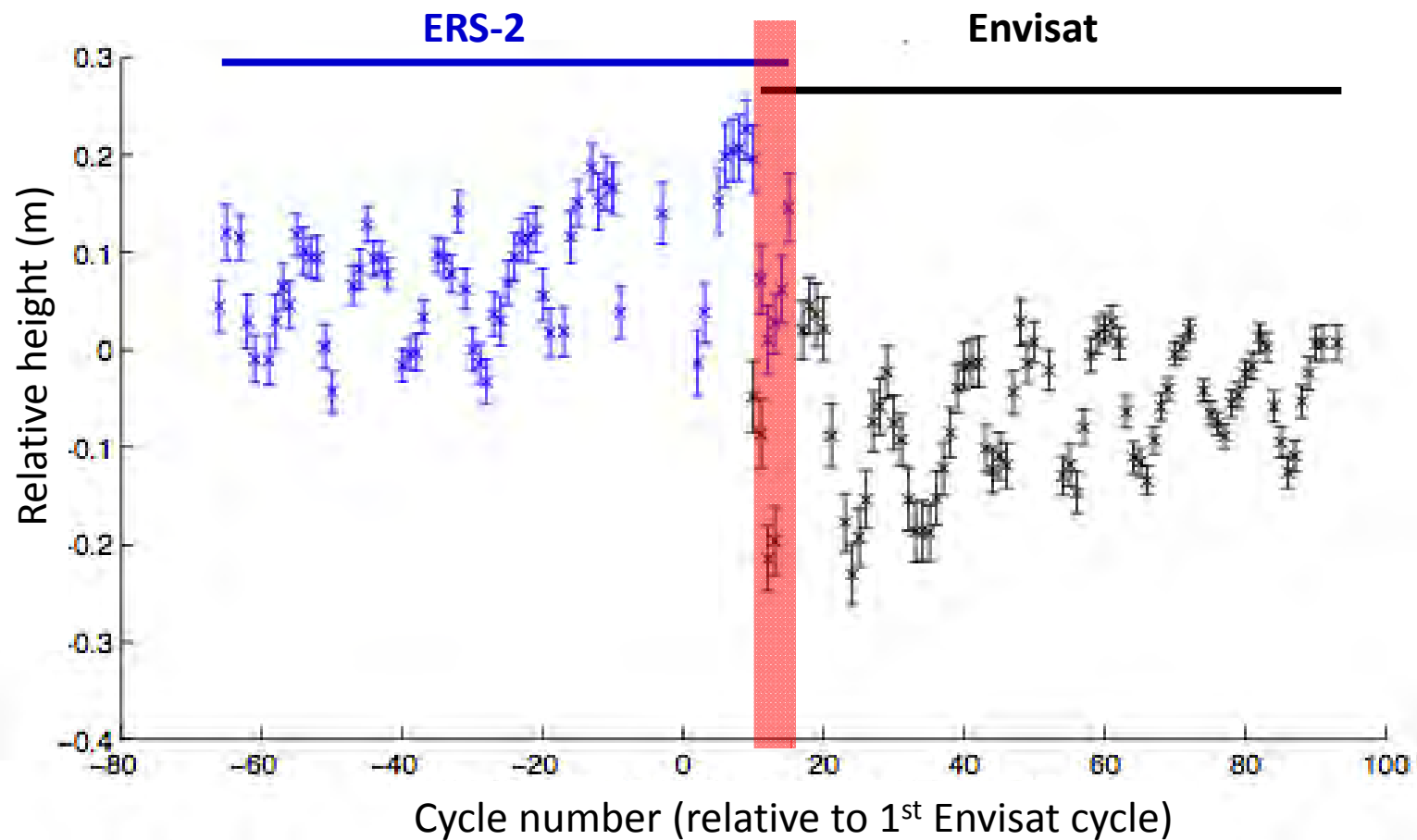
1. Improving understanding of radar wave interaction with the snowpack.

Change in scattering characteristics during summer 2012 melt event.



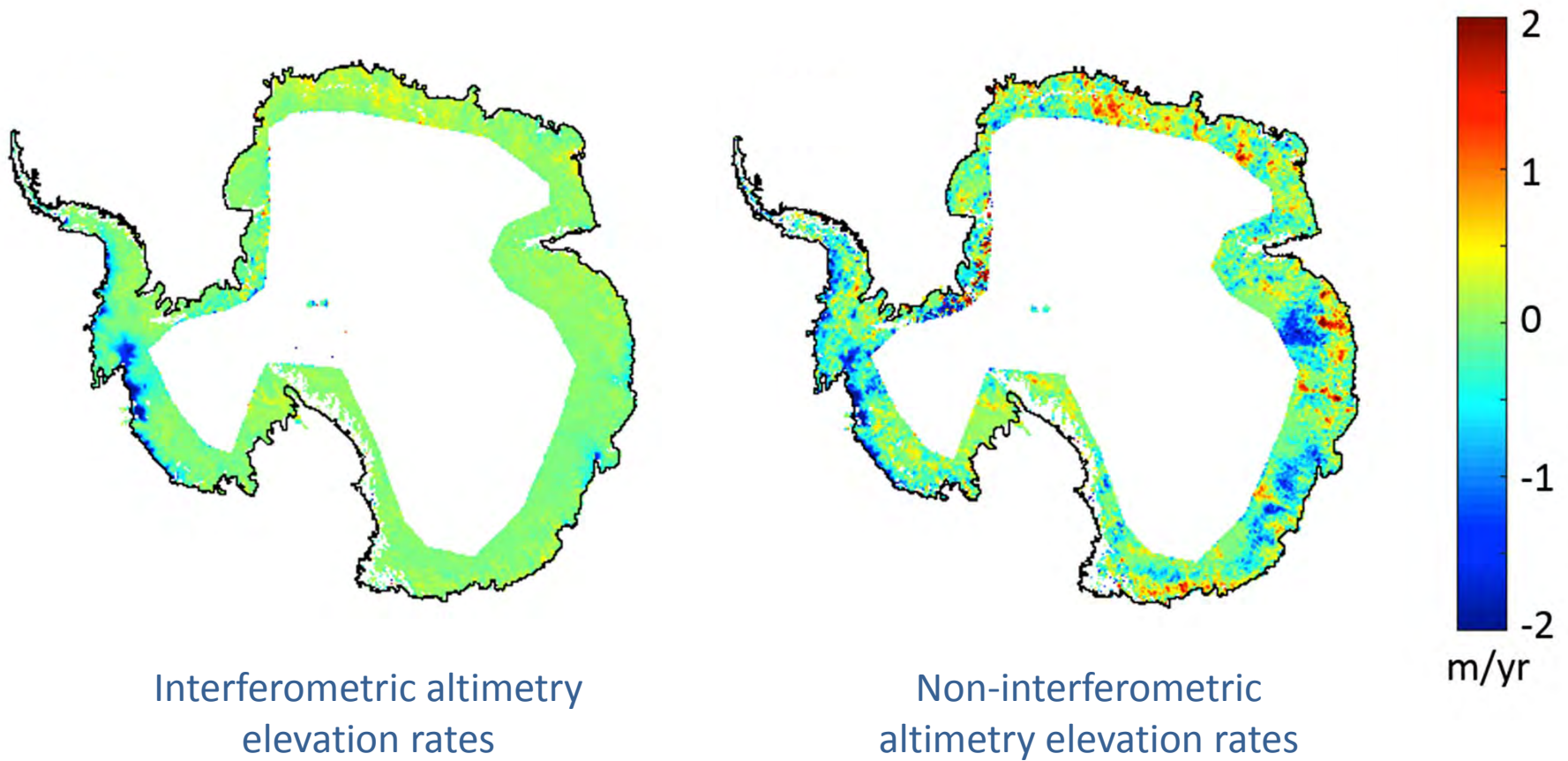
- Retrieval of scattering properties from the radar echo.
- Use to investigate snowpack related artifacts.

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



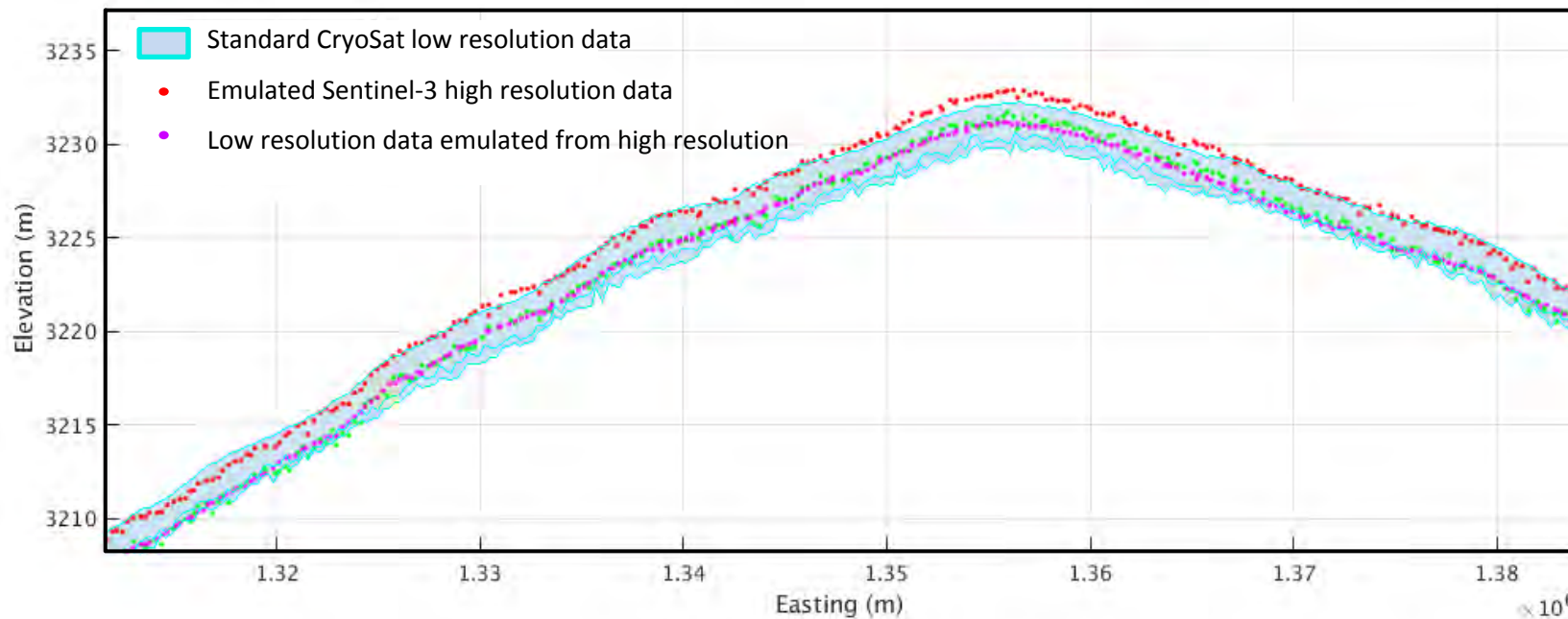
3. Managing the transition from low to high resolution measurements.

- Comparisons between interferometric and non-interferometric high resolution altimetry

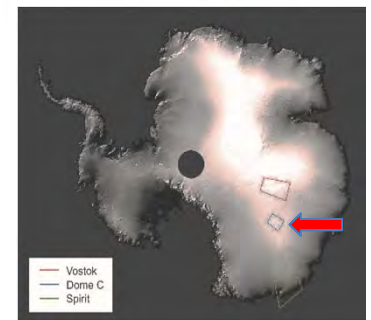


3. Managing the transition from low to high resolution measurements.

- 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.

