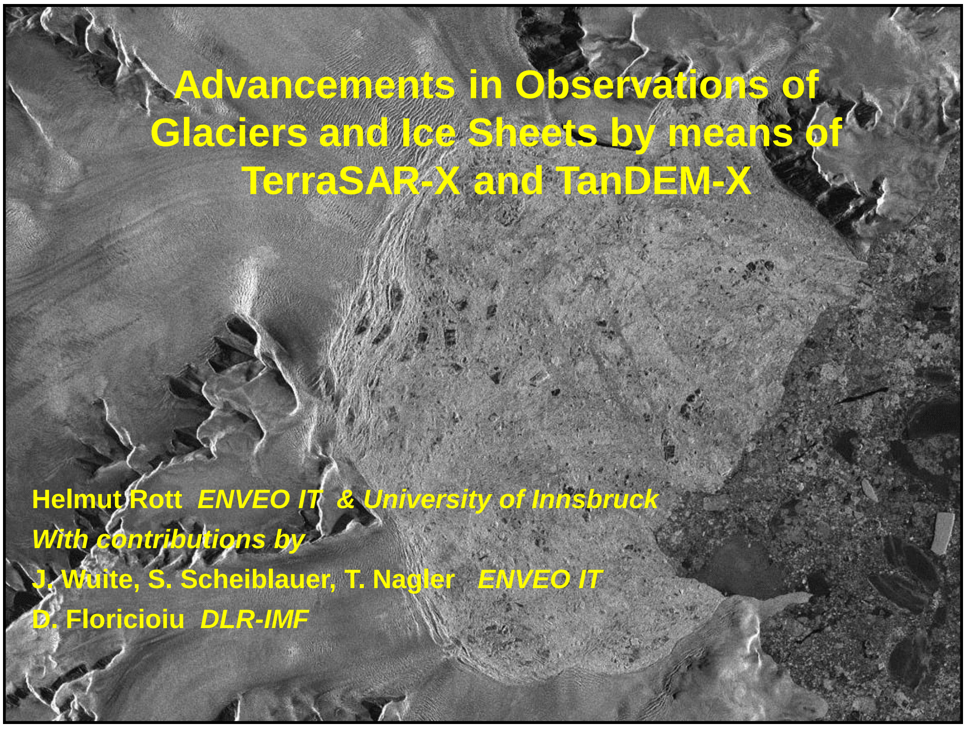

Advancements in Observations of Glaciers and Ice Sheets by means of TerraSAR-X and TanDEM-X

Helmut Rott *ENVEO IT & University of Innsbruck*
With contributions by
J. Wuite, S. Scheiblauer, T. Nagler *ENVEO IT*
D. Floricioiu *DLR-IMF*

SAR – Key Tool for Observation of Ice Sheets and Glaciers

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TDX & Altimetry

SAR & Scatterometry: Surface melt and accumulation and

TDX & Altimetry: Surface topography

$$\frac{dS}{dt} = \frac{1}{\rho}\frac{\partial b}{\partial t} + v_z + \vec{v}_h \cdot \vec{\alpha}$$

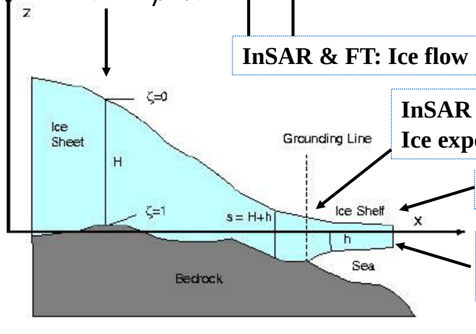
TDX – TanDEM-X high resolution DEM
FT – feature tracking

InSAR & FT: Ice flow

InSAR & FT : Ice export & grounding line

SAR: Ice front, iceberg calving

Altimetry, InSAR, FT: Ice shelf mass balance



Contents of Presentation

SAR Signal Propagation for Mapping Surface Topography

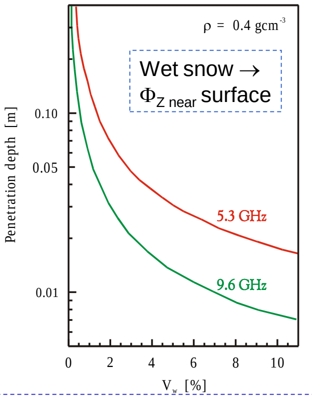
TanDEM-X repeat observations are an excellent source for spatially detailed mapping of glacier volume change by means of **DEM-differencing.**

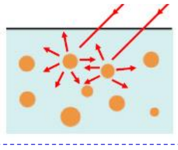
The change in glacier volume ΔV over time interval Δt can be converted into change of glacier mass (the net mass balance, B_N) :

$B_N(\Delta t) = V(\Delta t)\,\rho$ Typical value for glacier ice: ρ = 900 kg m^{-3}

Effects of SAR signal penetration (position of scattering phase center, Φ_Z) need to be taken into account for DEM differencing. Options:

- Using repeat observations at **same radar frequency and snow state** (either dry or wet)
- Estimate penetration **for given snow state and radar frequency** (using model and/or empirical data)





Φ_Z in **dry** snow and firn →
1 to several metres below surface
Depends on scattering efficiency

Surface Elevation Change 2011- 2013 by TDX DEM Differencing

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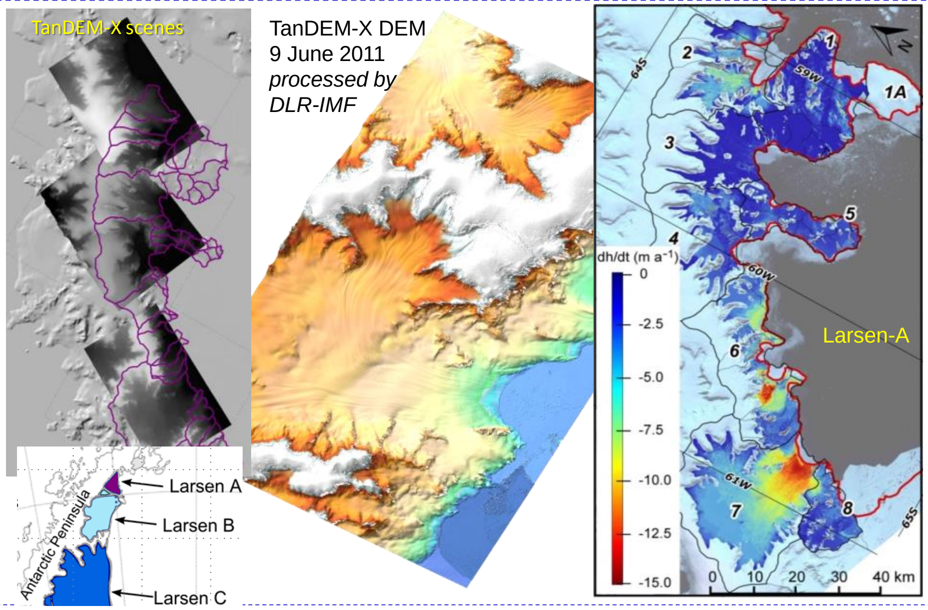

Elevation Change TanDEM-X / 9 June 2011 – 21 April 2013

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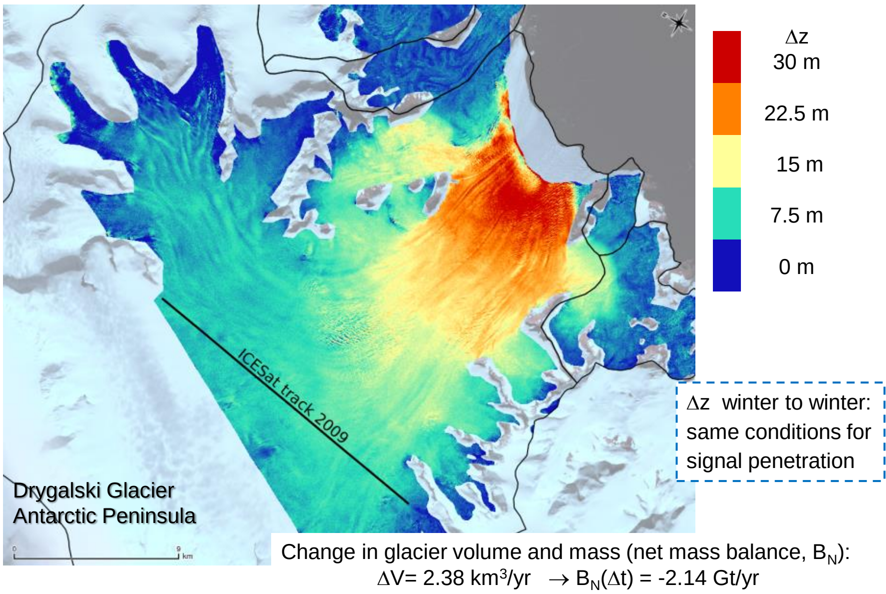
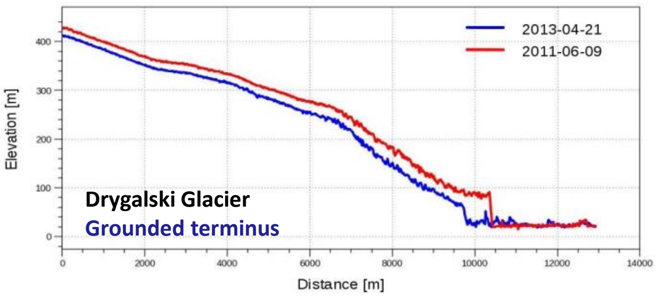
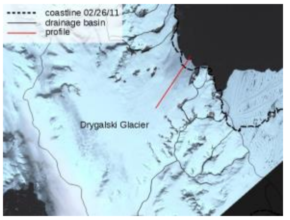


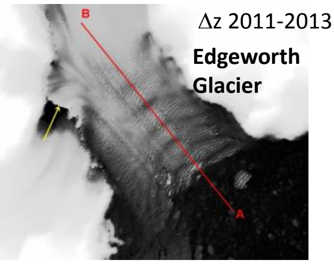
Δz winter to winter: same conditions for signal penetration

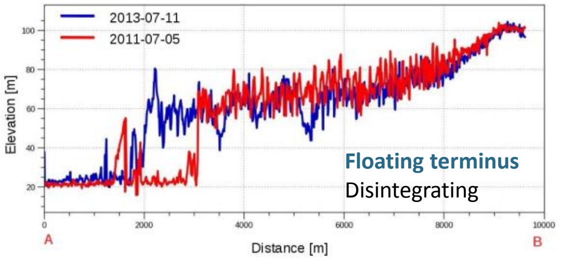
Change in glacier volume and mass (net mass balance, B_N):
$\Delta V = 2.38\ km^3/yr \rightarrow B_N(\Delta t) = -2.14\ Gt/yr$

DEM Differencing reveals Details on Glacier State

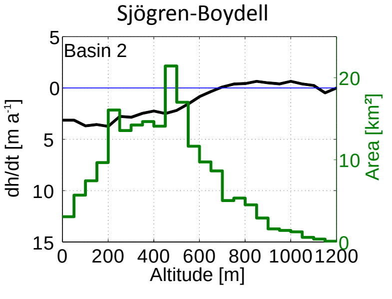


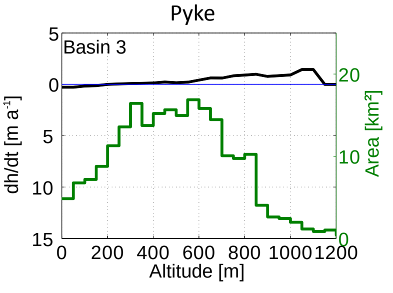


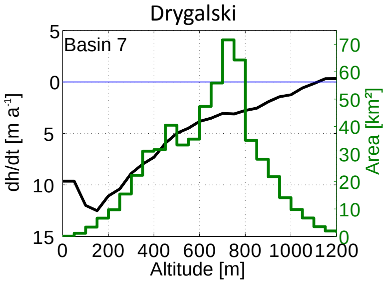


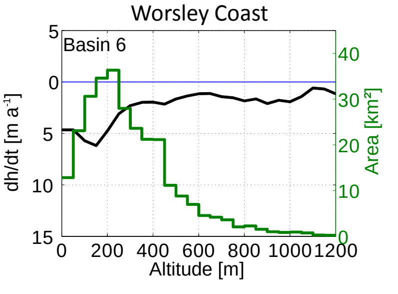


Surface Elevation Change vs. Altitude – Different Glacier Response



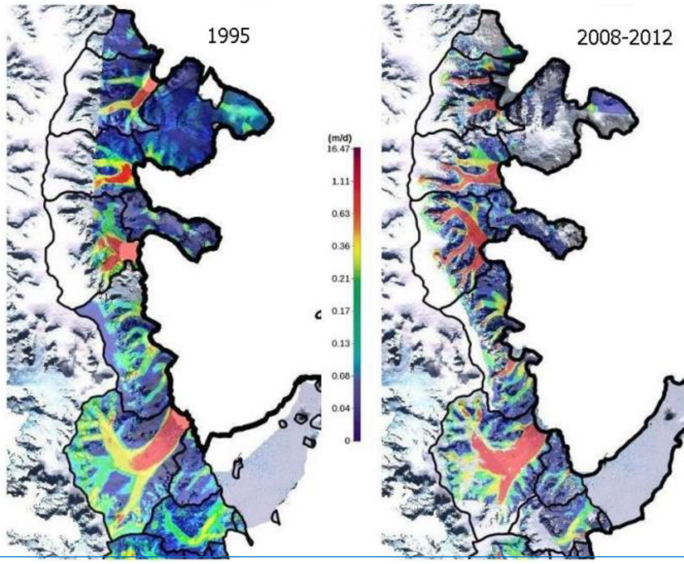






Detailed Maps of Glacier Velocities – Larsen A

Data Base:
ERS-1/-2 InSAR analysis of crossing orbits

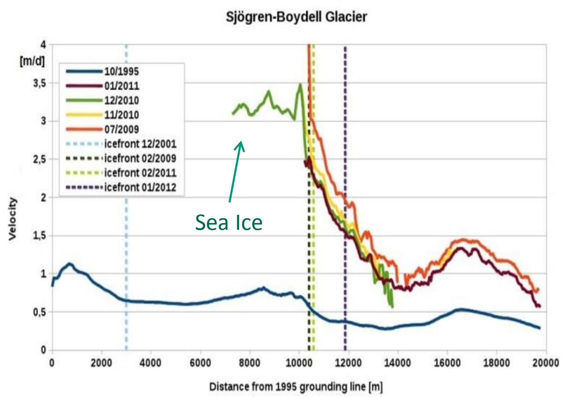


Data Base:
TanDEM_X 11-day Repeat pass
Offset tracking

Digital maps of ice velocity at 50 m grid

Work supported by ESA project **GlacAPI http://glacapi.enveo.at**

Velocities and Calving Flux Sjögren Glacier



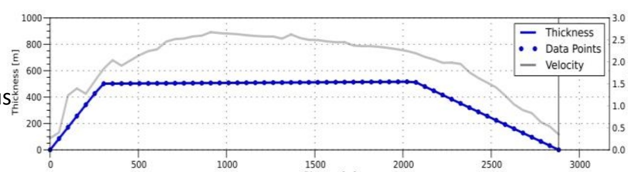
Retreat of grounded ice 1995-2012: 76 km^2

Calving flux:

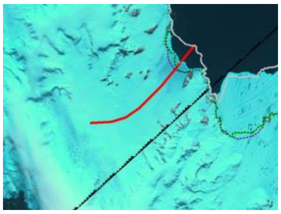
2008/09: 1.04 Gt/yr

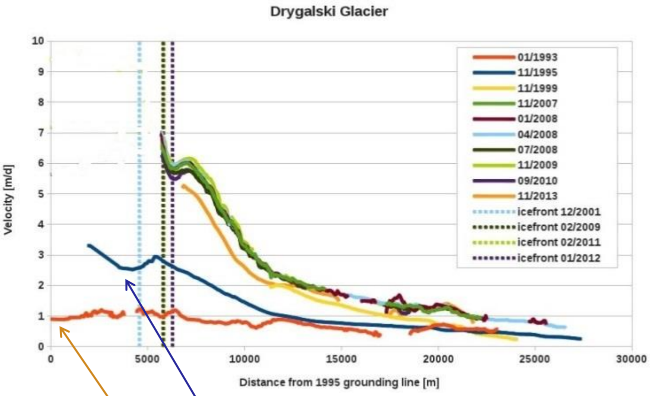
2012: 0.94 Gt/yr

Thickness of floating terminus inferred from frontal height



Velocities and Calving Flux - Drygalski Glacier





Retreat of grounded ice 1995-2012: 40 km²

Calving flux: 2008/09: 3.80 Gt/yr

2012: 3.40 Gt/yr

Gradual slow-down of calving velocity after 2008

Synergy of DEM Differencing and Input-Output Method

IOM: Net balance B_n as difference between surface mass balance SMB and calving flux B_{cv}

SMB

$$B_n(\Delta t) = B_{ac} + B_{ab} - B_{cv} = \int_{S_{ac}} b_n dS + \int_{S_{ab}} b_n dS - \rho \int_{y} \left[u_{cv}(y) h(y)\right] dy = \langle b_n \rangle S - B_{cv}$$

SMB estimates supplied by GCM driven regional climate models and/or extrapolation of in situ point measurements.

SMB is essential for modelling glacier response to atmospheric forcing

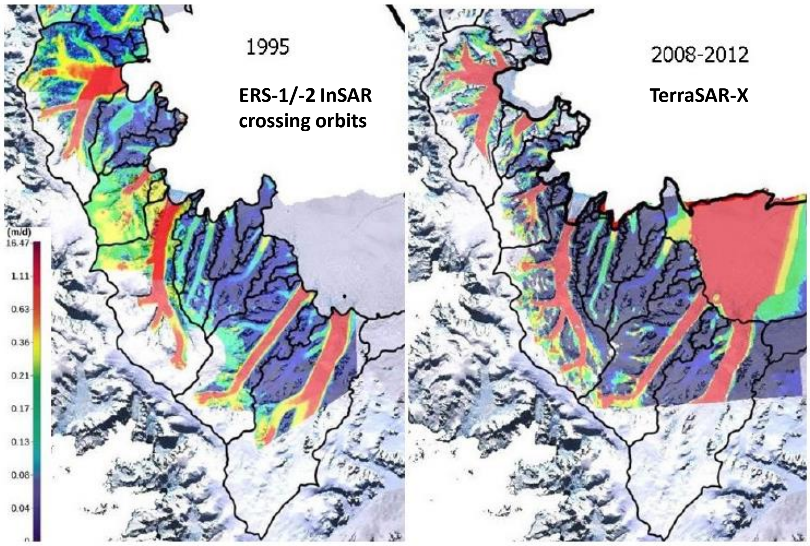
Uncertainty in SMB can be reduced by synergy of B_n from DEM –Diff. and data on calving flux

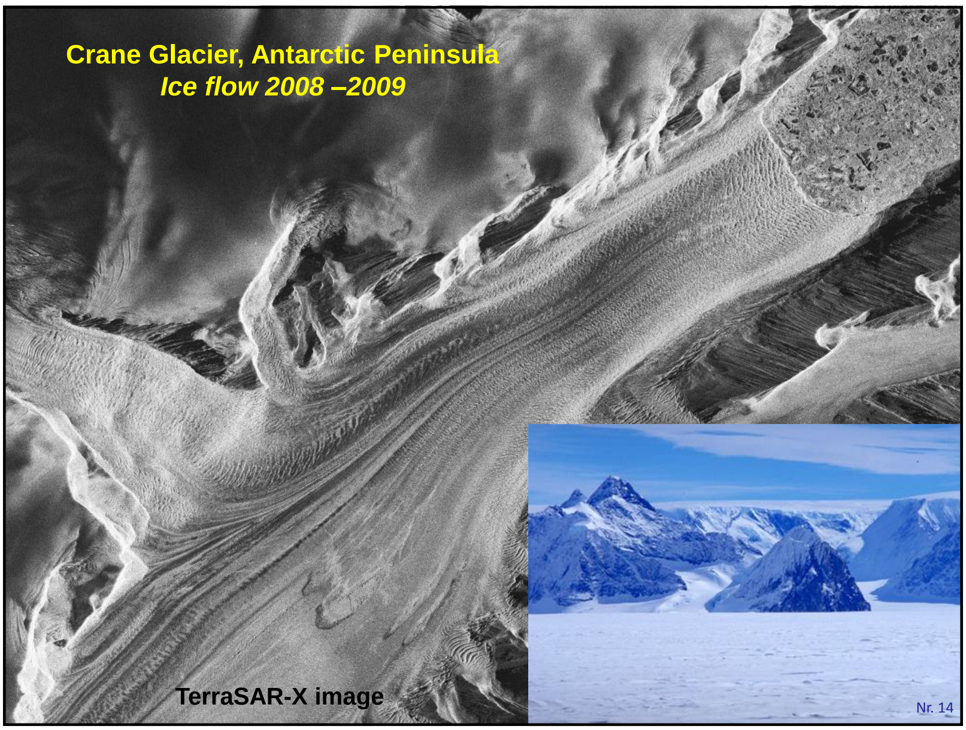
$$SMB = B_{ac} + B_{ab} = B_n - B_{cv}$$

Examples for some Larsen-A glaciers **SMB by synergy TDD and CV**

Glacier	B_n by TDX [Gt/yr]	B_c [Gt/yr]	SMB [Gt/year]	SMB b_n [kg/m² yr]
Sjögren/ Boydell	-0.367	0.936	0.569	1083
Pyke	+0.056	0.64	0.696	1364
Drygalski	-2.140	3.40	1.260	1258

Maps of Glacier Velocities- Larsen B





Variations in Velocity and Calving Flux – Crane Glacier

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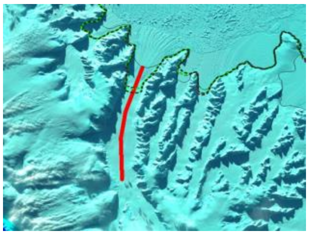

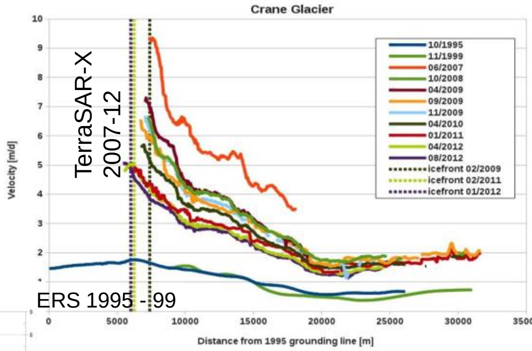

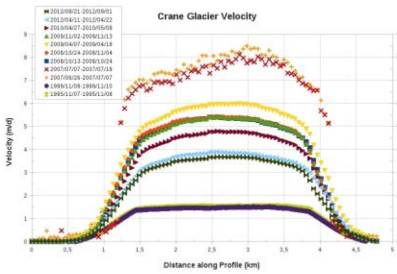

Velocity at frontal flux gate

Date	Flux Gt/yr	Deficit Gt/yr
1995-99	1.15 (→ B_A)	0
2008/09	2.92	1.77
April 2012	2.03	0.88
Oct 2012	1.92	0.77

Velocity & Flux at Grounding Line – Flask Glacier

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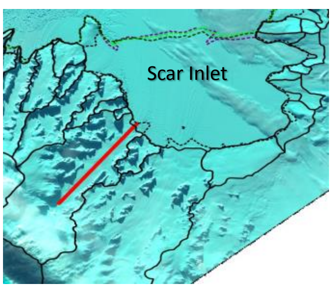

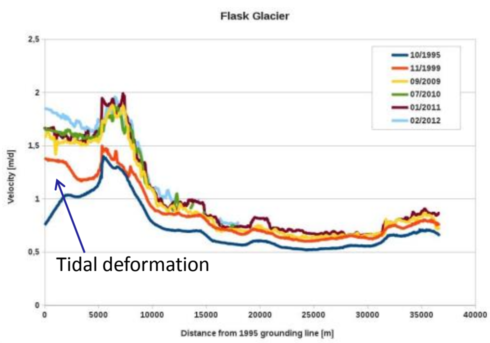

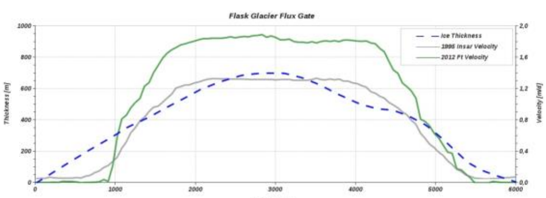

Flux gate: Velocity 1995 and 2012
Ice thickness: Farinotti et al (2013)

Flask Glacier (1131 km²)

Flux 1995 : 0.84 Gt/yr

b_N = 743 kg $m^{-2}a^{-1}$

Flux 2012: 1.20 Gt/yr

Deficit vs. 1995: 0.36 Gt/yr

Retrieval of 3D Ice Motion - Offset Tracking

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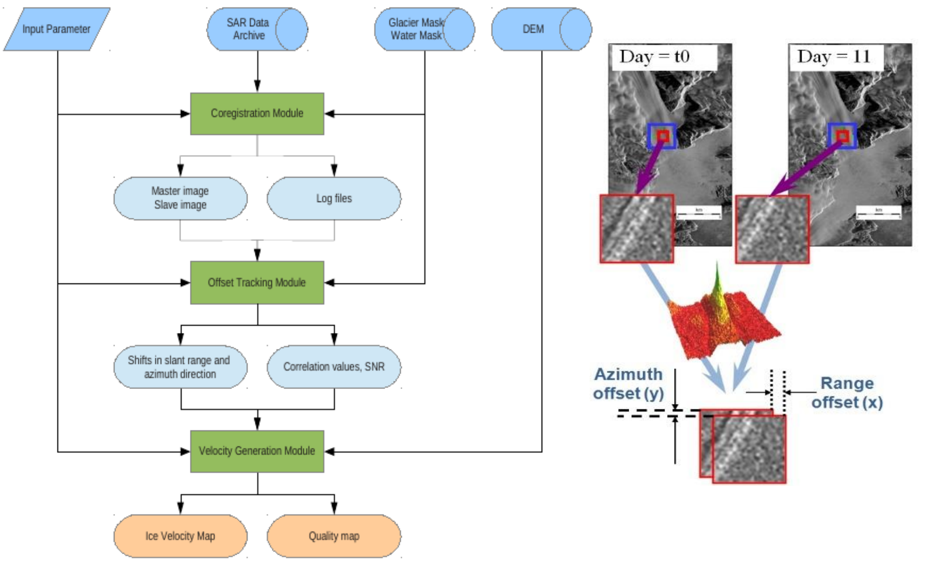
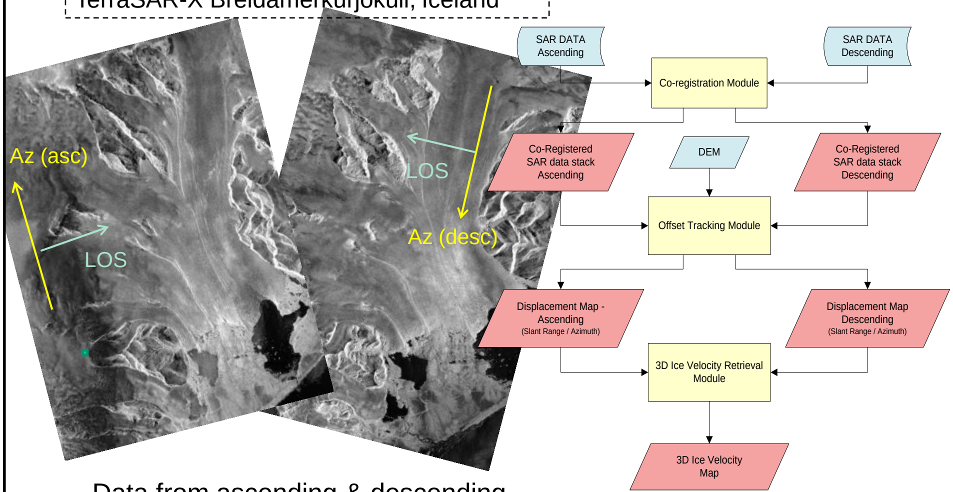


Retrieval of 3D Ice Motion by SAR Offset Tracking

enveo

TerraSAR-X Breidamerkurjökull, Iceland



Data from ascending & descending orbits deliver 4 different projections of velocity vector

Maps of 3D Ice Motion by SAR Offset Tracking

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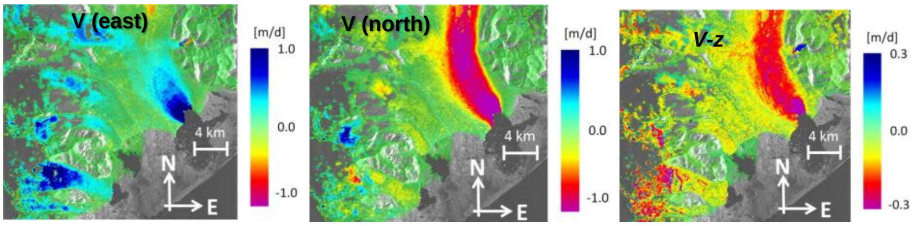
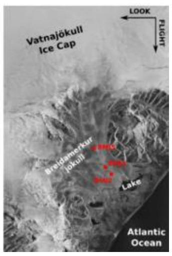
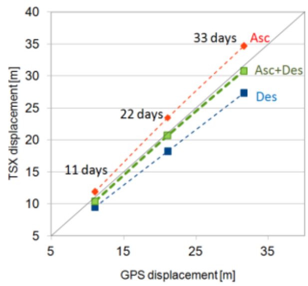
Breidamerkurjökull, Iceland, TerraSAR-X
Data base: 11/8, 22/8, 2/9, 13/9 2010 ascending and descending orbits





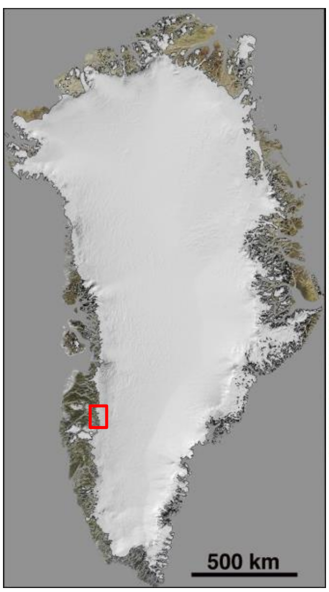


Validation with GPS
Asc + Desc: based on full 3D vector from TSX

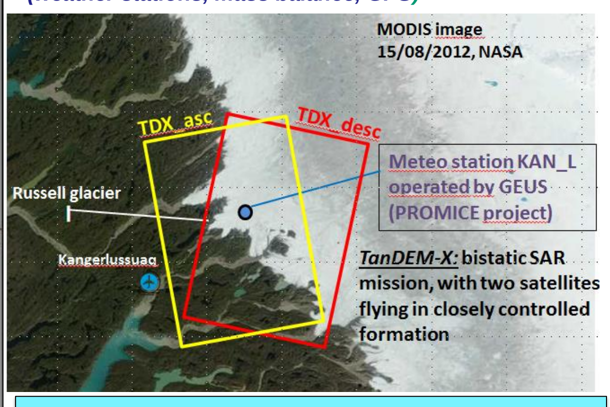
Vertical displacement includes contributions by
- **surface melt**
- **emergence**
- **surface parallel motion**

3D Ice Motion and DEM Differencing for Glacier Hydraulics

enveo



K-transect at 67°N
(weather stations, mass balance, GPS)



Data sets:
- Landsat-5 TM, -7 ETM+, -8 OLI from 1987 – 2013
- SPOT-5 SPIRIT (IPY) DEM 02/07/2008
- TanDEM-X DEMs (12/06/2011 and 08/09/2011
- TanDEM –X time series (summer 2011)

Seasonal Surface Elevation Change by DEM Differencing

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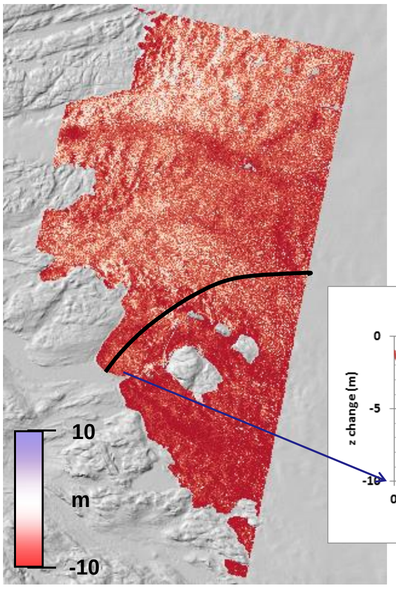
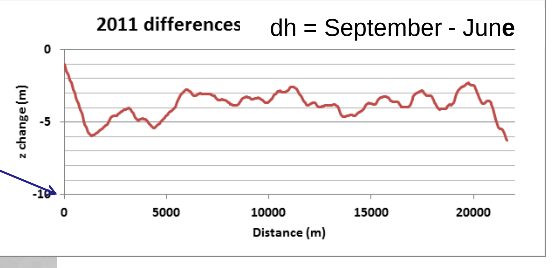


Seasonal changes in elevation June to September 2011

DEMs:

- TanDEM-X DEM 12/06/2011
- TanDEM-X DEM 08/09/2011

DEMs adjusted for bias (in ice-free areas)



Retrieval of 3D Ice Motion

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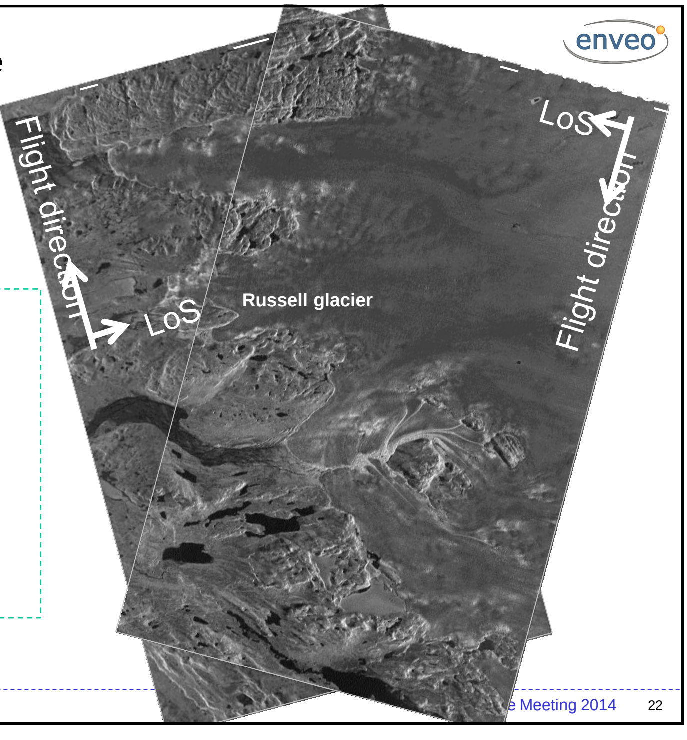
TDX repeat pass image pairs of ascending & descending orbits:

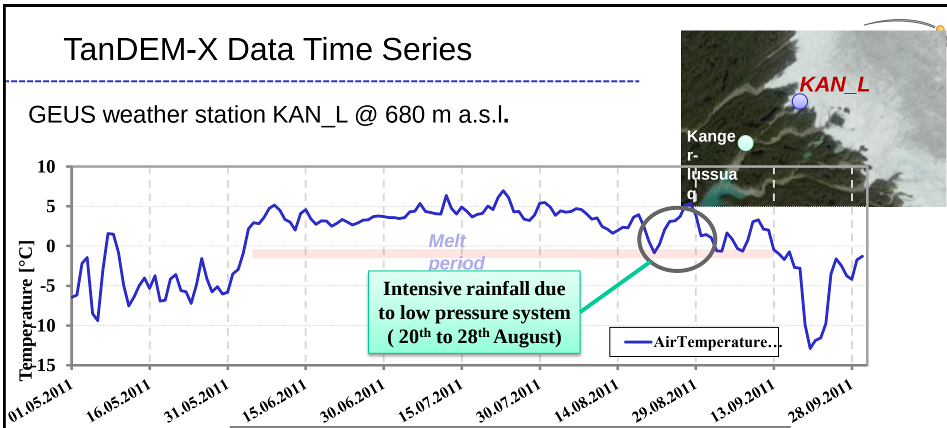
4 projections of the surface displacement vector:

ΔLOS + ΔFD, *Asc* + *Desc* → 3D Displacement

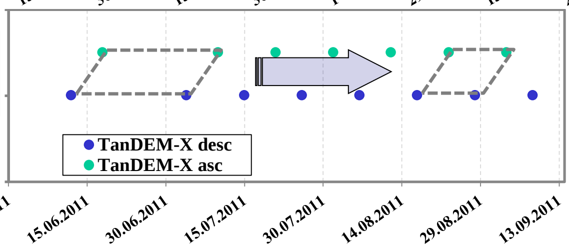


TanDEM-X Data Time Series

GEUS weather station KAN_L @ 680 m a.s.l.



Dataset of 15 scenes covering 2011 melt season

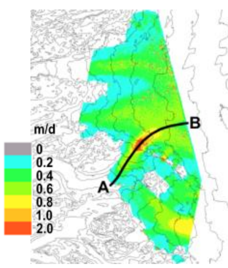


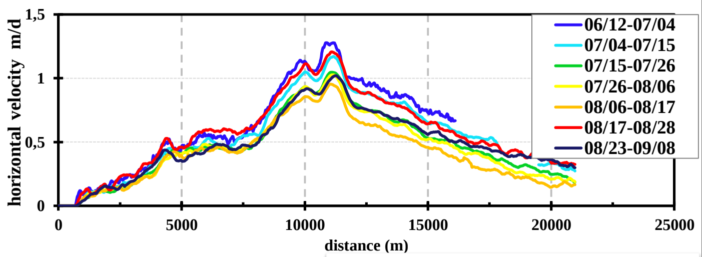
Asc /desc combinations for 3D-retrieval

TanDEM-X ascending and descending acquisitions for 3D retrieval

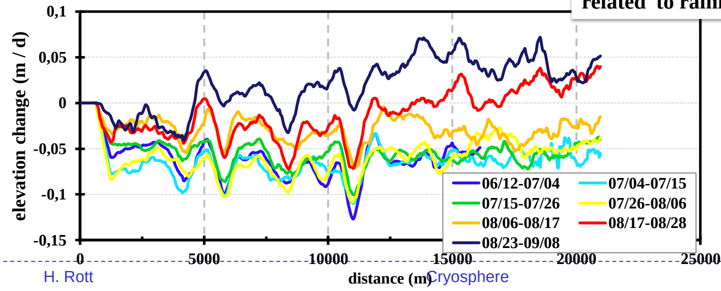
Horizontal and Vertical Displacement Rates

Horizontal flow velocity along centre line

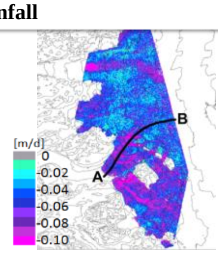




Vertical displacement rates along centre line



Uplift and acceleration in late August related to rainfall



Δz indicates Location of Glacier Drainage Channels

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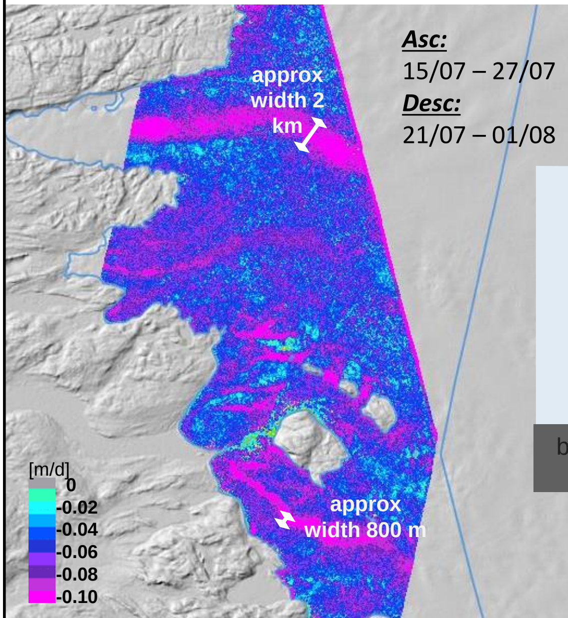
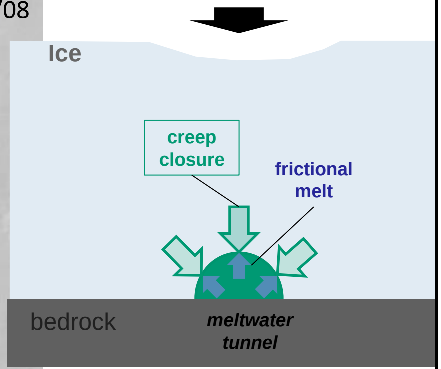


Asc:
15/07 – 27/07
Desc:
21/07 – 01/08

← Periods of subsidence



Decrease in water pressure due to gradual enlargement of water channels

Intercomparison of Surface Elevation Changes from 3D Displacement vs. DEM Differencing

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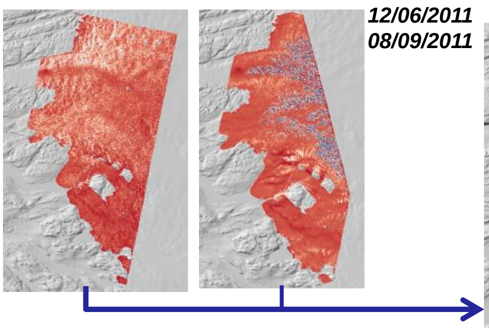
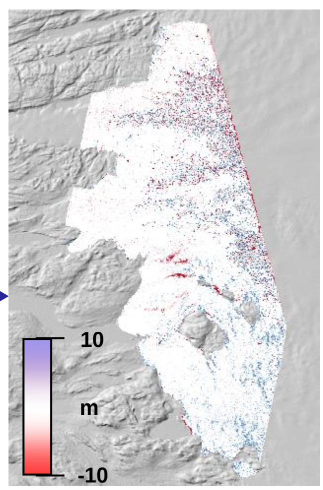
TDX DEM differences
12/06/2011
08/09/2011

Summed differences
from 3D retrieval
12/06/2011
08/09/2011

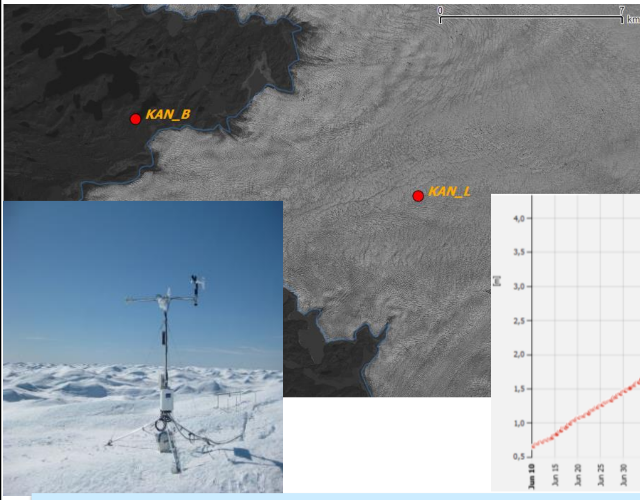
Difference





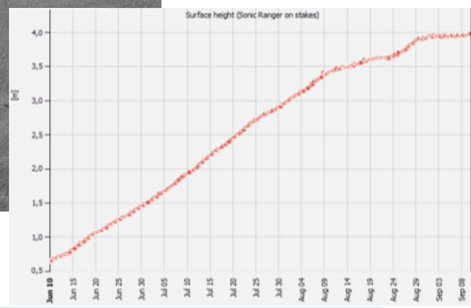
Mean difference of elevation changes between Δ-TDX and retrieved by 3D = 0.21 m
(n = 1 687 644 pixels)

Comparison of TDX Elevation Change with In-situ Data



Downward looking sonic ranger mounted at KAN_L (GEUS, PROMICE project)

=> *In situ ablation*



Total surface lowering for the period 12/06/2011 – 08/09/2011:
Δz from Sonic ranger -3.24 m
Δz from SAR 3D velocity -3.19 m (includes ablation and emergence)

Conclusion

- Single-pass InSAR DEM Data of the TanDEM-X/TerraSAR-X formation are an excellent basis for monitoring glacier topography and volume change, and for retrieving glacier mass balance.
- The TDX/TSX formation, with its high spatial resolution and accuracy, has the potential to greatly reduce the uncertainty of glacier mass balance world-wide.
- Repeat-pass data of TSX and TDX enable spatially detailed mapping of ice motion and deformation, including retrieval of 3D ice vectors, an important basis for studies of glacier dynamics
- The synergy of DEM differencing and monitoring of ice motion is a very powerful approach for studying processes of ice deformation and glacier hydraulics, and for validating and advancing models of glacier mass balance
- For optimum exploitation of the TDX/TSX formation it is advisable to proceed with a dedicated acquisition strategy, focusing at regions with high sensitivity of glaciers to changing boundary conditions