Photogrammetric Techniques for Spatio-temporal Analyses of Glacier Motion Patterns

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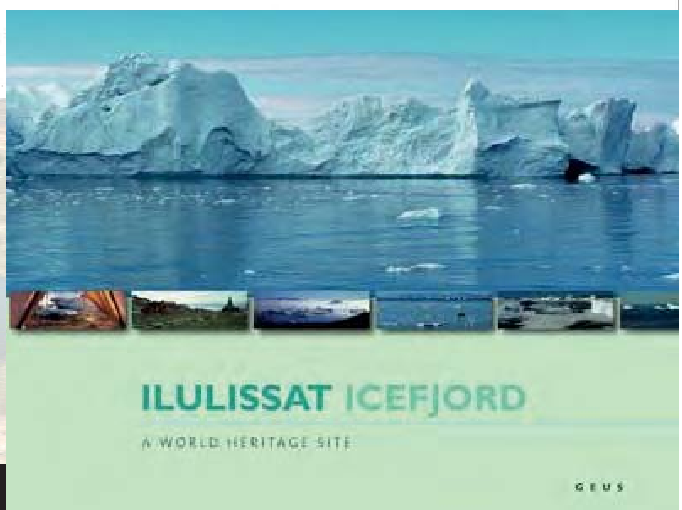
Greenland (Kalaallit Nunaat)

- 2,166,086 km²
- 81% ice covered
- Ice cap up to 3000 m high
- Annual precipitation < 200 mm … 900 mm
  → main drainage by large outlet glaciers
- Melting of the ice cap would cause 7 m global sea level rise

Jacobshavn Isbræ (Sermeq Kujalleq)

Jacobshavn Isbræ (Sermeq Kujalleq) – facts:

- One of the fastest moving and most productive glaciers in the world
- Catchment area ca. 110‘000 km^2
- Motion velocity ca. 20 meter per day (1890 … 1965 … 1995)
- Annual iceberg production ~35 km^3
- Drains ca. 7% of the total precipitation of Greenland
- UNESCO world natural heritage site 2004 (Jacobshavn Isbræ + Kangia Fjord)




Jacobshavn Isbræ 7.7.2001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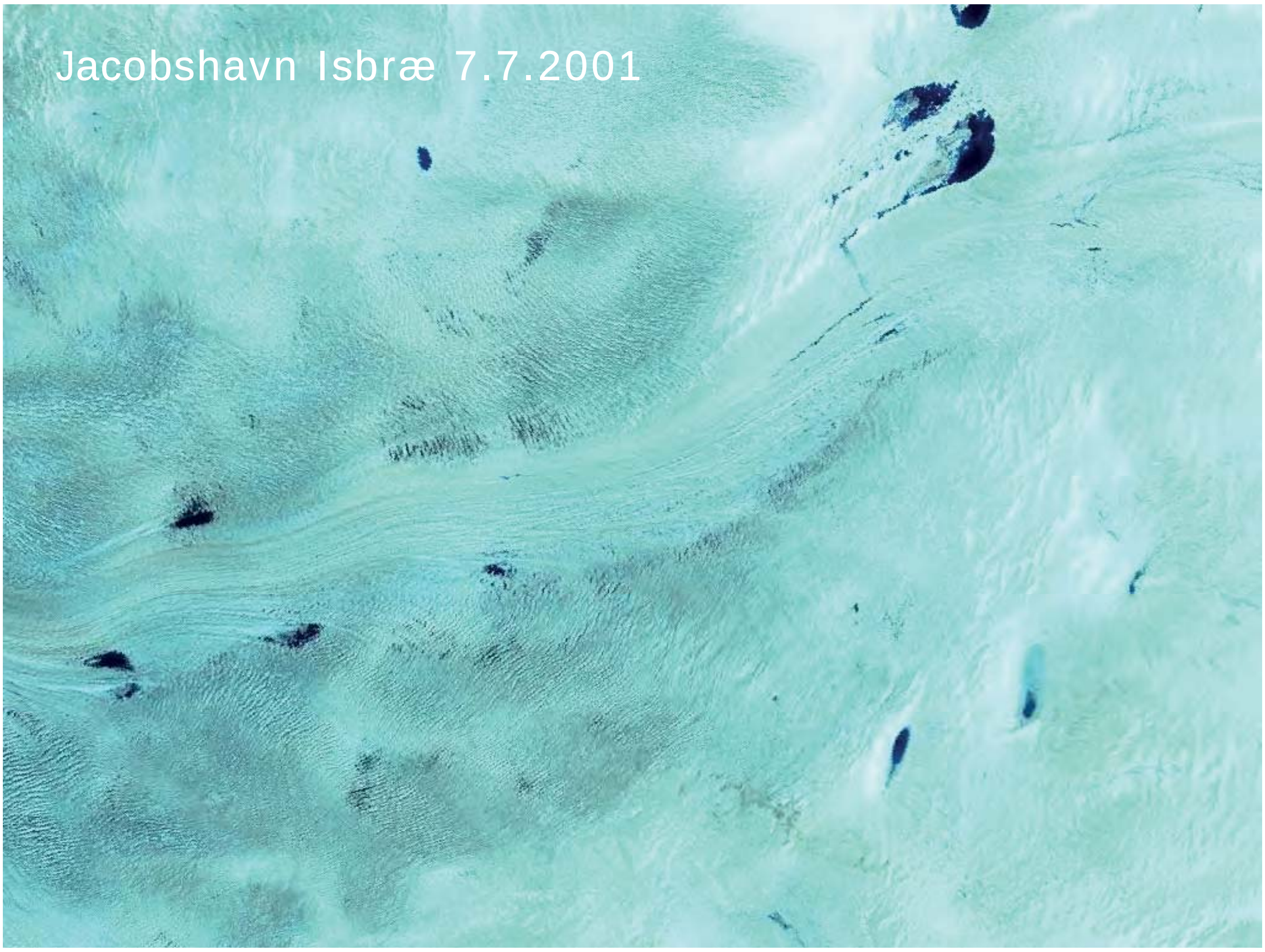
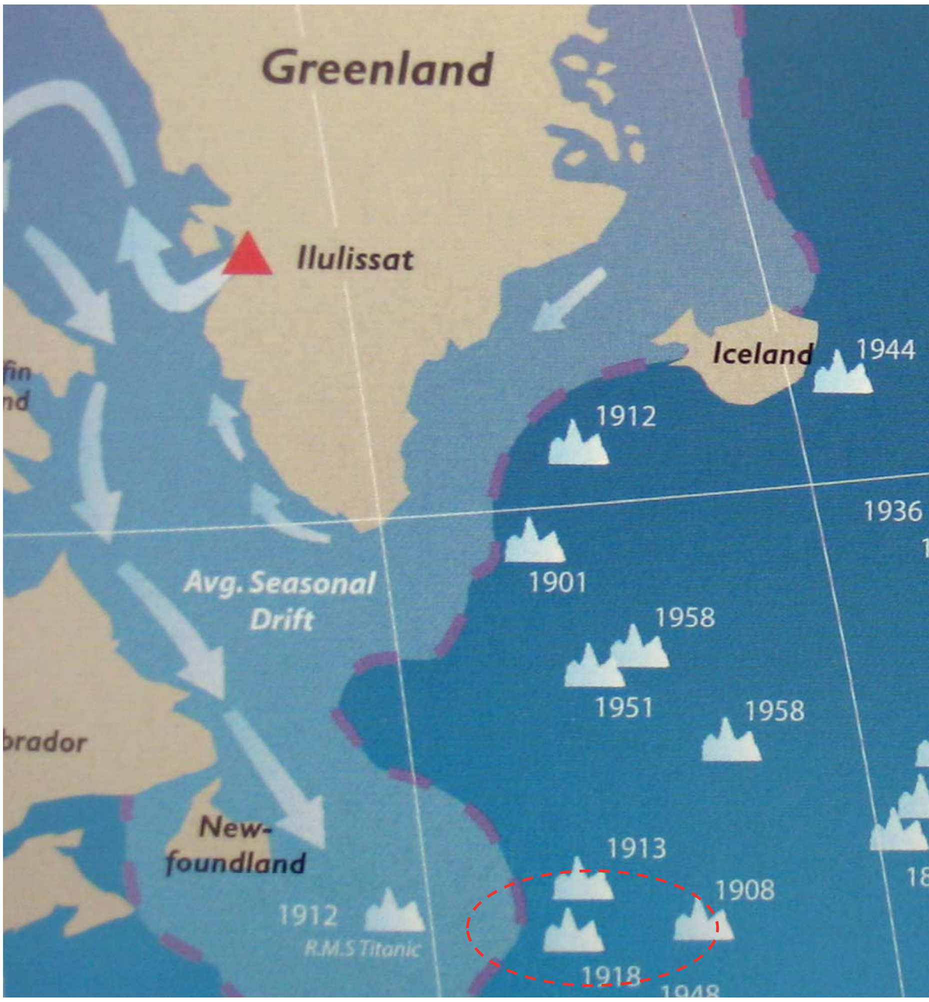

Jacobshavn Isbræ 7.7.2001


Kangia Fjord 7.7.2001

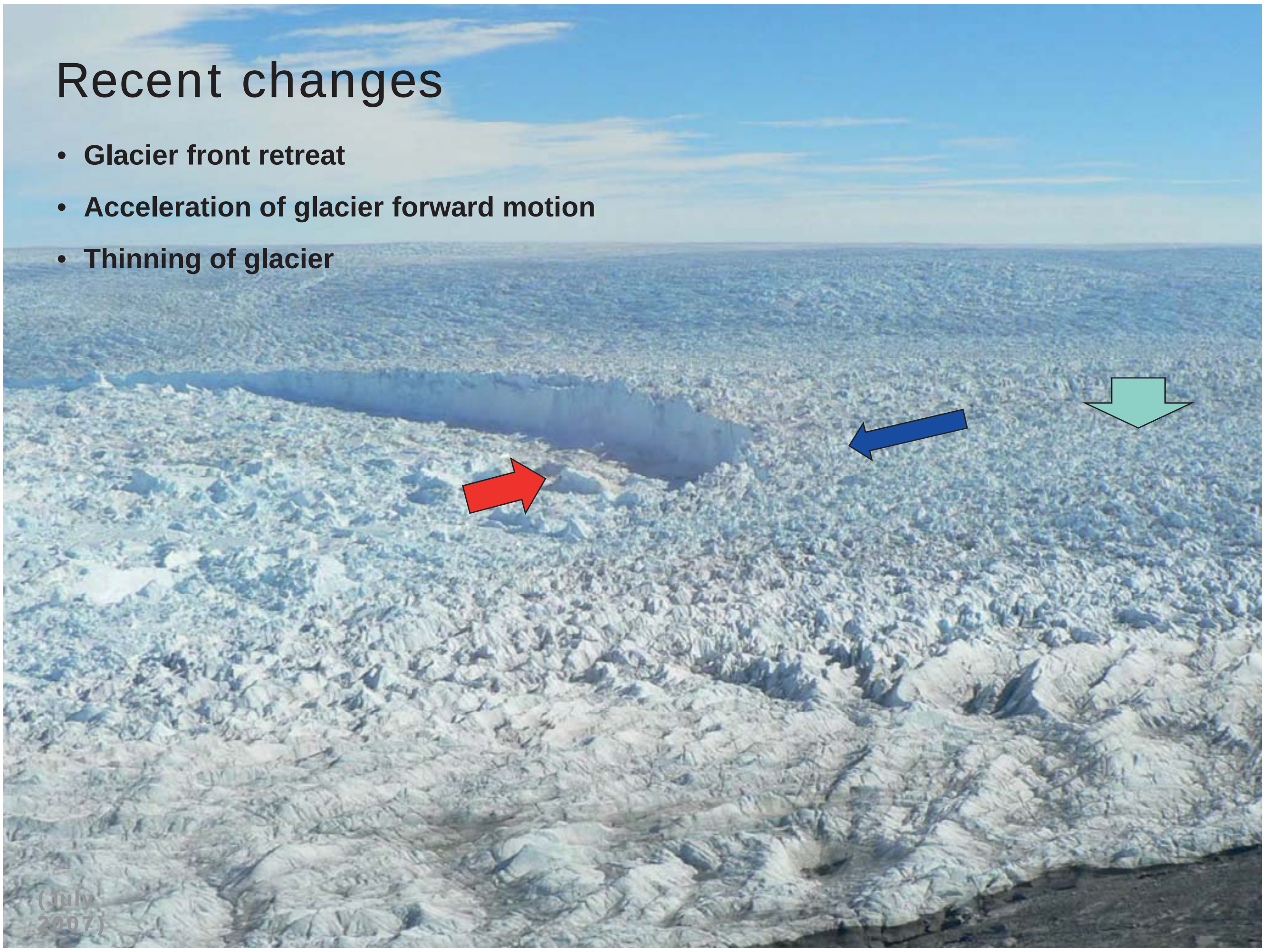
GEUS - De Nationale Geologiske Undersøgelser for Danmark og Grønland

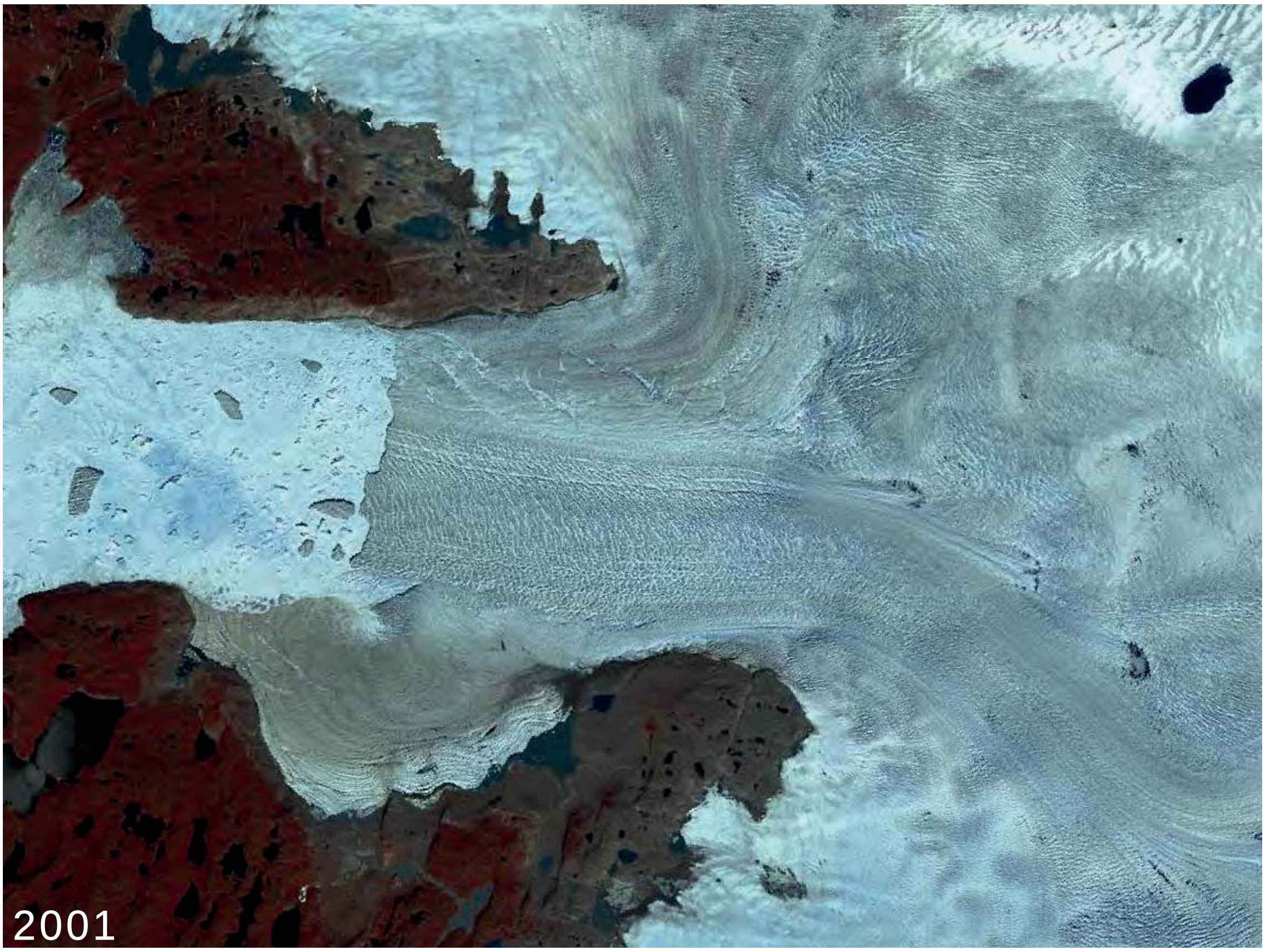


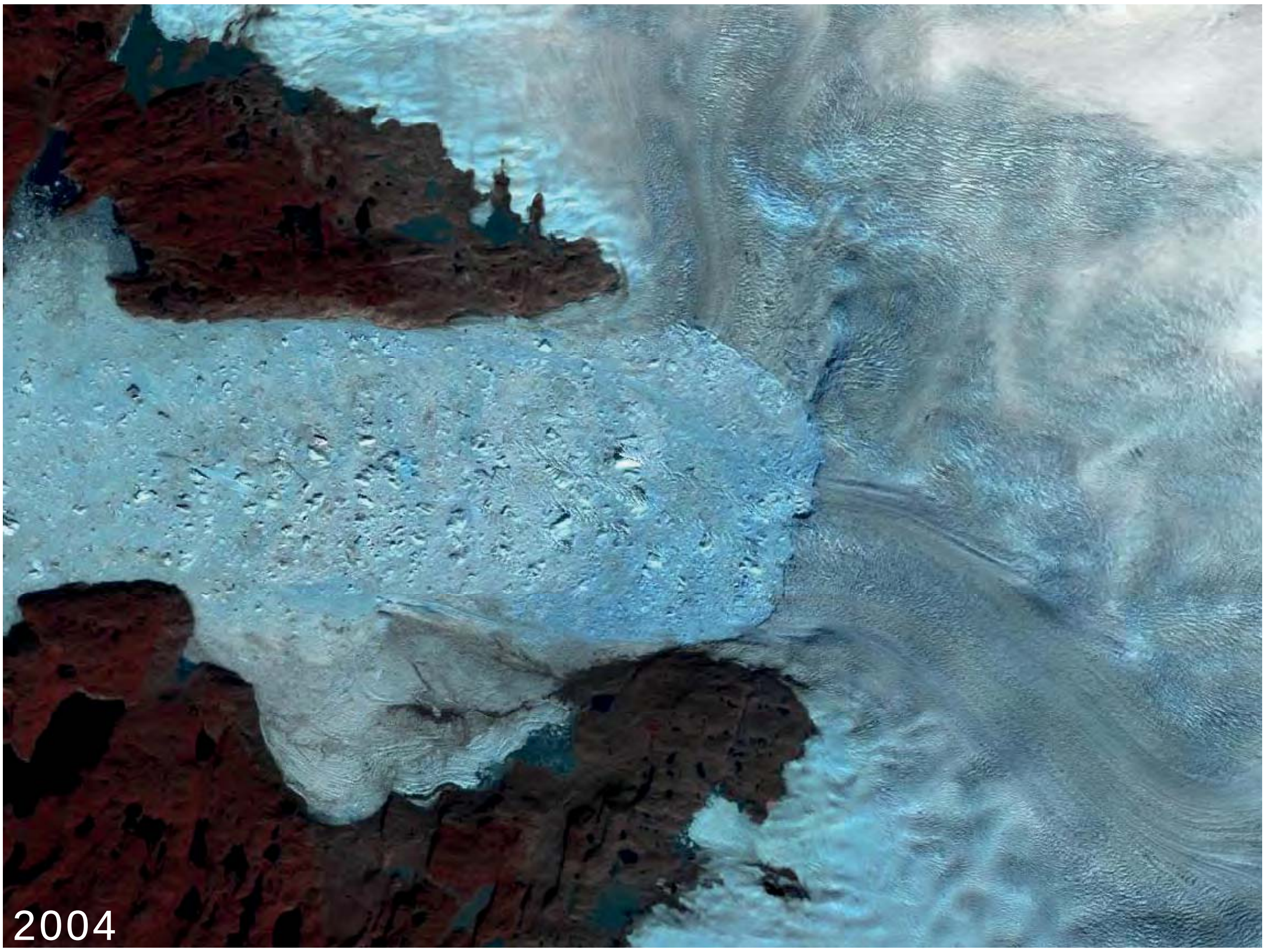
Bennike, O., Mikkelsen, N., Pedersen, H., Weidick, A., 2004: Ilulissat Isfjord - a world heritage site. GEUS, Kopenhavn, ISBN 87-7871-136-3

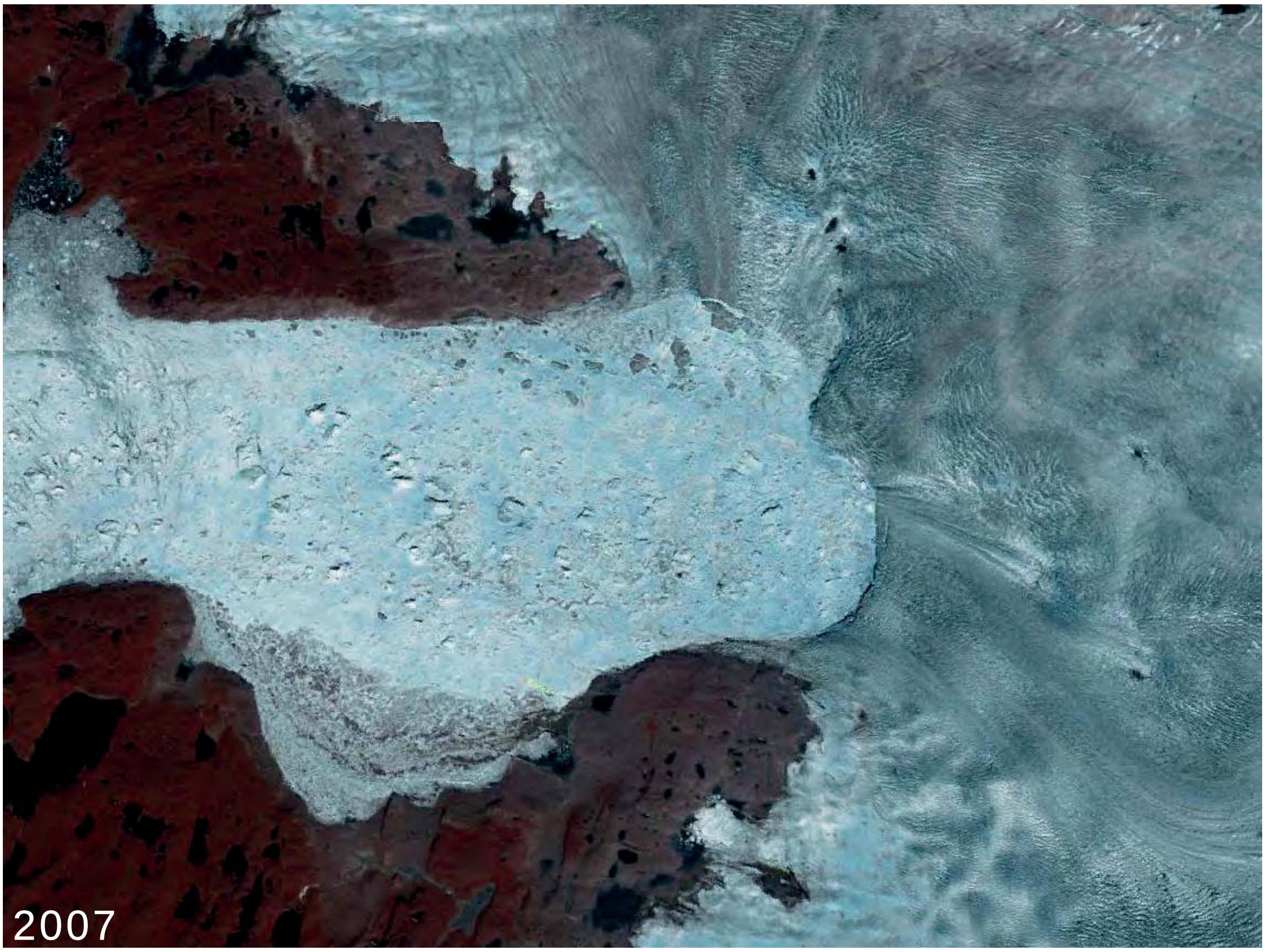
Recent changes

- **Glacier front retreat**
- **Acceleration of glacier forward motion**
- **Thinning of glacier**






2004


2007

Bennike, O., Mikkelsen, N., Pedersen, H., Weidick, A., 2004: Ilulissat Isfjord - a world heritage site. GEUS, Kopenhavn, ISBN 87-7871-136-3

Data source: Satellite images + aerial images + geodetic measurements + oral testimony

- Advance 1750 – 1850 (Little Ice Age)
- Retreat 1850 – 1950
- Stationary 1950 – 2000
- Rapid retreat after 2000

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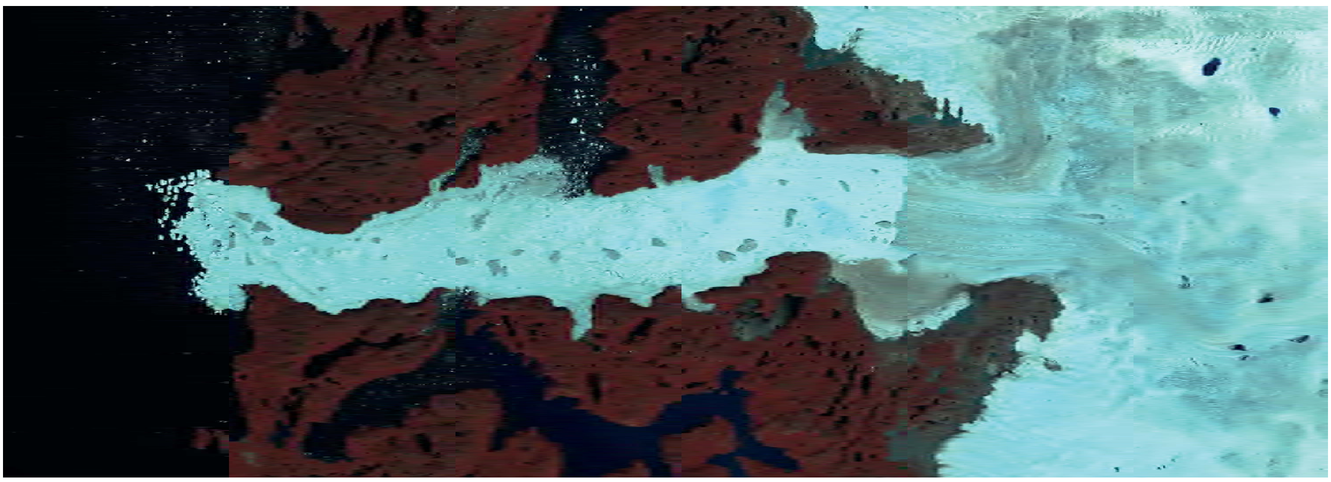
Determination of glacier velocity

Early measurements:

- Hammer (1893) and Engell (1904), geodetic measurements: Up to 20 m/day
- Carbonell and Bauer (1968): 20 - 22 m/day from 1 : 50‘000 aerial images (19 vectors)



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Determination of glacier velocity

Joughin et al. (2004): Aerial images, InSAR, Landsat images, airborne laserscanner data

- 1985: 18 m/d
- 1992: 16 m/d
- 2000: 26 m/d
- 2003: 35 m/d
- Thinning of up to 10 m/year since 1997 (airborne laserscanner data)

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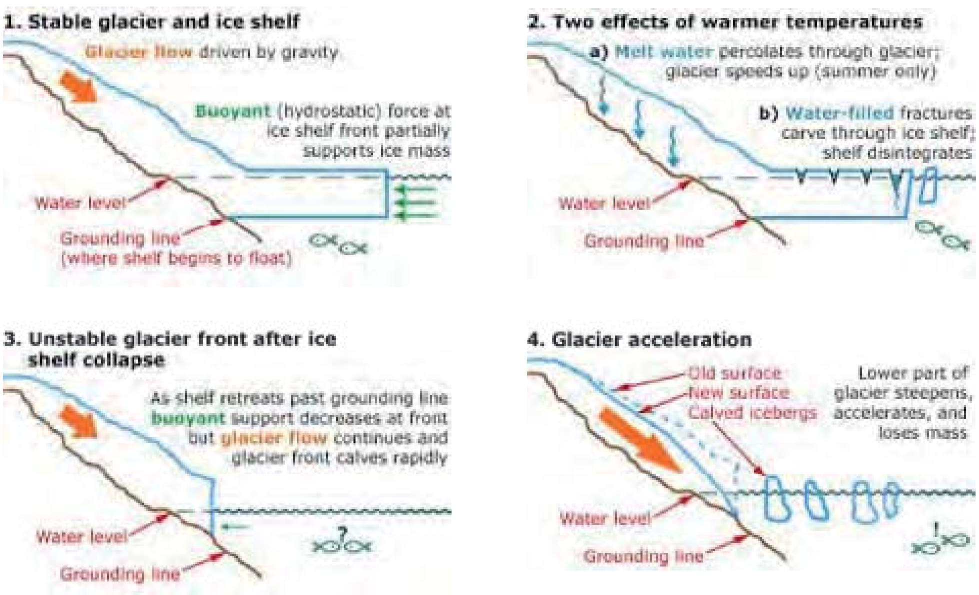
Mechanism

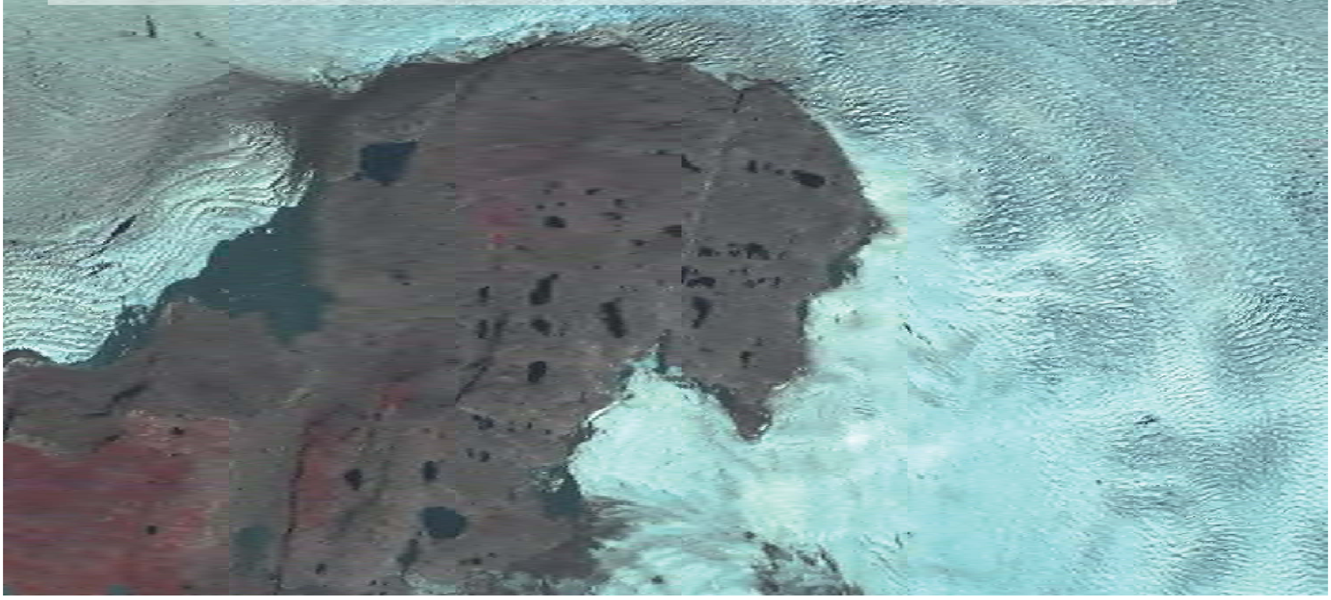


http://www.nasa.gov/vision/earth/lookingatearth/icecover.html

Jacobshavn Isbræ – TU Dresden expeditions 2004/2007/2010

Goals:

- Measurement of the recent glacier motion velocities
- Determination of short-term spatio-temporal motion velocity variations
- Analysis of tidal effects on motion pattern



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Spatio-temporal glacier surface velocity fields – options

Terrestrial geodetic techniques (applied since late 19. century)

\+ Accurate

\- Large effort, often difficult physical access, limited number of points

Optical satellite images

\+ Availability, large region coverage

\- Fix revisit cycles, cloud-dependent, limited resolution and accuracy

Radar satellite images

\+ Availability, large region coverage, high accuracy, weather independency

\- Fix revisit cycles, often limitations posed by decorrelation

Aerial images

\+ Higher flexibility in revisit cycle planning, high accuracy

\- Cloud-dependent, costs

\- Usually too much wind for UAV operation

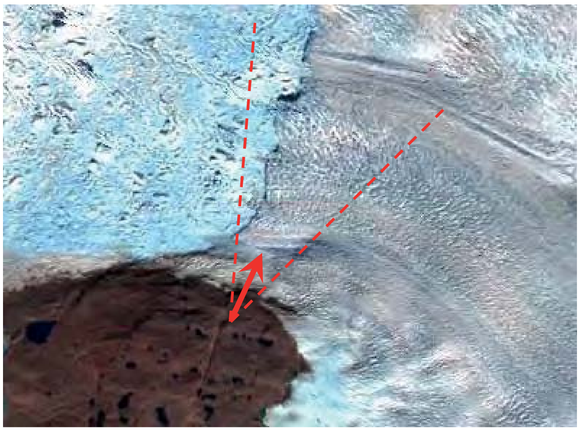
Terrestrial image sequences

\+ Arbitrarily high temporal resolution, cost-effective (for local measurements), high accuracy

\- No region coverage, terrain-dependent

Equipment

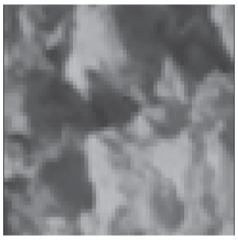
- Various high resolution cameras
- Intervallometer mode: 24+ hour sequences in 15 minute intervals
- Generator + batteries + solar panels
- 2D problem → monocular sequences
- Geodetic reference measurements (scale, geo-referencing)

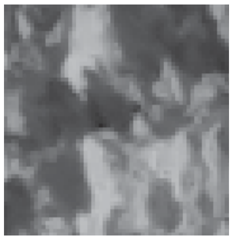


Jacobshavn Isbræ front in time lapse (72h, July 2007)

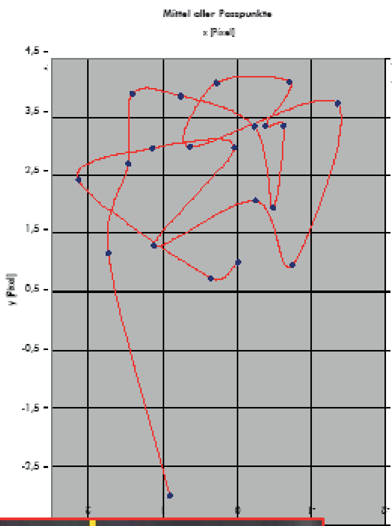
Motion determination (image sequence analysis)

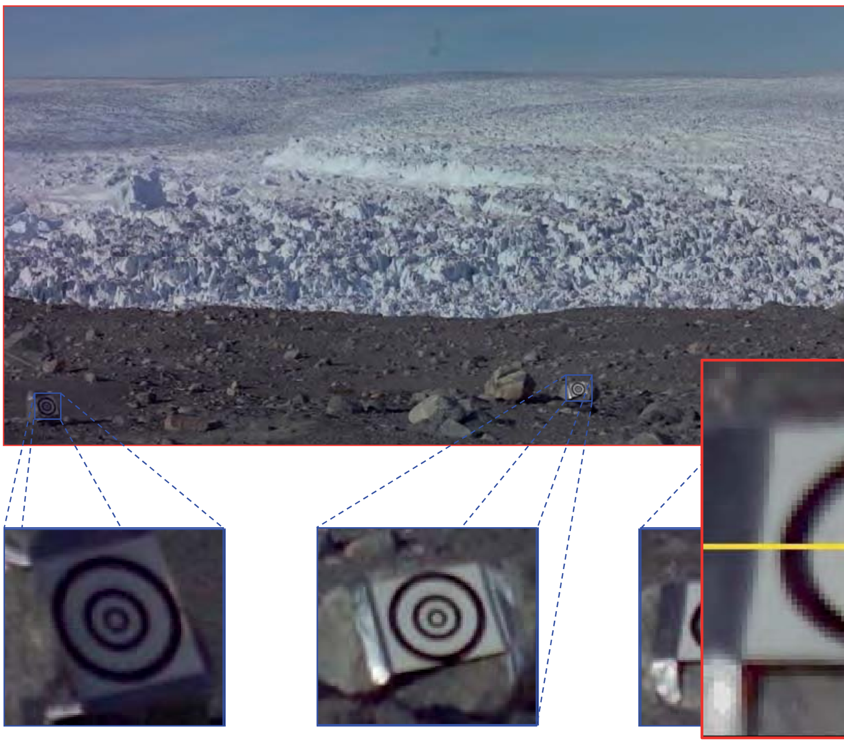
- Least Squares Matching
- Shadow correction technique
- Continuity constraints (space/time)
- Camera movement correction
- Result: 2D feature trajectories
- Image space → object space transformation
- 0.1 pixel → 6 cm @ 3 km distance

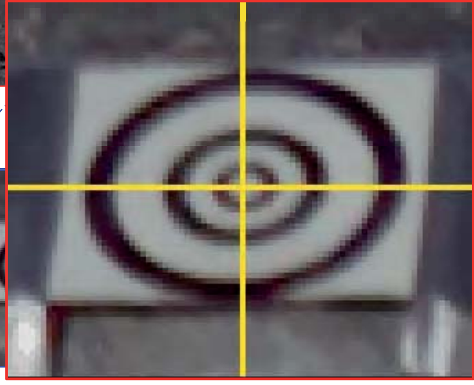




Camera motion correction







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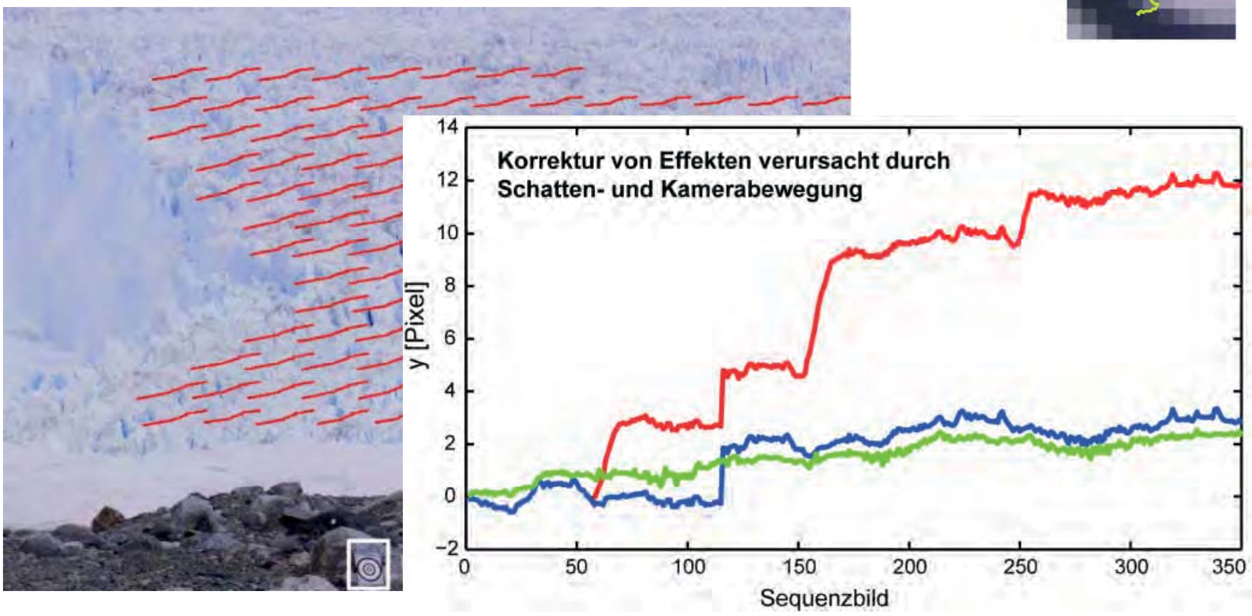
Motion correction

- Result = LSM motion trajectories
- Corrected for shadow pixel induced errors
- Corrected for camera motion effects



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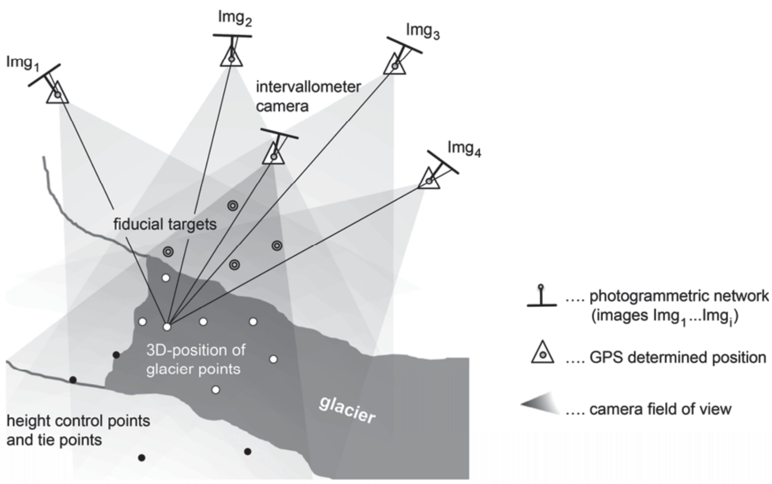
Georeferencing options

→ Georeferencing, motion vector scale

- Photogrammetric network (stereo imagery)
- GPS measurements
- Disto measurements
- Water level points
- ...



- Result:
  - Distance for each point to be tracked
  - (rough) glacier surface model (→ ray intersection)

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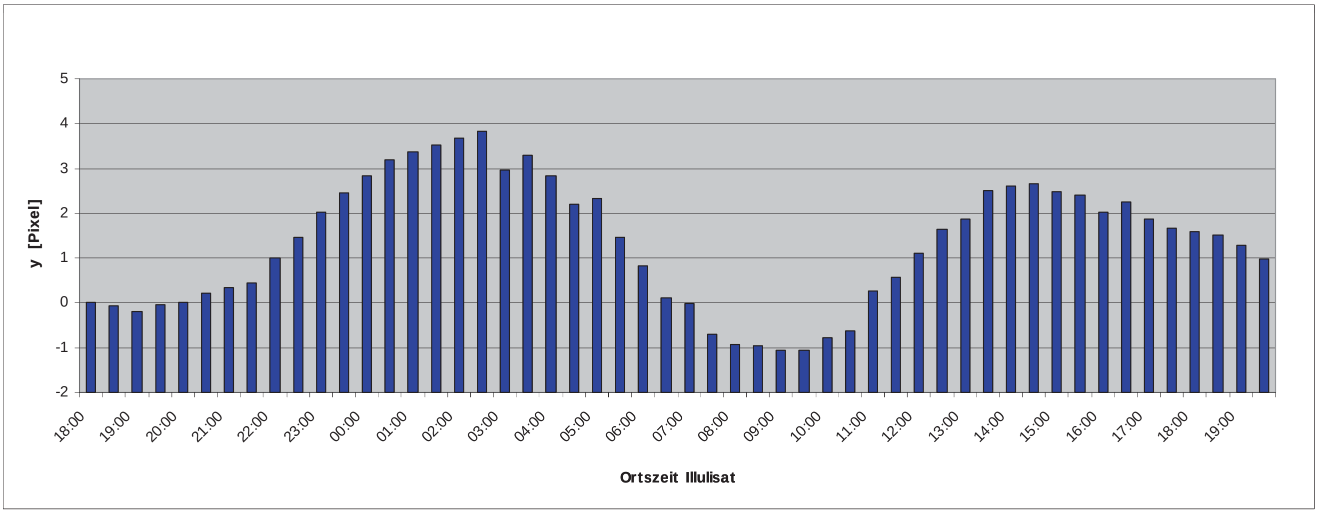
Result (example)

- 26-hour trajectory derived by cross correlation
- Camera movement and shadow correction applied
- 1 pixel = ~30 cm
- Length: 140 pixel (→ horizontal movement ca. 40 meter/day)
- Vertical movement: 5 pixel (ca. 1,50 meter)



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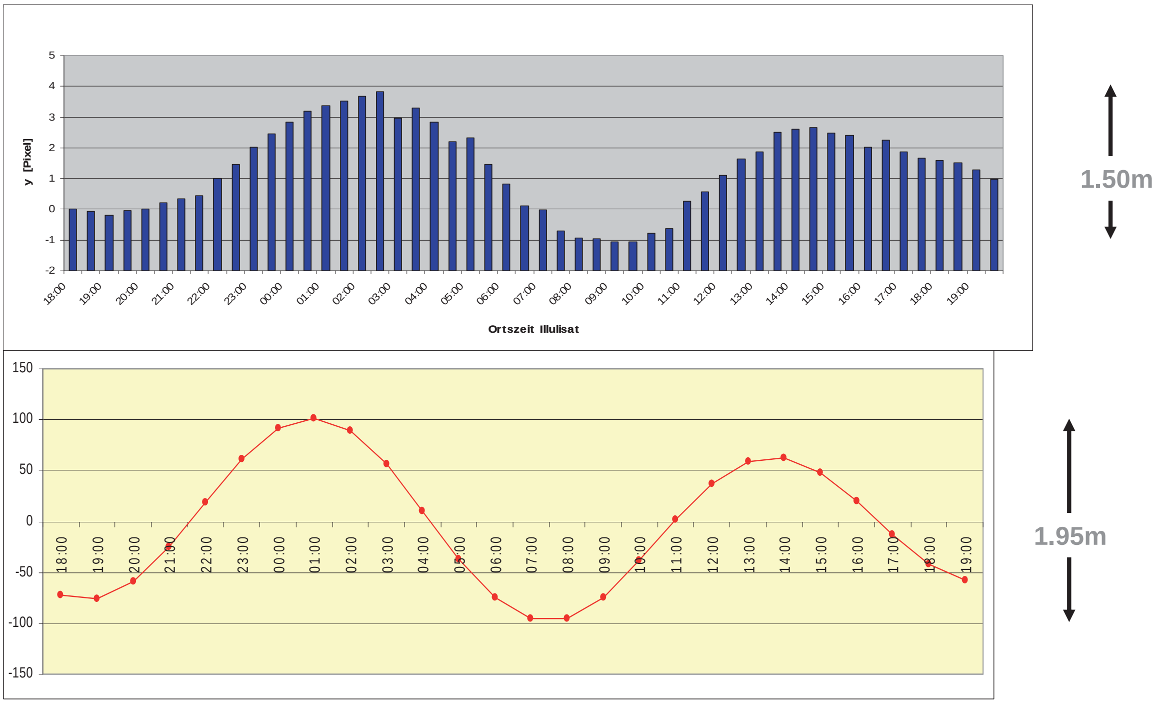
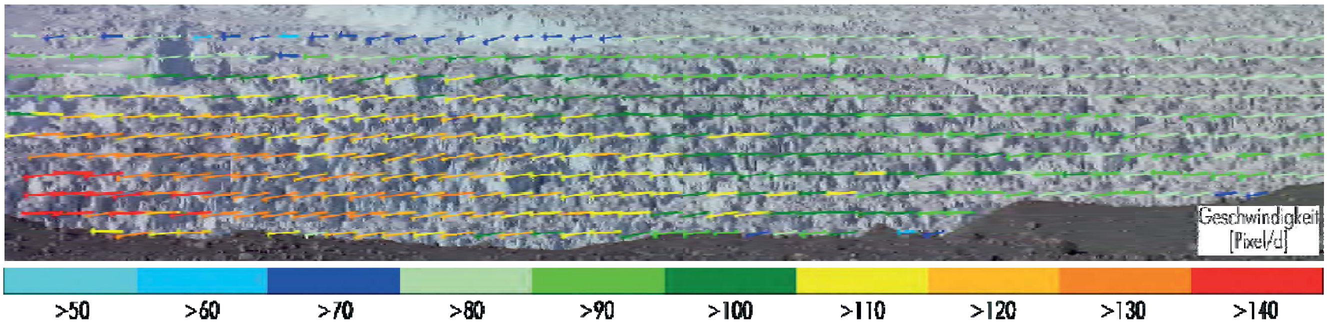
Glacier movement vs. tides

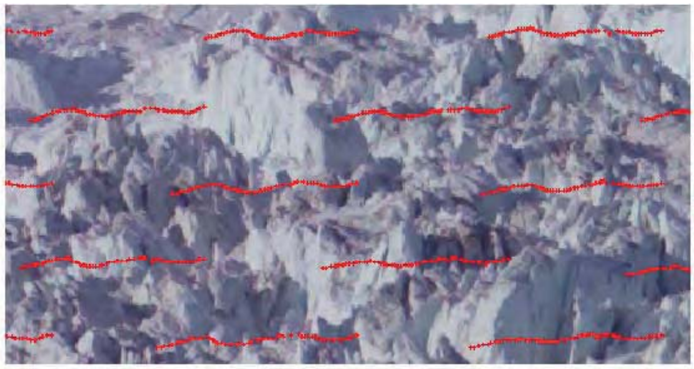


Very high correlation with computed tidal curve, slight latency and damping

Motion field analysis

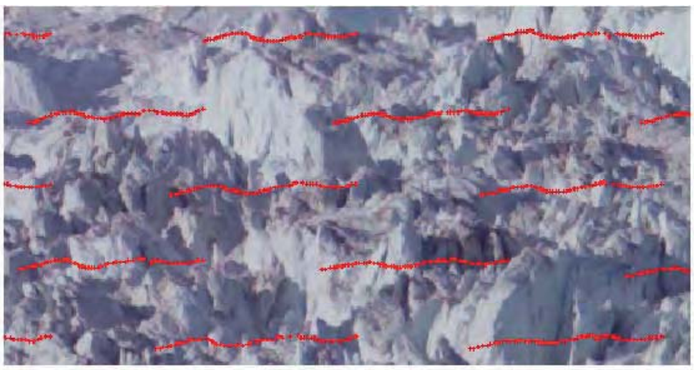


- Totally 4500 trajectories
- Local variations of tidal effects



Motion field analysis

- Fit prototype trajectory (tidal curve) into measured trajectories
  - Position
  - Slope (trajectory tilt)
  - Length scale
  - Vertical damping factor
- Remove outliers

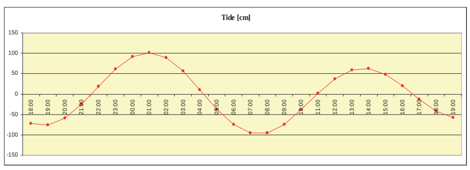


$$X_i(t_j) = t_{X_i} + m_{X_i} \cdot \cos\alpha_i \cdot \bar{X}(t_j)$$

$$Y_i(t_j) = t_{Y_i} + \sin\alpha_i \cdot \bar{X}(t_j) + m_{Y_i} \cdot \bar{Y}(t_j)$$

length scale (m_{X_i}); tilt (α_i); translation (t_{Y_i}); downward movement ($\sin\alpha_i \cdot \bar{X}(t_j)$); damping of tidal movement (m_{Y_i})

Prototype trajectory (40m/d, 100% tidal movement participation)



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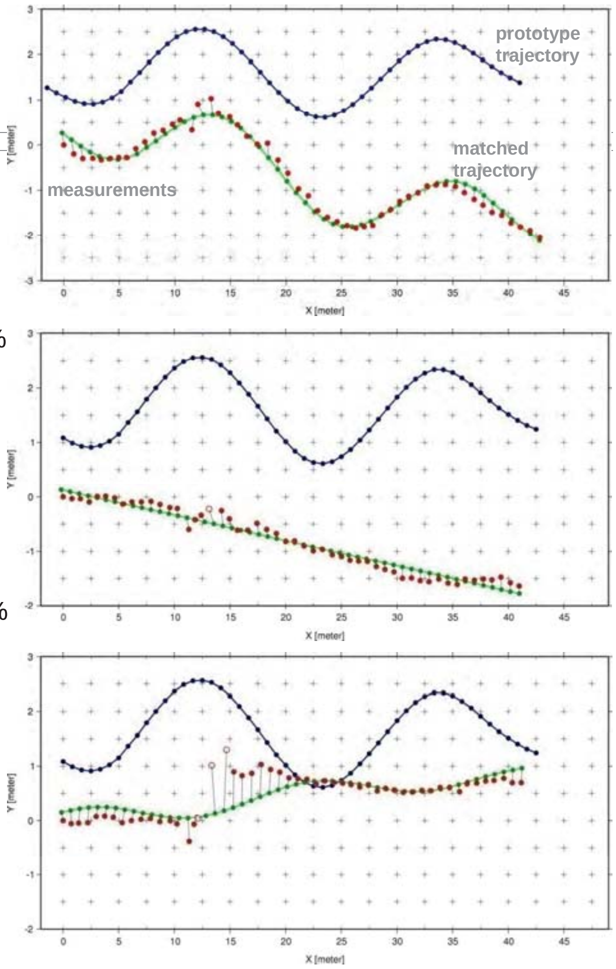
Matched trajectories

- Trajectory close to glacier front
  - Velocity: 40.49 ± 0.08 m/day
  - Tidal movement participation: 92.3%±4.2 %
  - Tilt: -3.3°
  - Delay: 40 minutes
  - rms = 0.17 m (largest deviations during night)
- Trajectory ca. 1 km from glacier front
  - Velocity: 38.78 ± 0.05 m/day
  - Tidal movement participation: 0.5% ± 2.8 %
  - Tilt: -2.7°
  - rms = 0.11 m
- Problematic trajectory
  - Velocity: 38.92 ± 0.08 m/day
  - Error (step) during tracking at night, eliminated
  - Totally 2% of trajectories eliminated



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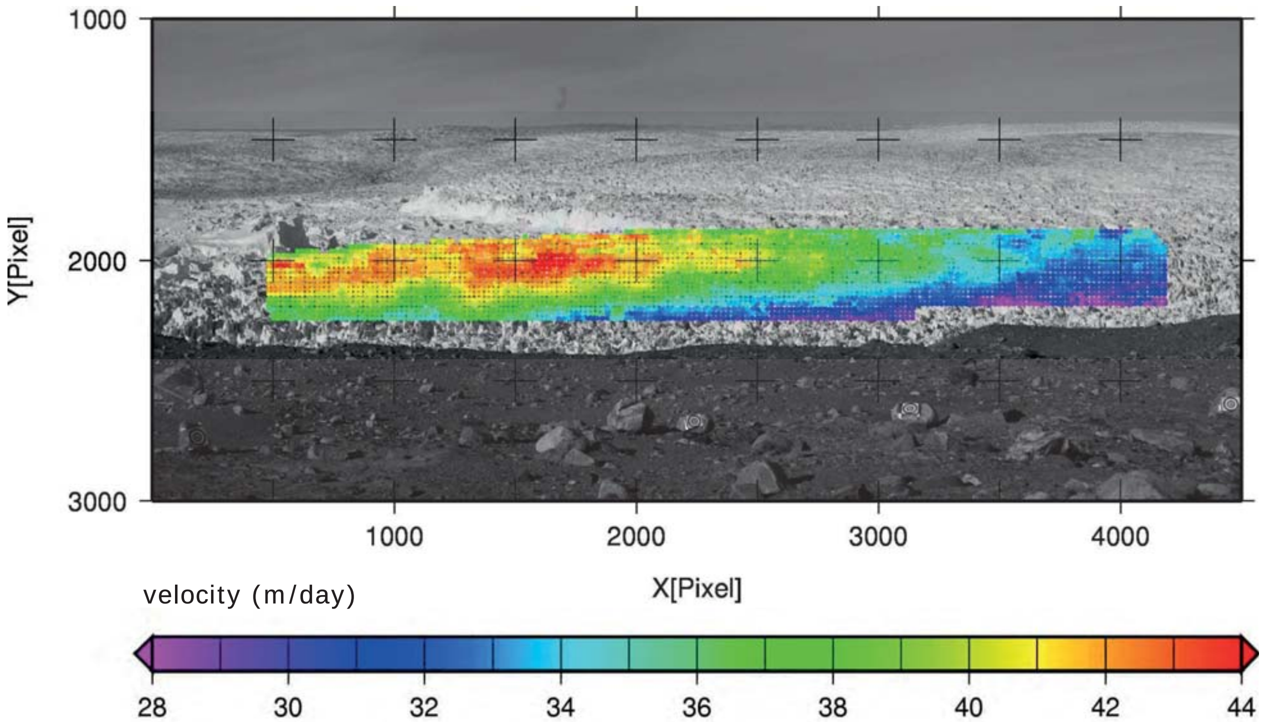
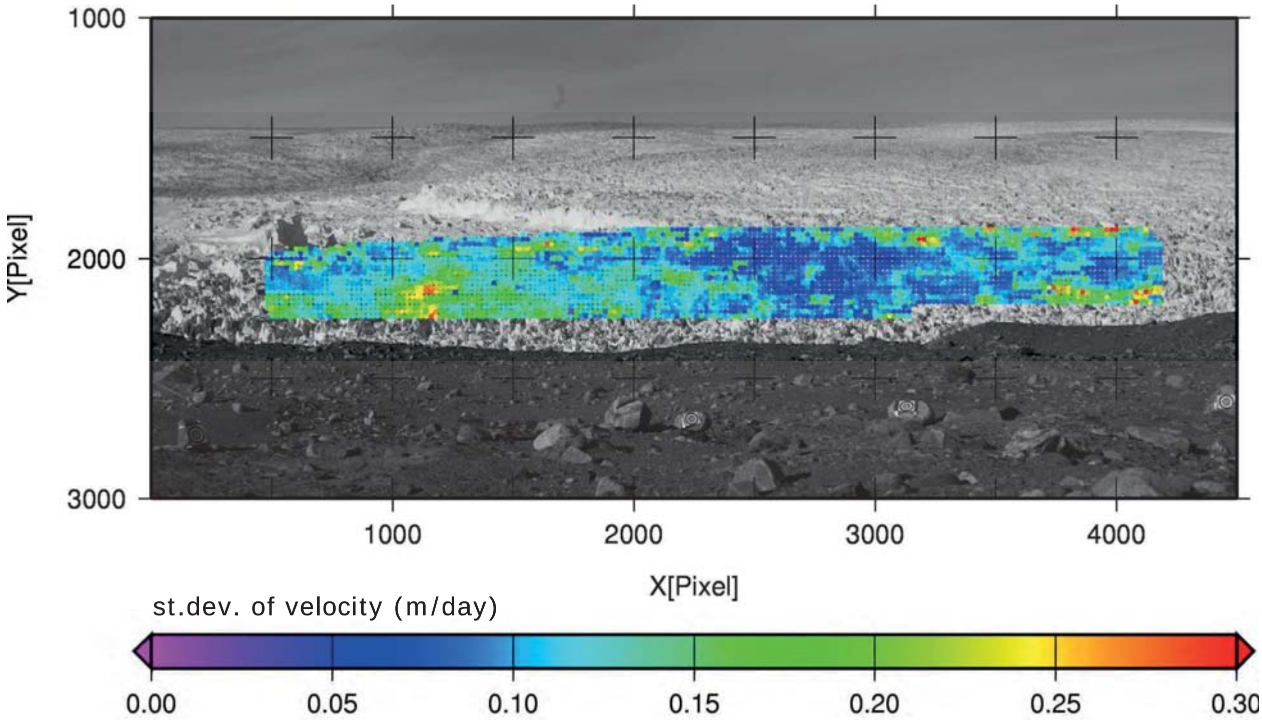
Motion velocity field (4400 matched trajectories, 2004)





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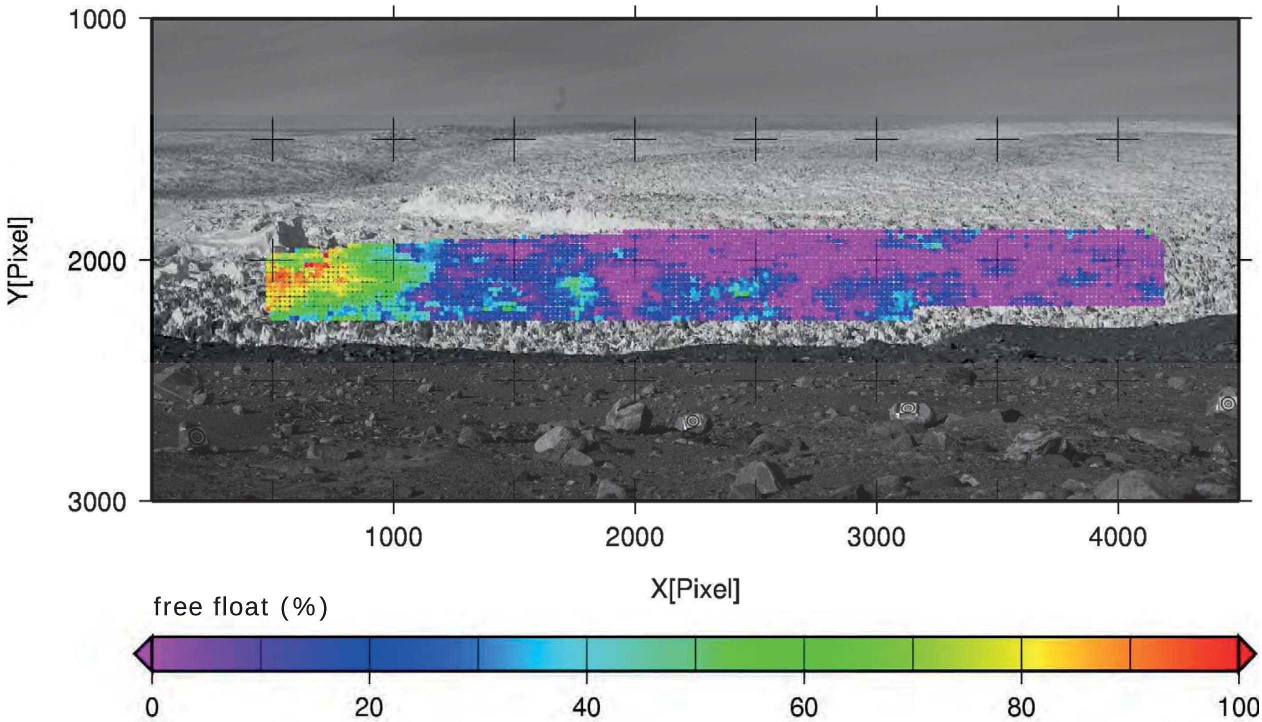
Tidal movement participation (→ grounding line)



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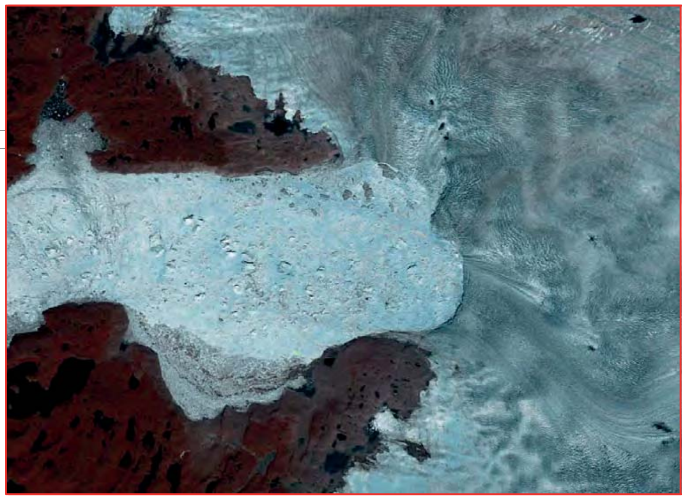
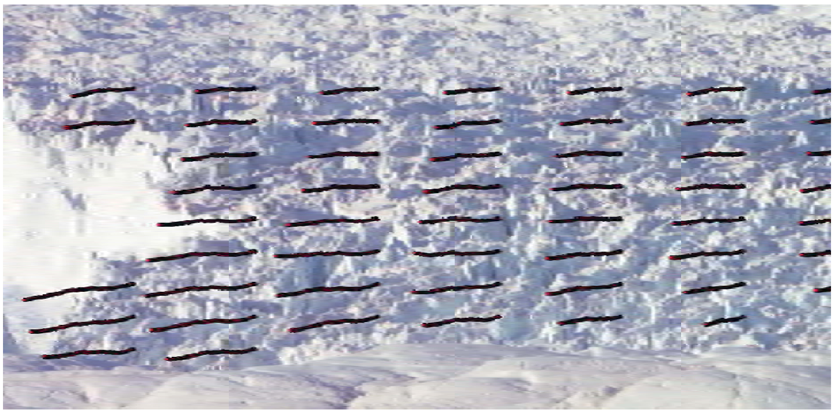
Effects 2004 – 2007 – 2010

- Velocity almost constant (40 m/d)
- Much weaker tidal pattern, glacier front has (almost) reached 2004 grounding line
- Implications for calving behaviour
- No more huge icebergs!





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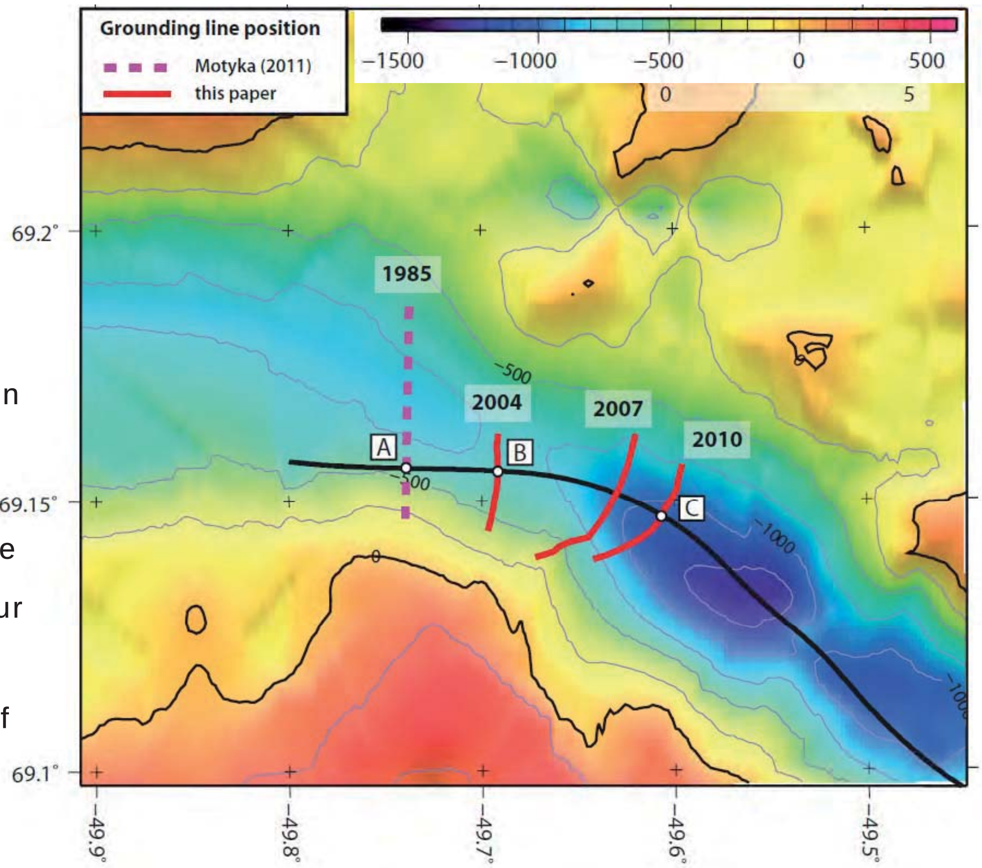
Cmp. bedrock topography

- CReSIS radar data, Plummer and van der Veen (2008)
- 1300m deep hole
- Calving behaviour might change again after further retreat of glacier front



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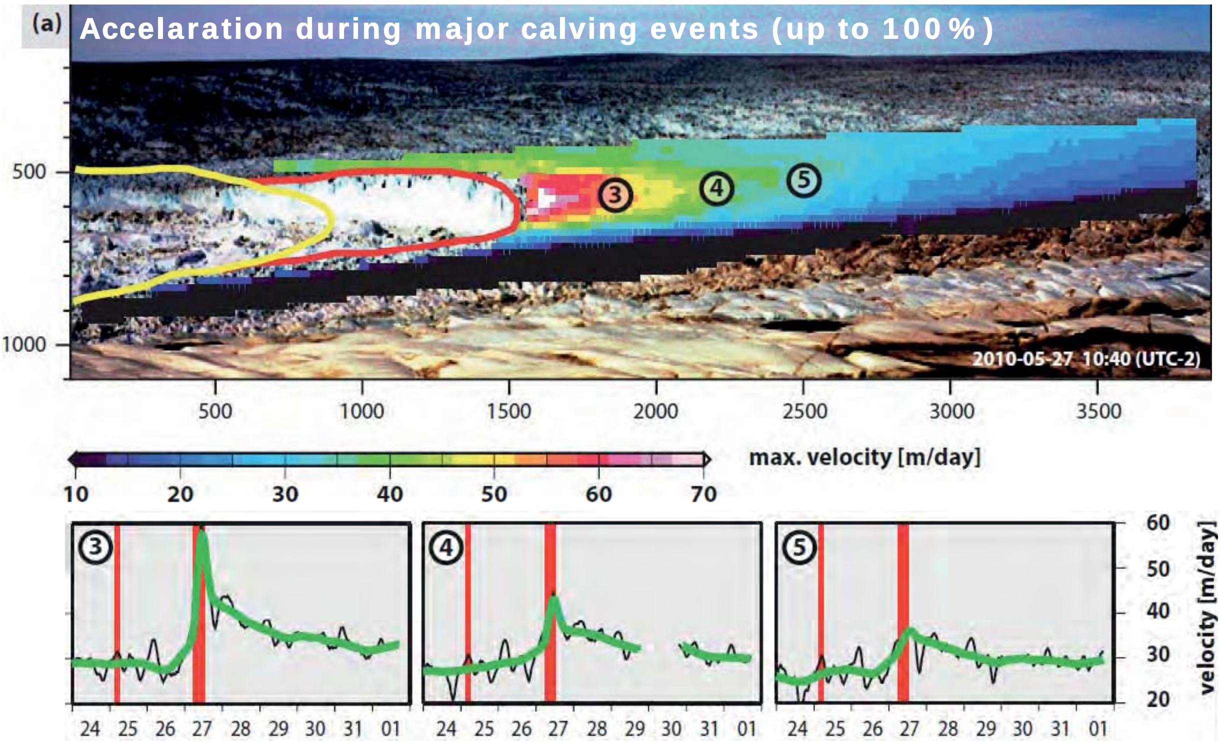
Short-term velocity variations



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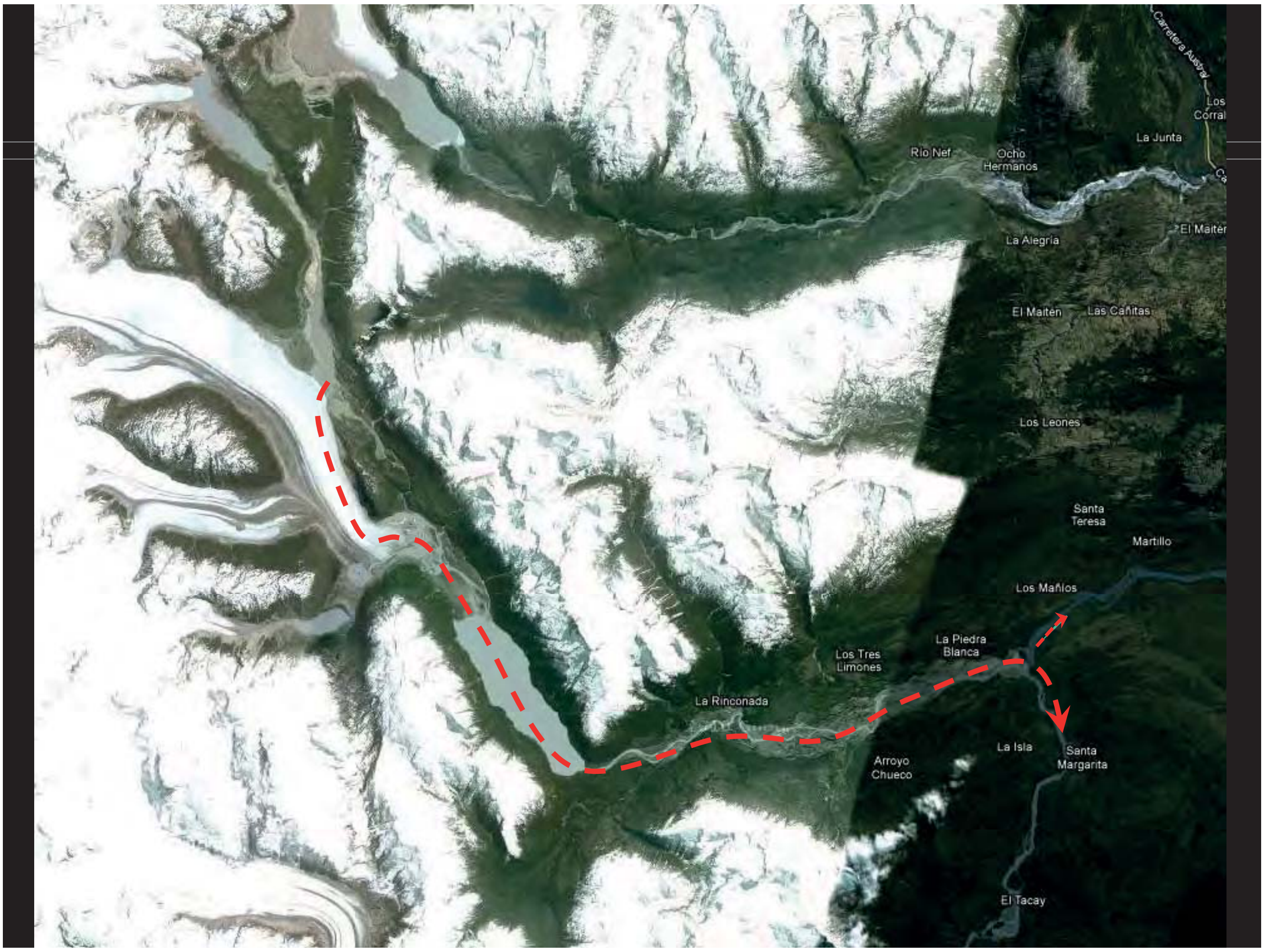
GLOF monitoring Lago Cachet II

- Dammed ca. 15.000 years ago
- Length 5 km, width ca. 1 km, depth 100 m
- Volume ca. 200.000.000 m^3

- Increasing destabilization with retreating glacier front
- Hydrostatic pressure of water gets pre-dominant
- Water finds a way underneath the glacier → melting + erosion



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GLOF – dynamics

- Complete drainage in <48h
- Max. run-off 4000 m³/s
- **GLOF-cycle:**
  - Glacier blocks river
  - Formation of a lake
  - Barrier destabilises
  - Water creates tunnel
  - Exponential run-off
  - Complete drain
  - Tunnel collapses
  - Water is being dammed again
  - ...
- Increasing risk for humans, nature, infrastructure, economy
- **Need for early-warning systems**

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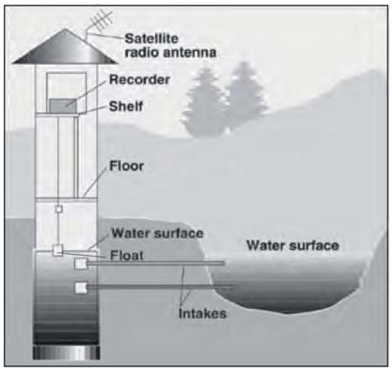
GLOF – early warning system

- Basic idea: Gauge as an indicator for beginning drainage
- Data telemetry to alarm system
- Warning time = detection + data transfer + tunnel development + flow time + … → typically ~24h



- Requirements to gauge: 100m water level difference, remote operation
- Conventional gauges (pressure gauges, GPS buoys) not suited (tech. effort, risk of damage due to ice and sediment dynamics)

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Photogrammetric system

- Time-lapse camera observing (part of) the lake
- Tripod, water-proof housing, solar panel, buffer battery
- Automatic detection of water level by image processing methods

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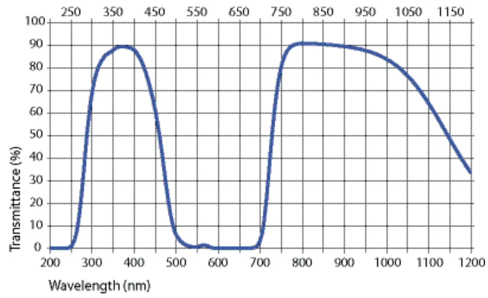
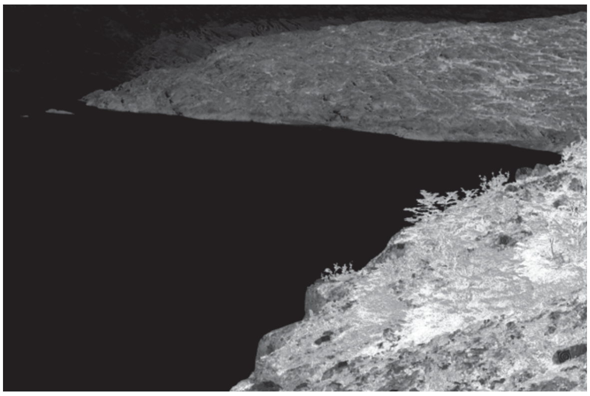
Image analysis

- NIR-extended camera (IR cut filter removed)
- Optical bandpass filter
- NDWI (normalized difference water index)

$$NDWI = \frac{CH_{NIR} - CH_{Blue}}{CH_{NIR} + CH_{Blue}}$$





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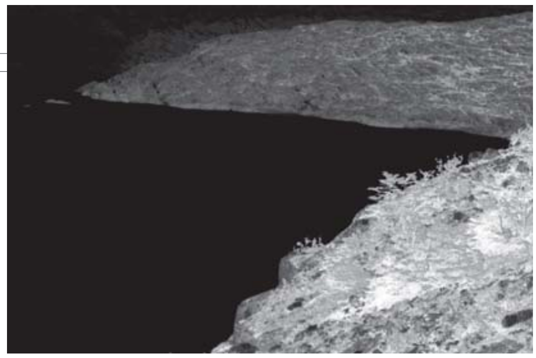
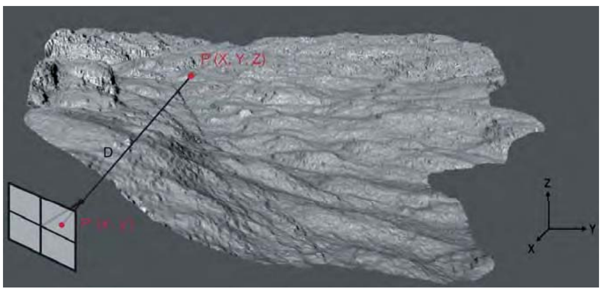
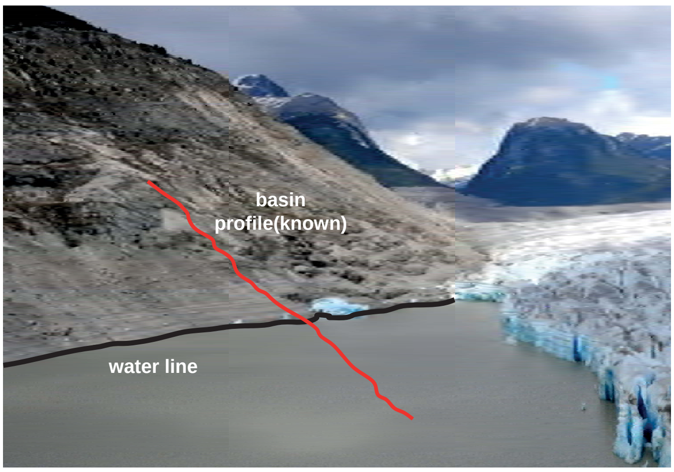
Virtual gauge



- Detection of water line in image
- Intersection with known terrain model / profile(s)
- Camera movement control





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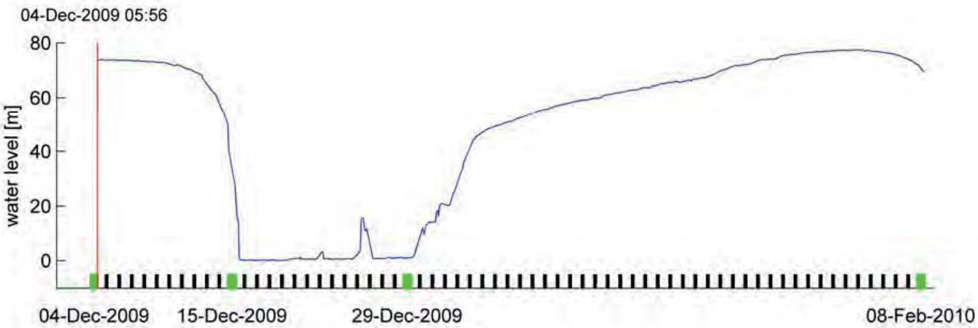
Lago Nef Norte: GLOF on 10.2.2010

Water level dropping 15cm/h → GLOF at early stage

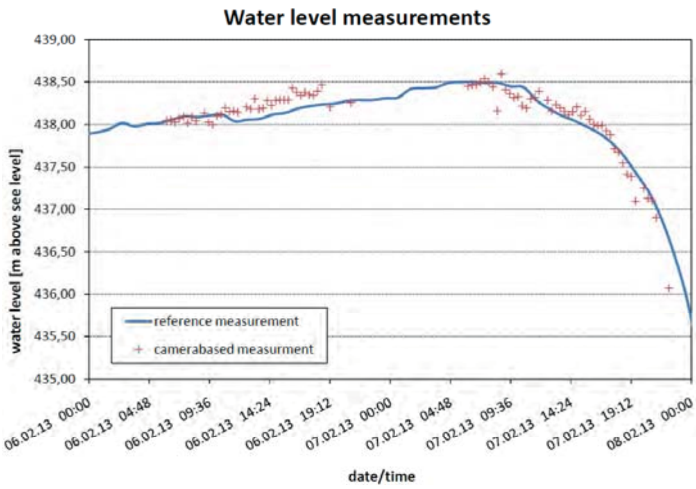
Lago Nef Norte – Results

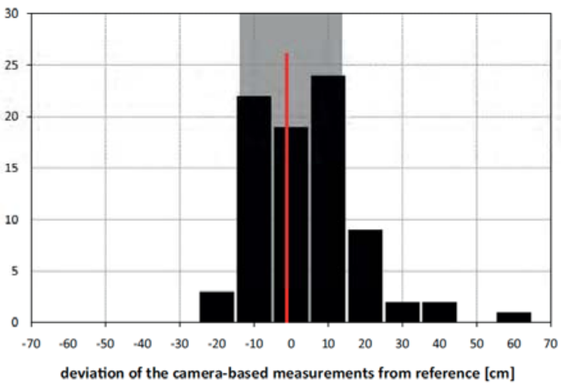


Lago Cachet II – Results

Comparison photogrammetric gauge – pressure gauge

- 2013 dataset, two days before a GLOF
- RMS deviation 13 cm (ca. 0.75 pixel)





Lago Cachet II – Results

Post-GLOF glacier surface velocity field → collapse of tunnel (2010 terrestrial data)