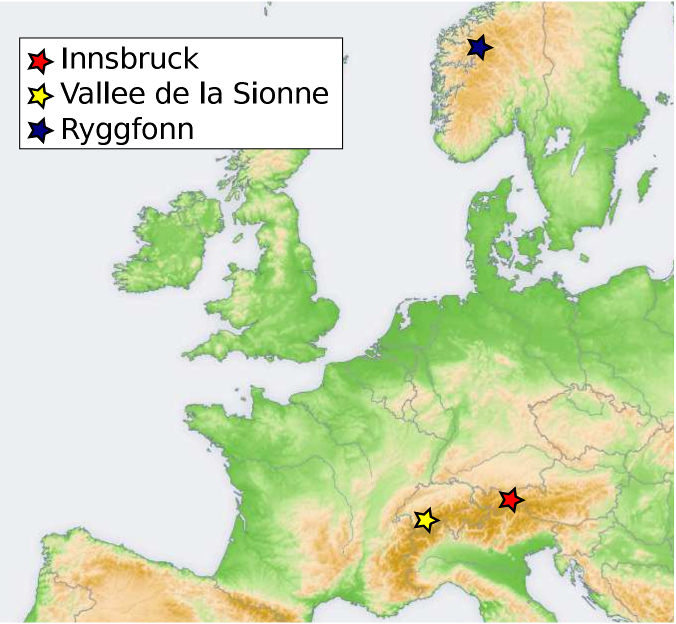
connecting computational and experimental snow avalanche dynamics

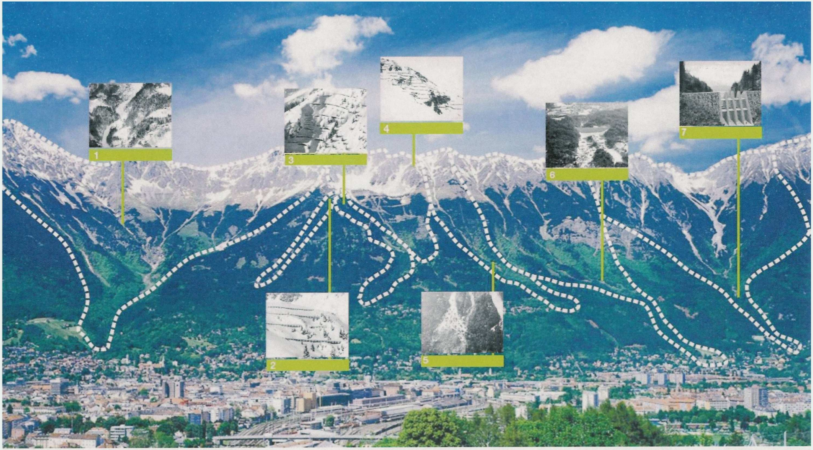
Jan-Thomas Fischer*,
Fromm, R.*, Gauer, P., Sovilla, B., Fellin, W.

* Department for natural hazards - Austrian Research Centre for Forests BFW
Rennweg 1, 6020 Innsbruck, Austria

Fluid-mediated Particle Transport in Geophysical Flows
KITP, UCSB, 2013


Innsbruck
Vallee de la Sionne
Ryggfonn

Innsbruck, Tyrol, Austria

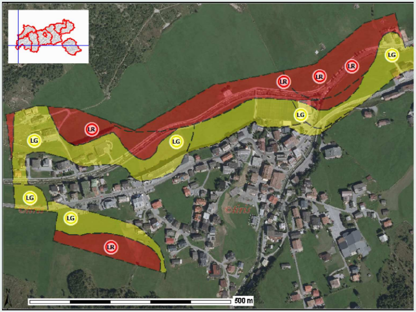


Avalanches north of Innsbruck
1: „Höttinger Graben“ avalanche
5: „Penzenlahn“ avalanche,
2: „Schneckengufl“avalanche
6: „Arzler Alm“ avalanche,
3: „Gerlehner“ avalanche
7: „Mühlauer Klamm“ avalanche
4: „Rastlboden“ & „Gerschrofen“ avalanches,

1999 Galtür, Austria

destructive potential of extreme snow avalanches

hazard mapping



how far?

→ **runout**

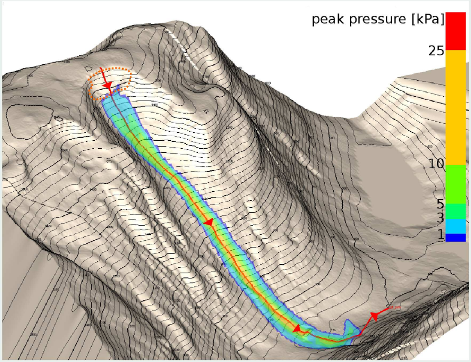
mitigation planning

how destructive?

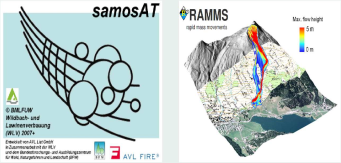
→ **pressure**

methods: computational and experimental avalanche dynamics

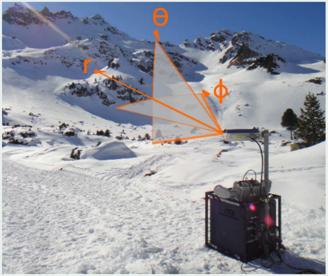
simulation results



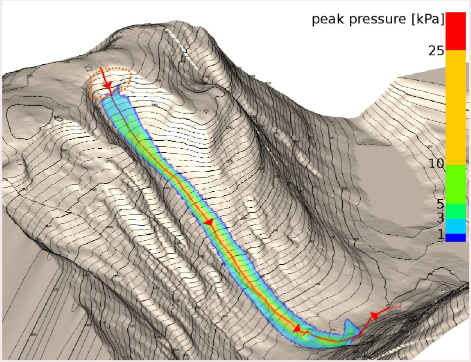
computation [5]



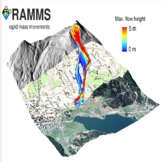
experiment [3, 4]



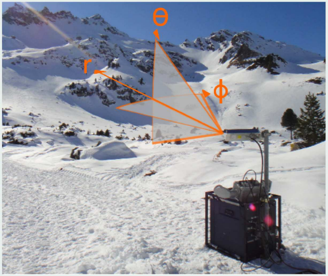
simulation results

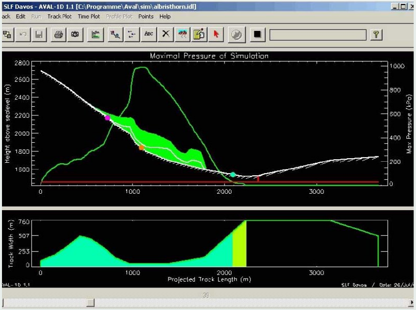


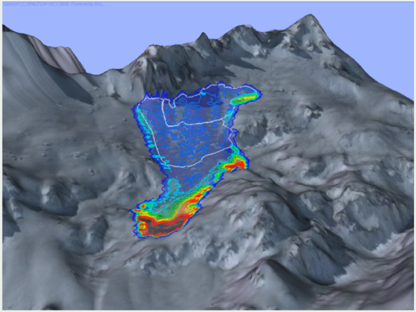
computation [5]



experiment [3, 4]







- simulations for: back calculation and prediction (inverse calibration/optimization)
- learn something new about snow avalanche simulation in three dimensional terrain (simulation concepts, uncertainties, ...)
- objective analysis method for comparison and evaluation of 100,1000,10000,... simulation runs
- provide definitions representing main avalanche features

dfa - dense flow avalanche

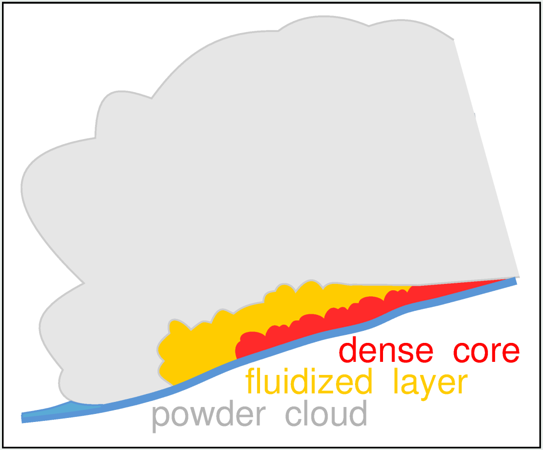
psa - powder snow avalanche

dfa - dense flow avalanche

psa - powder snow avalanche

snow avalanche model

three layer structure - dense core - fluidized layer - powder cloud

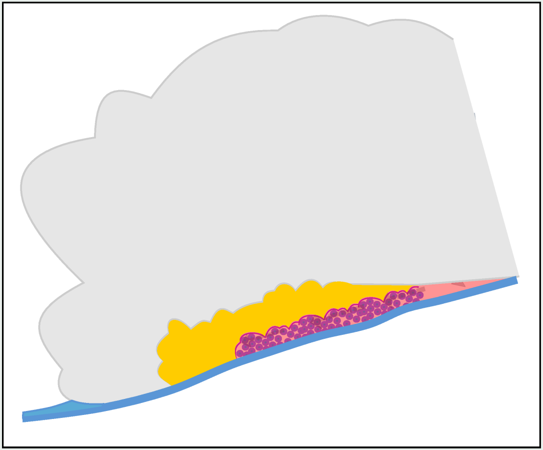


- flow depth
- flow velocity
- impact pressure

[11, 10, 9, 7]

dense flow avalanche model

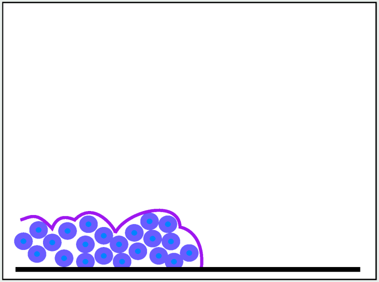
dfa - dense flow avalanche



- dense snow
- granular flow
- moderate velocity, high density

dense flow avalanche

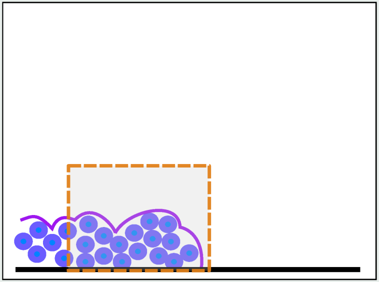
dense core



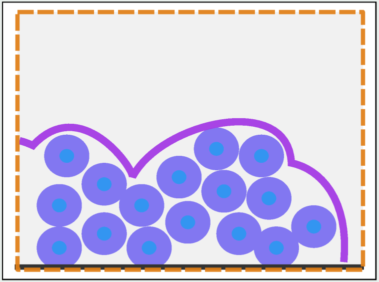
- 2d depth averaged shallow water/Savage Hutter equations
- model parameters: density, bottom friction...
- $c = 10^{-1}$, $\overline{\rho} = 150 - 400\,\mathrm{kg\,m^{-3}}$, [10]

dense flow avalanche

dense core



frictional regime



- 2d depth averaged shallow water/Savage Hutter equations
- model parameters: density, bottom friction...
- $c = 10^{-1}$, $\overline{\rho} = 150 - 400\,\mathrm{kg\,m^{-3}}$, [10]

model equations - shallow water/Savage Hutter

$$\partial_t \begin{pmatrix} h \\ hu_x \\ hu_y \end{pmatrix} + \partial_x \begin{pmatrix} hu_x \\ hu_x^2 + \frac{g_z h^2}{2} \\ hu_x u_y \end{pmatrix} + \partial_y \begin{pmatrix} hu_y \\ hu_x u_y \\ hu_y^2 + \frac{g_z h^2}{2} \end{pmatrix} = \begin{pmatrix} 0 \\ S_x \\ S_y \end{pmatrix}$$

$$S_i = hg_i - \frac{u_i}{\|\mathbf{u}\|} \frac{\tau^b}{\rho}$$

flow height: h, *velocity:* $\mathbf{u} = (u_x, u_y)$, *grav. acceleration:* $\mathbf{g} = (g_x, g_y, g_z)$

model assumptions

- incompressible material
- shallowness/dimension analysis
- boundary conditions
- depth integration

phenomenological bottom friction

$$\tau^b_{RAMMS} = \mu\,\rho\,h\,g_z + \frac{\|\rho\,\mathbf{g}\|}{\xi}\mathbf{u}^2$$

$$\tau^b_{SamosAT} = \mu\,(1 + \frac{R^0_s}{R^0_s + R_s})\,\rho\,h\,g_z + \frac{\rho\,\mathbf{u}^2}{(\frac{1}{\kappa}\ln\frac{h}{R} + B)^2} + \tau_0$$

$$\tau^b_{XYZ} = \ldots$$

with

$$R_s = \frac{\rho\mathbf{u}^2}{h\,g_z},\ \textit{friction parameters: } \mu,\ \xi,\ R^0_s,\ \kappa,\ R,\ B,\ \tau_0,\ \ldots$$

model results and their interpretation

model results - spatiotemporal evolution of flow variables:

- $h(x, y, t)$ - flow depth
- $\mathbf{u}(x, y, t)$ - flow velocity

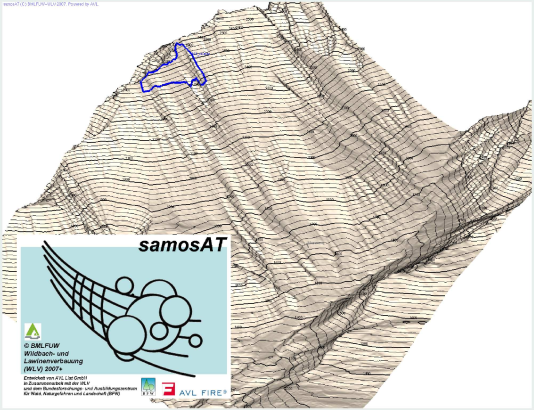
***simulation* results - maximum impact pressure**

- $P(x, y, t) = \rho_{flow}\, u^2$
- $\tilde{P}(x, y) = \max_t P(x, y, t)$

[9, 1]

example Vallée de la Sionne, Switzerland:

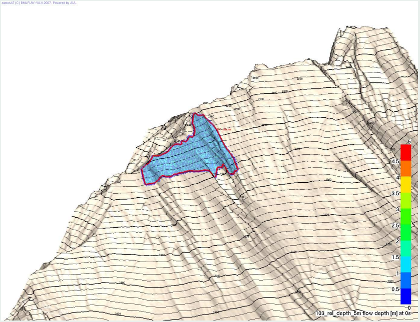
simulation input:



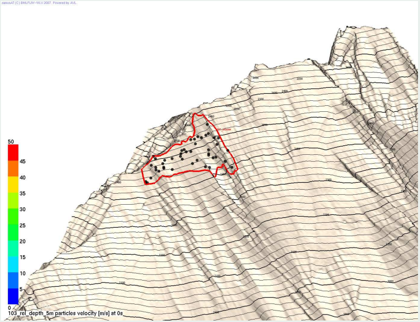
measurements

- Digital Elevation model
- release area
- release depth

dfa - SPH - continuum

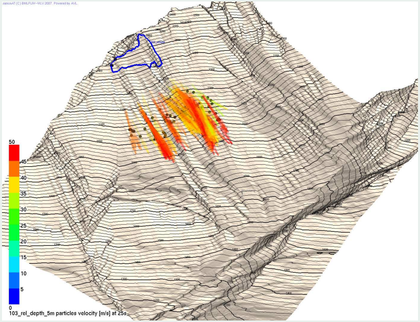


dfa - SPH - numerical particles

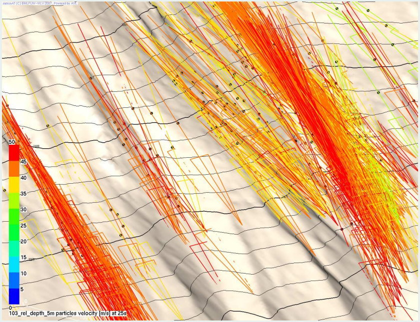


- discretization in: time, space, mass

dfa - SPH - 25 s



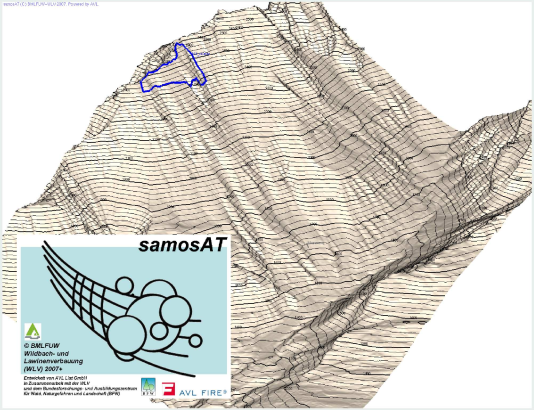
dfs - SPH - 25s



- computation of spatiotemporal evolution of flow variables

example Vallée de la Sionne, Switzerland:

simulation input:

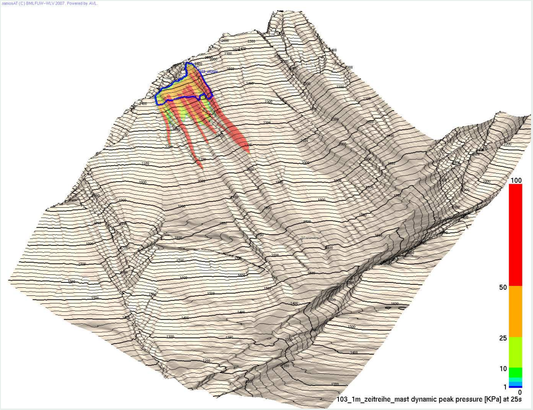


measurements

- Digital Elevation model
- release area
- release depth

example Vallée de la Sionne, Switzerland:

simulation results 25s:

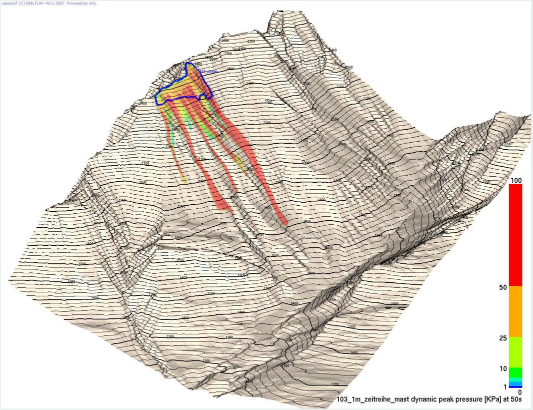


- how far?
  → **runout**
- how destructive?
  → **pressure**

- initial conditions → measurements

example Vallée de la Sionne, Switzerland:

simulation results 50s:

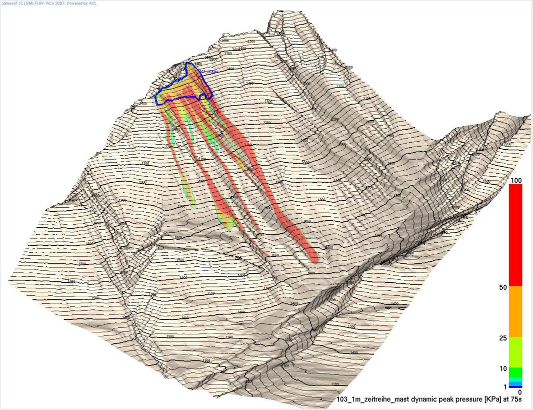


- how far?
  $\rightarrow$ **runout**
- how destructive?
  $\rightarrow$ **pressure**

- initial conditions $\rightarrow$ measurements

example Vallée de la Sionne, Switzerland:

simulation results 75s:

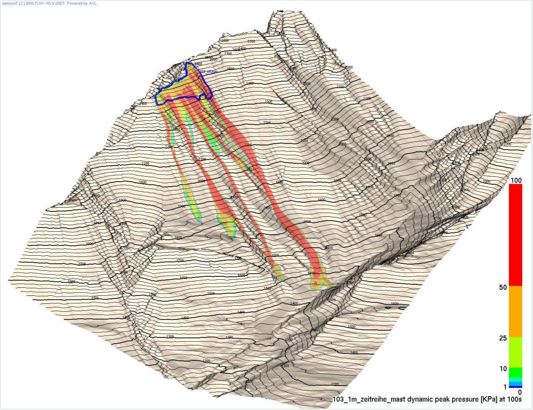


- how far?
  → **runout**
- how destructive?
  → **pressure**

- initial conditions → measurements

example Vallée de la Sionne, Switzerland:

simulation results 100s:

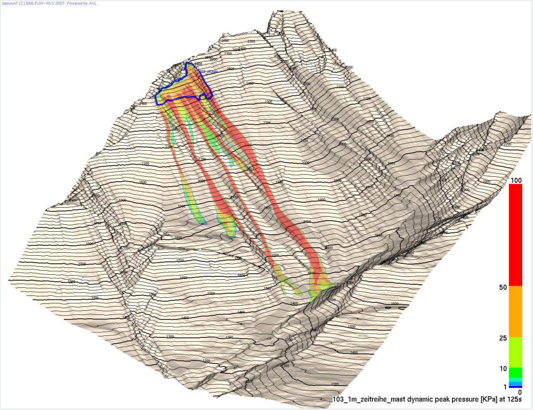


- how far?
  → **runout**
- how destructive?
  → **pressure**

- initial conditions → measurements

example Vallée de la Sionne, Switzerland:

simulation results 125s:

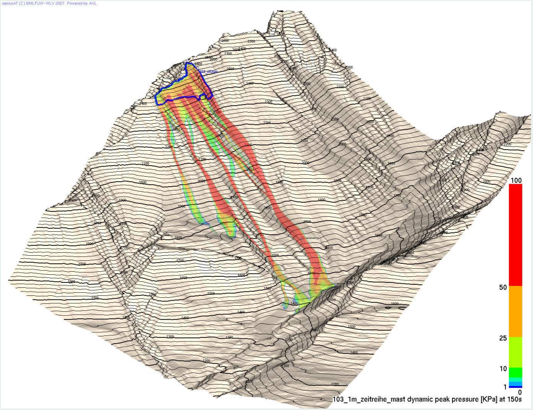


- how far?
  → **runout**
- how destructive?
  → **pressure**

- initial conditions → measurements

example Vallée de la Sionne, Switzerland:

simulation results 150s:

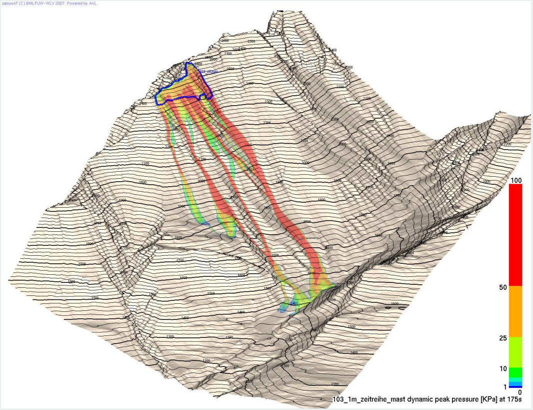


- how far?
  $\rightarrow$ **runout**
- how destructive?
  $\rightarrow$ **pressure**

- initial conditions $\rightarrow$ measurements

example Vallée de la Sionne, Switzerland:

simulation results 175s:

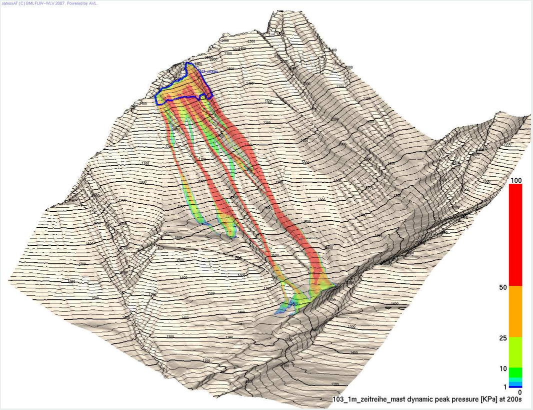


- how far?
  → **runout**
- how destructive?
  → **pressure**

- initial conditions → measurements

example Vallée de la Sionne, Switzerland:

simulation results 200s:

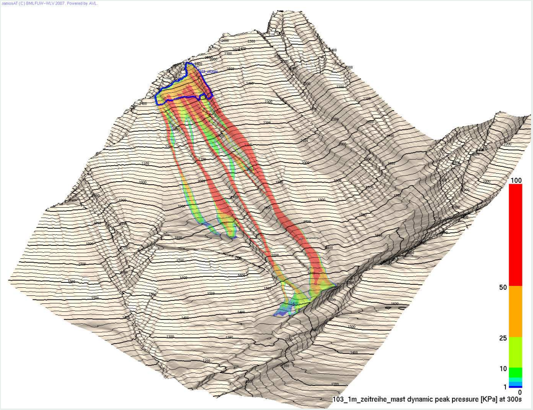


- how far?
  → **runout**
- how destructive?
  → **pressure**

- initial conditions → measurements

example Vallée de la Sionne, Switzerland:

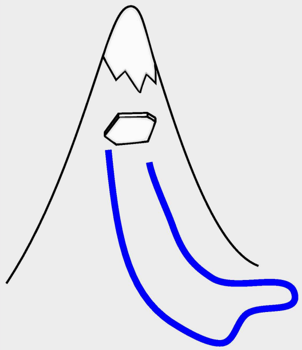
simulation results final:



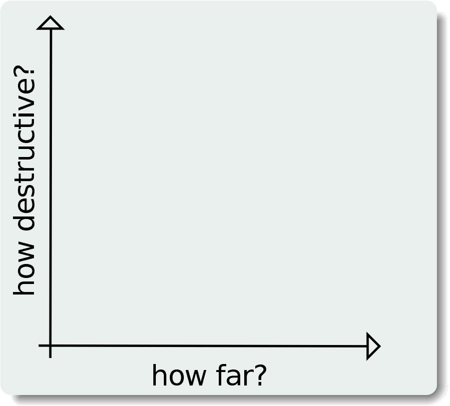
- how far?
  → **runout**
- how destructive?
  → **pressure**

- model parameters → back calculation

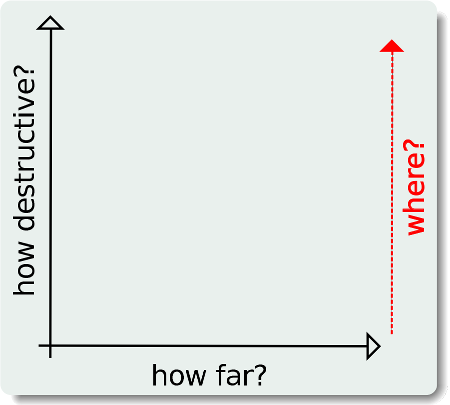
method for evaluation and comparison [2]



input: topography, release information, model parameters
output: flow depth, velocity, ... maximum impact pressure - $\tilde{P}(x, y)$



scalar metric, to represent main avalanche features

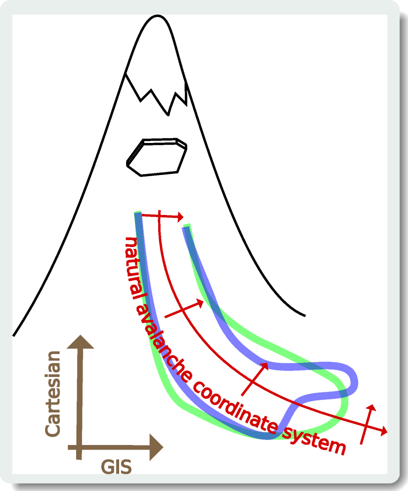


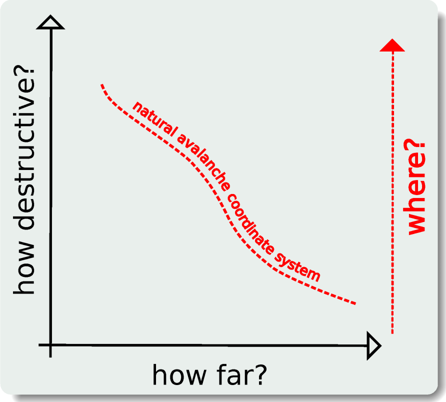
scalar metric, to represent main avalanche features

- how to determine start and end point in a global framework?
- how would an avalanche see it?

- how would an avalanche see it - change of framework
- coordinate transformation along the avalanche path

coordinate transformation

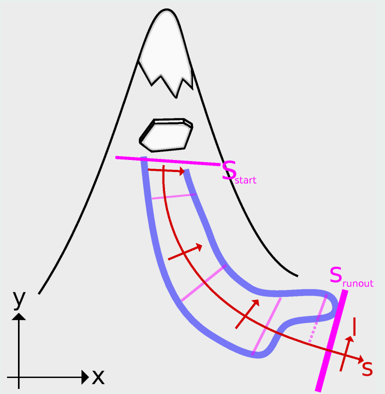




where? path dependent coordinate system

indicators - path dependent metric

runout



what is runout?

runout is a threshold, e.g.

$P_{limit} = 1\,\mathrm{kPa}$

of the cross sectional peak pressure maximum

$P^{max}_{cross}(s) = \max_l \; P(s, l)$

defines runout position

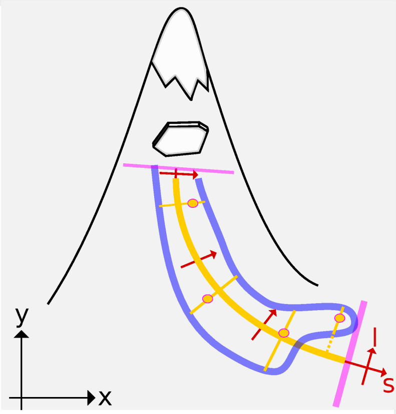
s_{runout}

along the avalanche path

two dimensional pressure results $\tilde{P}(x, y)$ to define scalar indicators in new coordinate system $P(s, l)$

indicators - path dependent metric

destructiveness



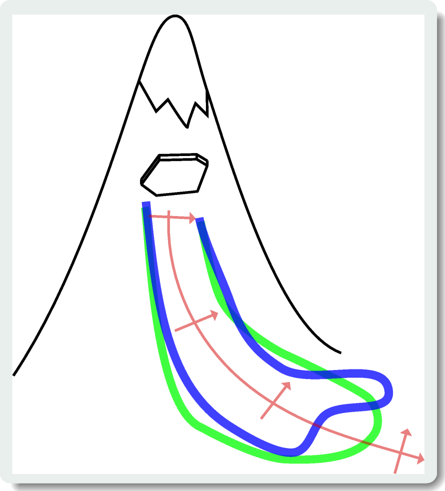
what is destructiveness?

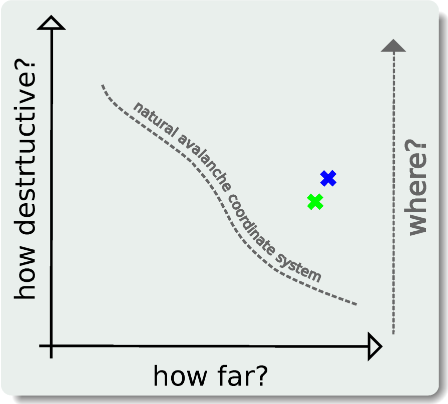
a measure for destructiveness is the **A**veraged (along the avalanche path) **M**aximum (cross sectional) **P**eak **P**ressure (*AMPP*)

$$P^{max}_{cross}(s) = \max_l \; P(s,l)$$

$$AMPP = \frac{1}{|s_{start} - s_{runout}|} \int_{s_{start}}^{s_{runout}} P^{max}_{cross}(s)\,\mathrm{d}s$$

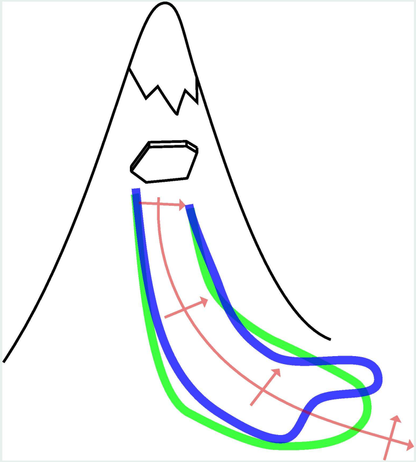
two dimensional pressure results $\tilde{P}(x,y)$ to define scalar indicators in new coordinate system $P(s,l)$

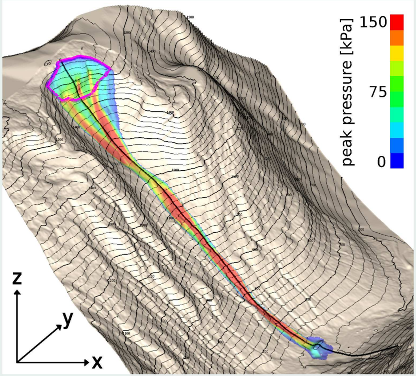




comparison of multiple simulation runs

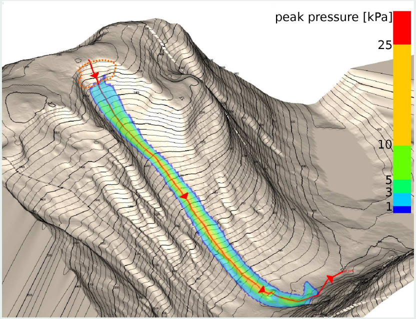
Example - Ryggfonn



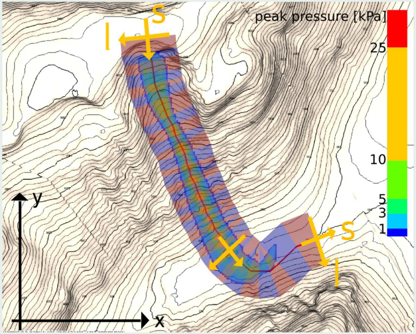


definition of path dependent coordinate system

Ryggfonn Norway

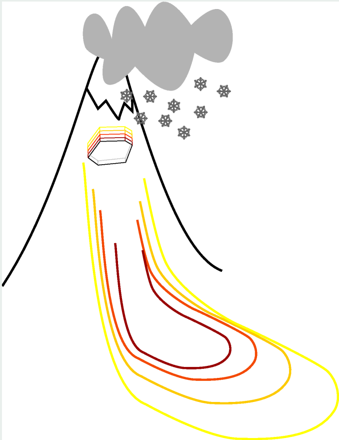


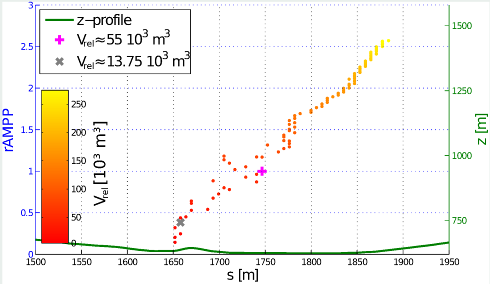
coordinate system



results of snow avalanche simulation in computational coordinate system and path dependent coordinate system

variation of release depth



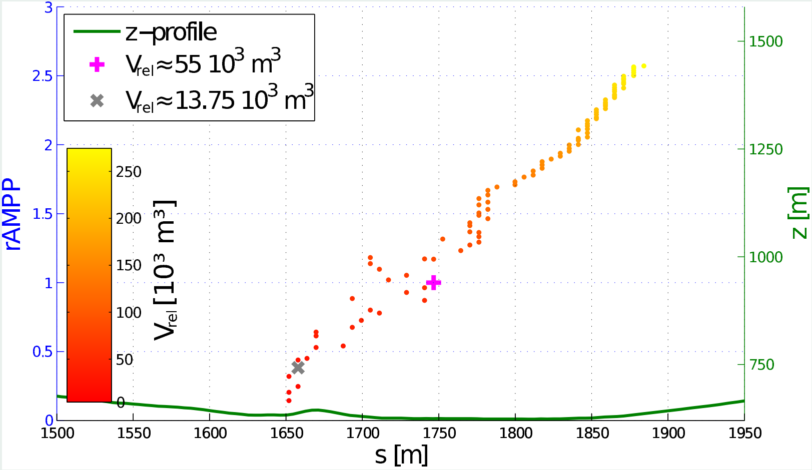


main avalanche features of 100 simulation runs with varying input

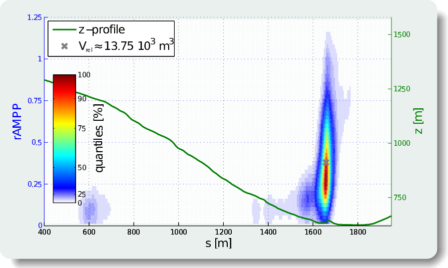
topography, release information, model parameters

summarized in objective and clear way

variation of release depth

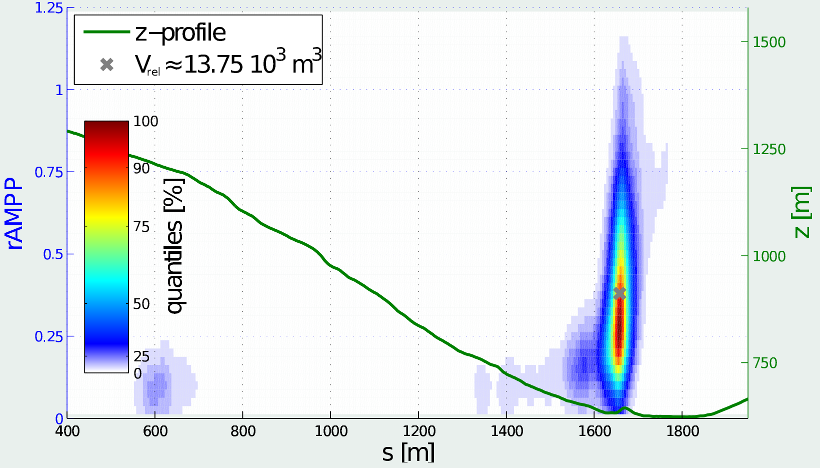


variation of model parameters



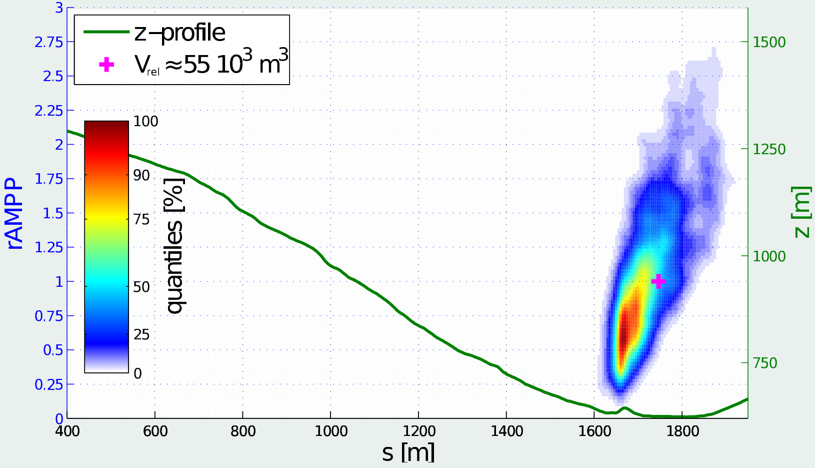
simulation input: topography, release information, model parameters
density distribution of main simulation features for 1000 simulation runs with varying friction parameters, and different release volume

variation of model parameters



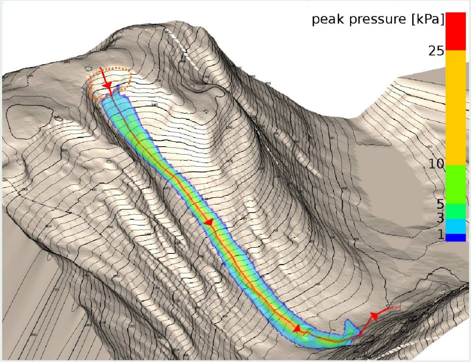
application in sensitivity analysis, calibration, uncertainty analysis ....

variation of model parameters

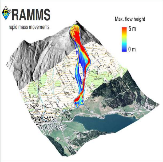


application in sensitivity analysis, calibration, uncertainty analysis ....

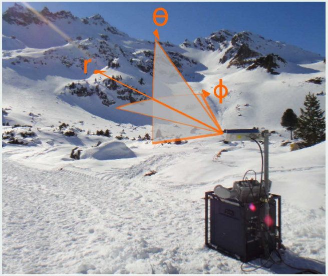
simulation results [2]



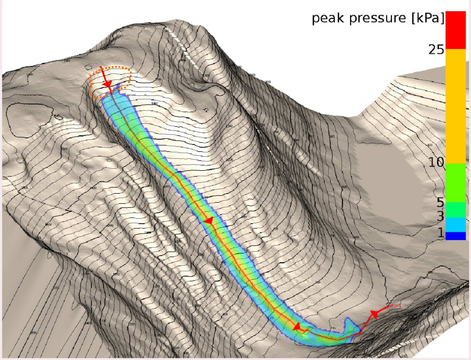
computation [5]



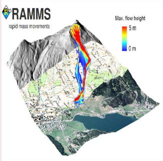
experiment [3, 4]



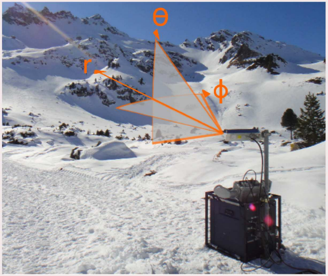
simulation results



computation [5]

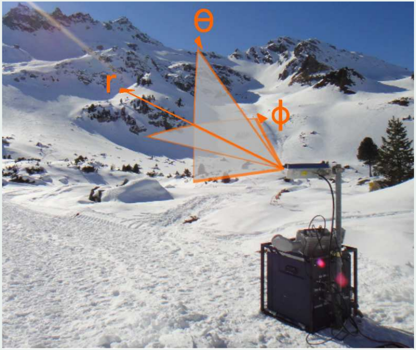


experiment [3, 4]

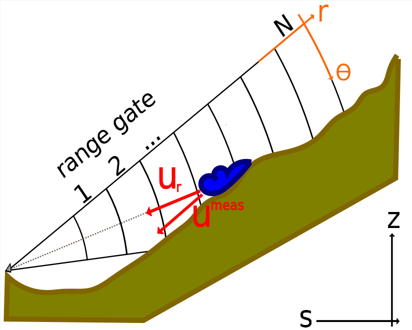


- learn about the velocities, mass balance and dynamics of avalanches
- estimate accuracy of simulated avalanche velocities
- provide optimized model parameters/input

field measurement



data processing

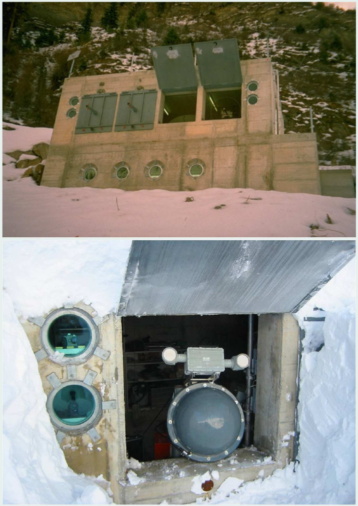


pulsed Doppler radar measurements
5.8 GHz ≈ 5 cm snow clods

range gate width ≈ 25 – 100 m
topographic correction and projection

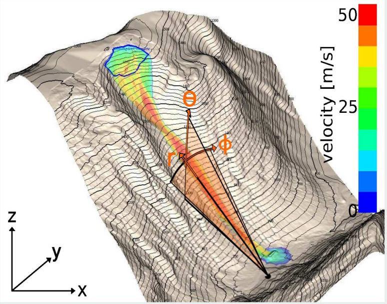
Ryggfonn

Vallée de la Sionne



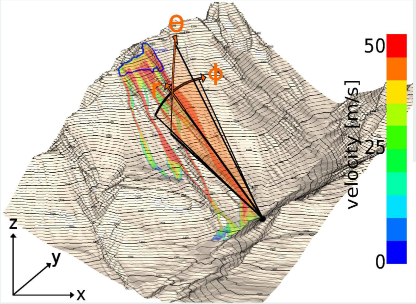
Doppler radar positions at test sites

Ryggfonn - 17.04.1997



- $V_{rel} \approx 12 - 30 \times 10^3\,\mathrm{m}^3$
- $V_{dep} \approx 40 \times 10^3\,\mathrm{m}^3$
- $\bar{\alpha} = 28°$
- $\Delta Z = 900\,\mathrm{m}$

Vallée de la Sionne - 10.02.1999



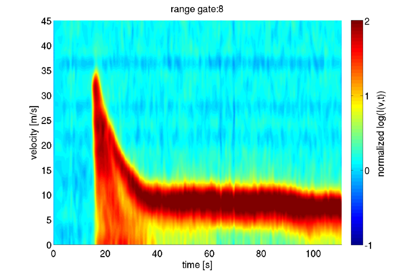
- $V_{rel} \approx 84 \times 10^3\,\mathrm{m}^3$
- $V_{dep} \approx 505 \times 10^3\,\mathrm{m}^3$
- $\bar{\alpha} = 30°$
- $\Delta Z = 1200\,\mathrm{m}$

Ryggfonn

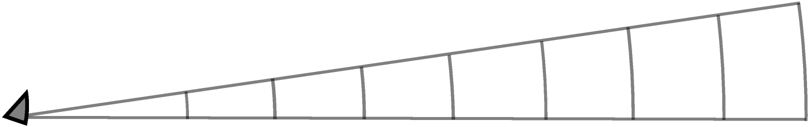
Vallée de la Sionne

Ryggfonn 17.04.1997

450-500 m

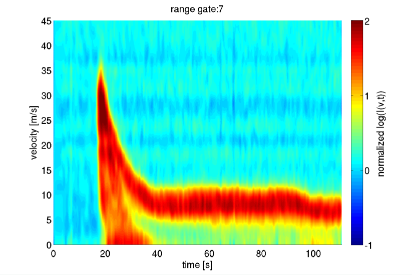


- range gate intensity spectra $I(t, \Delta f) \rightarrow I(t, v)$
- lowpass and noise filtering
- normalizing with background singnal

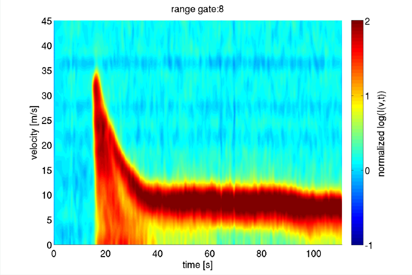


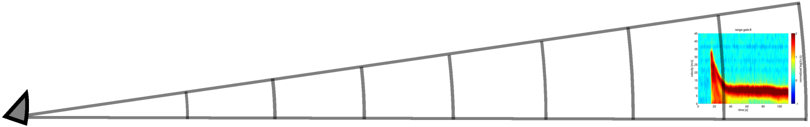
Ryggfonn 17.04.1997

400-450 m



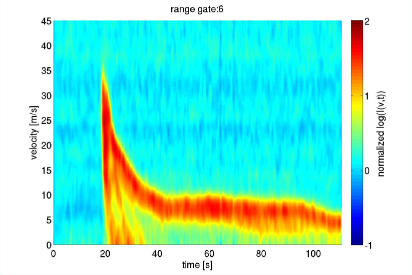
450-500 m



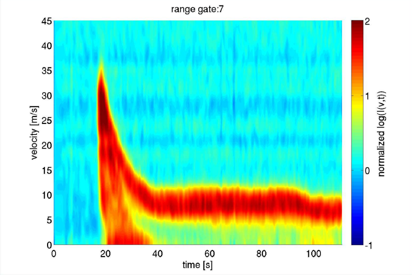


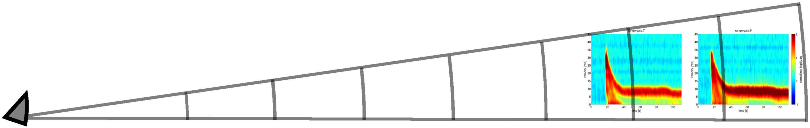
Ryggfonn 17.04.1997

350-400 m



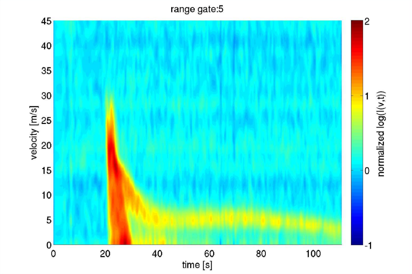
400-450 m



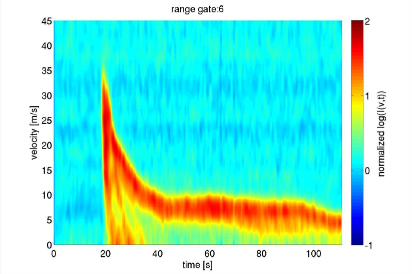


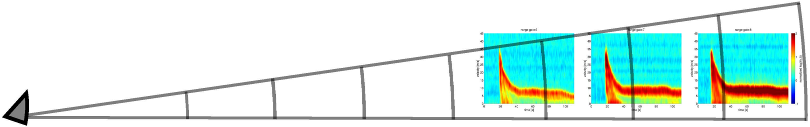
Ryggfonn 17.04.1997

300-350 m



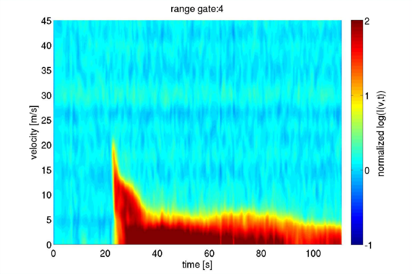
350-400 m



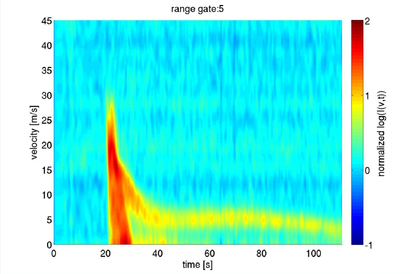


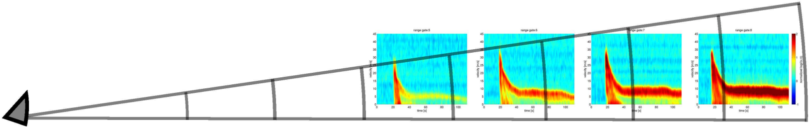
Ryggfonn 17.04.1997

250-300 m



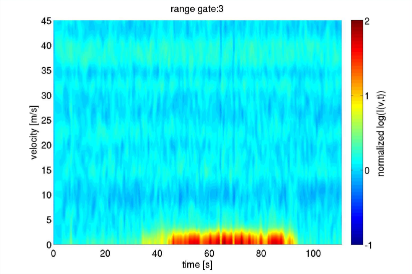
300-350 m



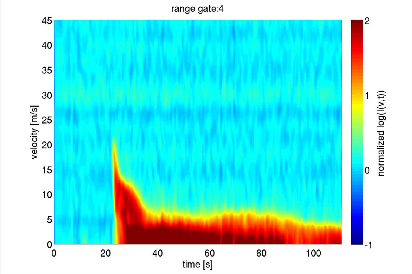


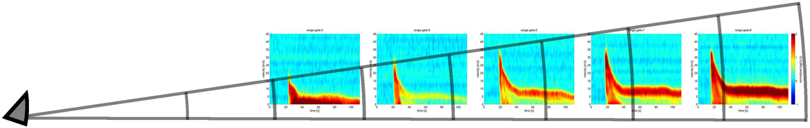
Ryggfonn 17.04.1997

200-250 m



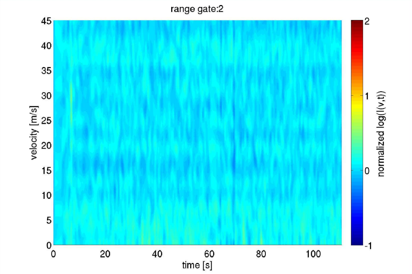
250-300 m



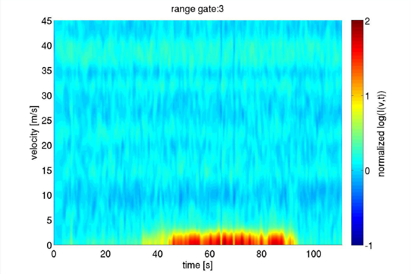


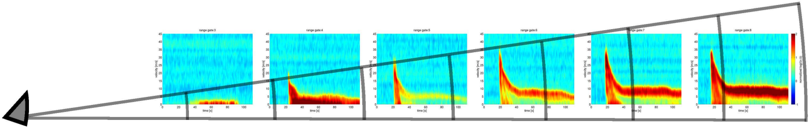
Ryggfonn 17.04.1997

150-200 m



200-250 m



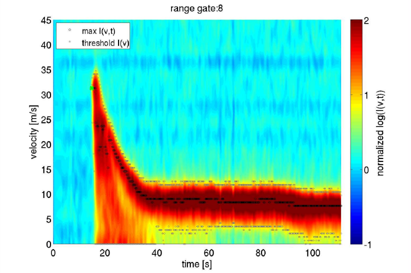


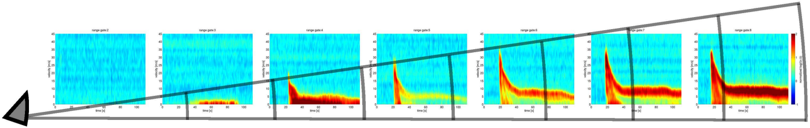
Ryggfonn 17.04.1997

different velocity types

- velocity of maximum intensity
- front velocity
- velocity range
- [12, 8, 6]...

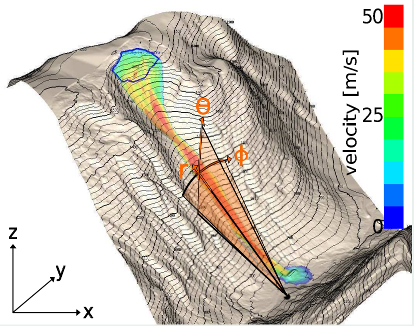
450-500 m



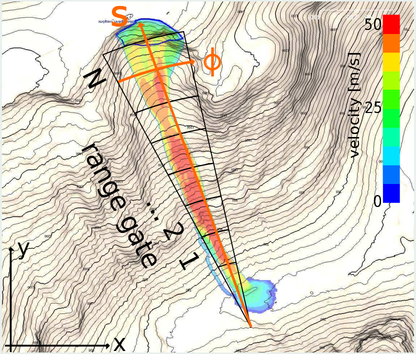


evaluation - Ryggfonn

simulation output

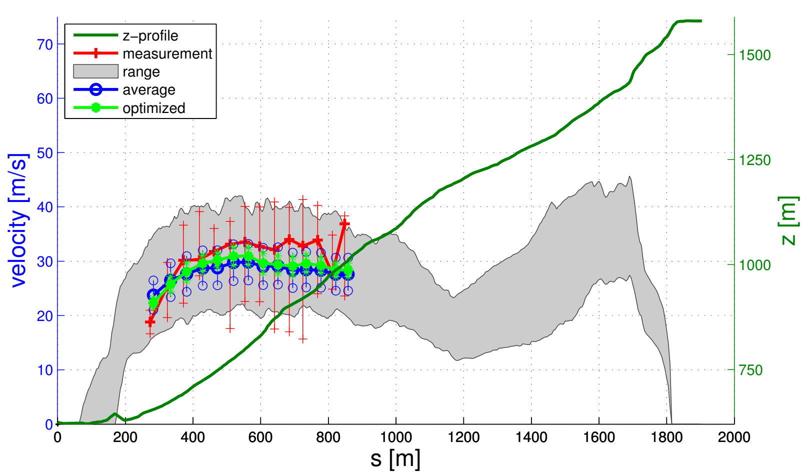


result processing



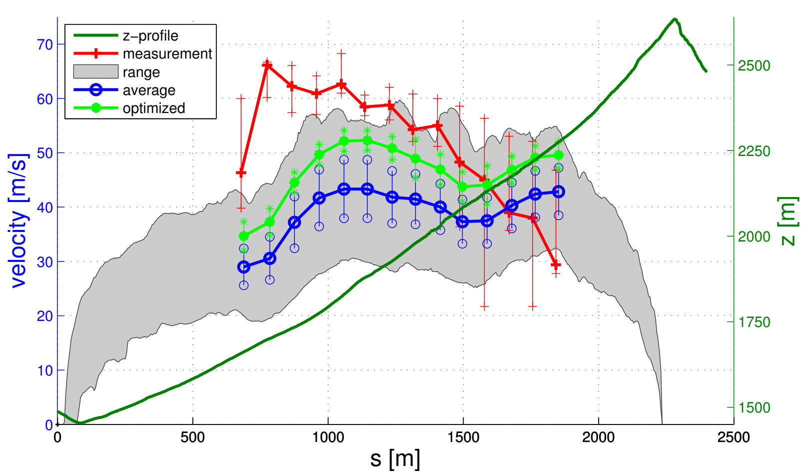
simulation input: topography, release height (measurement uncertainty), model parameters
transformation in measurement system,
comparison of multiple (10000) simulation runs.

Ryggfonn - avalanche simulation with release depth variations



velocity evaluation and uncertainty estimation with probabilistic methods

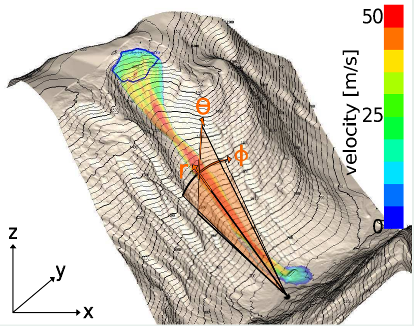
Vallée de la Sionne - avalanche simulation with release depth variations



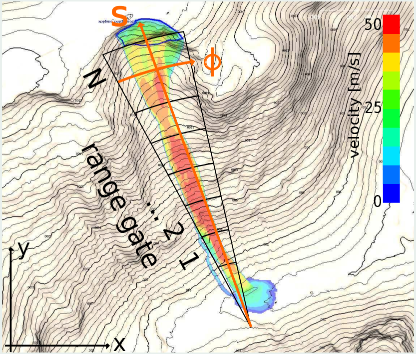
velocity range, average and best fit...

evaluation - Ryggfonn

simulation output

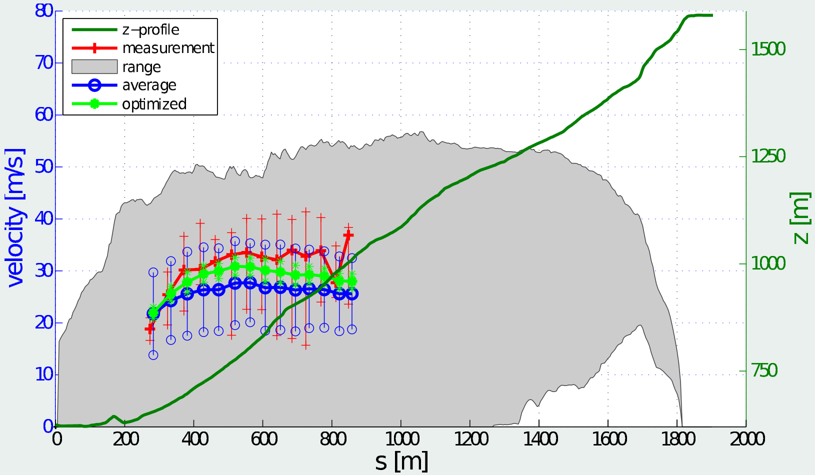


result processing



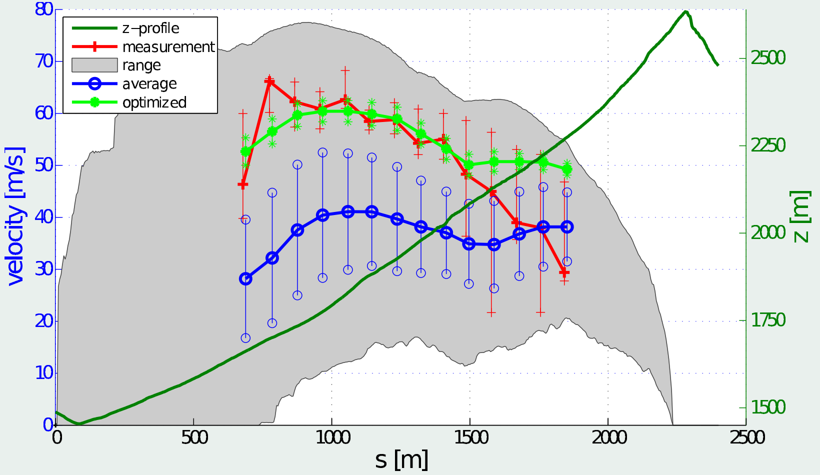
simulation input: topography, release height (measurement uncertainty), model parameters ($\pm 50\%$)
transformation in measurement system,
comparison of multiple (10000) simulation runs,

Ryggfonn - avalanche simulation with monte carlo input variations



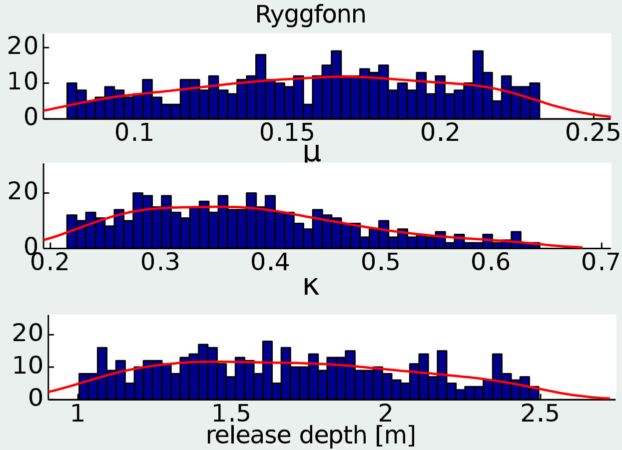
velocity evaluation and calibration/optimization with probabilistic methods

Vallée de la Sionne - avalanche simulation with monte carlo input variations



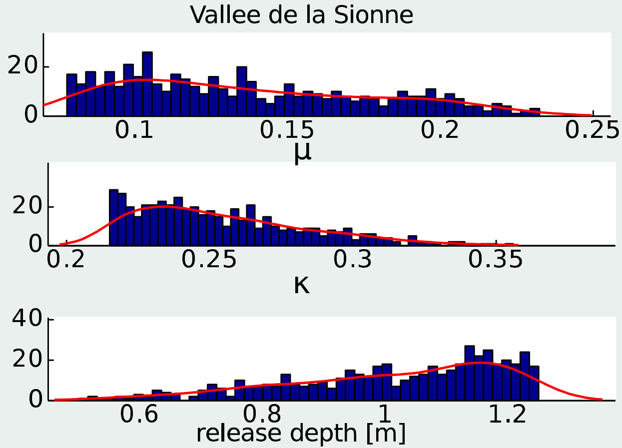
velocity range, average and best fit...

Ryggfonn - optimized for best 10% simulation runs



distributions of optimized model input/parameters

Vallée de la Sionne - optimized for best 10% simulation runs



distributions of optimized model input/parameters

laser scanning

lasser scanning

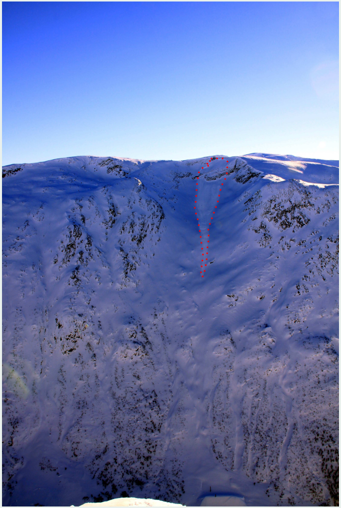
- terrestrial - airborne
- 3d topographic data
- digital elevation models
- mass balance
- ...

Ryggfonn, Norway - scanning position

avalanche release

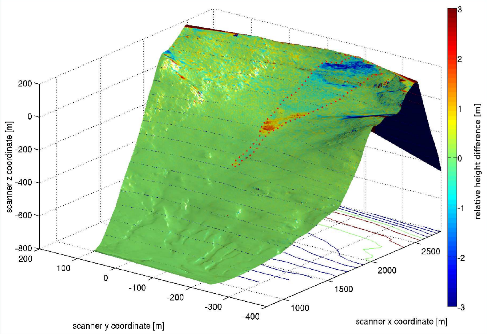
artificially released slab

avalanche deposition



field measurement

data evaluation

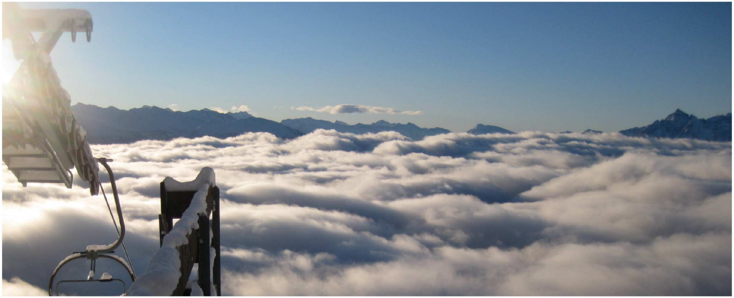


volume $\approx 15000\,\mathrm{m}^3$
areas of erosion and deposition

summary

- model independent method for the interpretation of avalanche simulations in three dimensional terrain with a broad applicability in model evaluation and comparison
- identify and quantify sources of uncertainties in dependence of input variations
- comprehensive evaluation of simulation results with velocity measurements
- improved calibration/optimization procedure of simulation software

thank you for your attention



BFW. NGI SLF

references (non exhaustive)

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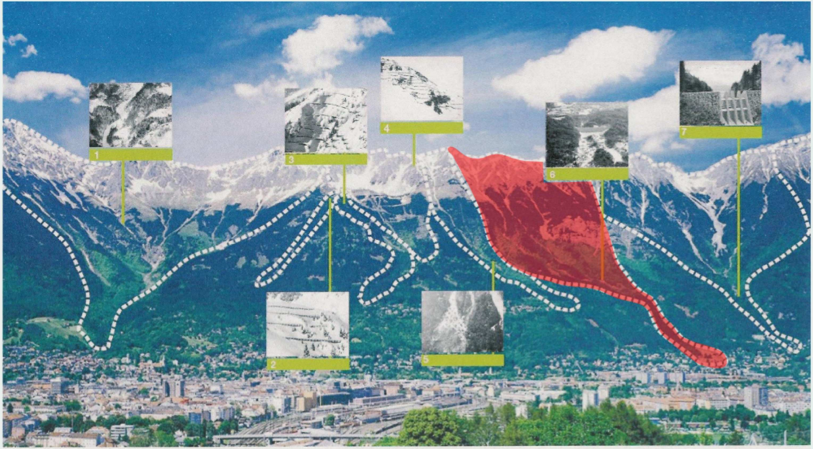
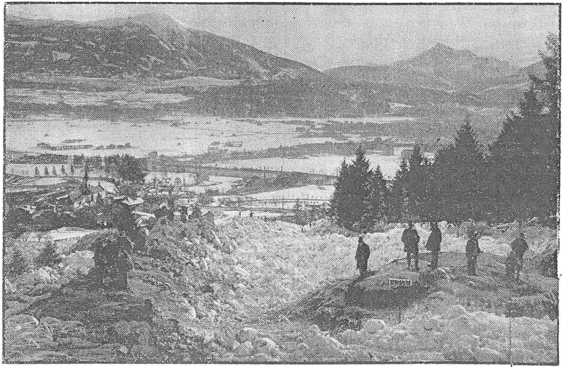
Arzler Alm avalanche, Innsbruck, Tyrol, Austria



Avalanches north of Innsbruck
1: „Höttinger Graben" avalanche
2: „Schneckengufl"avalanche
3: „Gerlehner" avalanche
4: „Rastlboden" & „Gerschrofen" avalanches,
5: „Penzenlahn" avalanche,
6: „Arzler Alm" avalanche,
7: „Mühlauer Klamm" avalanche

historical events - e.g. 1923

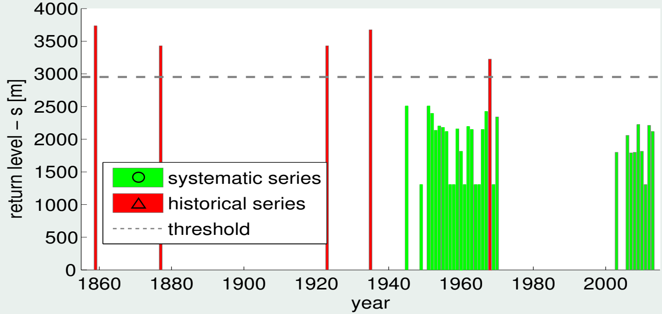


Phot. Richard Müller, Innsbruck.

Ein Bild der Mühlauer Lawine vom Jahre 1923, die fast am gleichen Tage, am 3. Februar, aus dem Gebiete des Arzler Horns herabkam.

- what run out is expected for a certain return period?
- what return period can be assigned to an event?
- can extreme value analysis be helpful?

time series data



- horizontally projected runlength - return level s [m]
- systematic series: block maxima of continous observation (30 y)
- historical series: observed events above limit (5 y)
- threshold: upper limit for all non observed events (121 y)

generalized extreme value (GEV) distribution

$$f_\theta(R) = \frac{1}{\sigma}(1-\xi\,\frac{(R-\mu)}{\sigma})^{(1/\xi-1)}\,\exp(-(1-\xi\,\frac{(R-\mu)}{\sigma})^{1/\xi}),\ \xi \neq 0,$$

$$F_\theta(R) = \exp(-(1-\xi\,\frac{(R-\mu)}{\sigma})^{1/\xi})\,,\ \xi \neq 0,$$

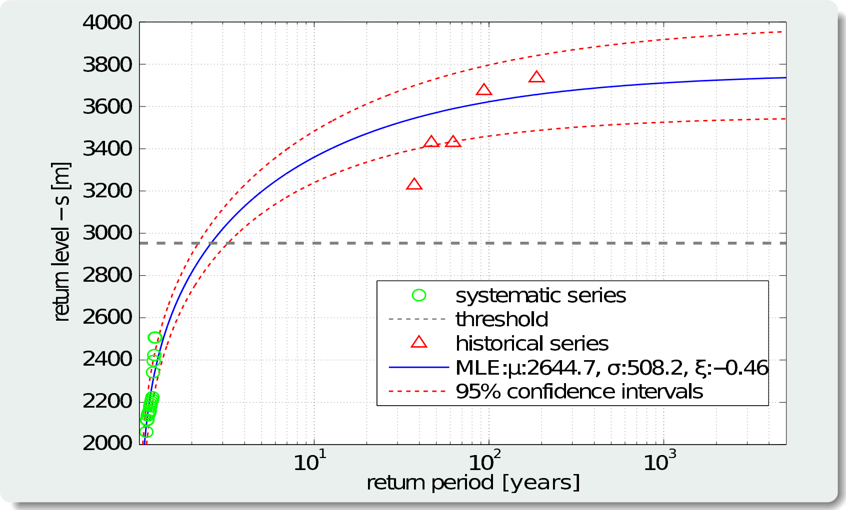
with $\theta = \{\mu, \sigma, \xi\}$: location μ, scale σ and shape ξ.

$\rightarrow$ maximum likelihood estimate fit with customized likelihood function

$$L = \prod_i^s f(R_i|\theta)\,F(R_{lim}|\theta)^{n-h-s}\,\prod_j^h f(R_j|\theta),$$

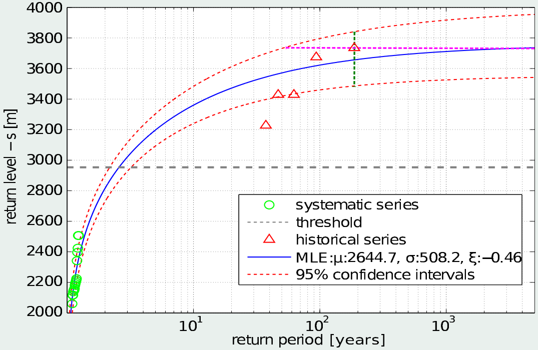
with n, the total length of the investigated series, the run out threshold R_{lim}, R_i the run out values of the systematic series of length s and R_j the run out values of the historical series of length h, respectively.

return level - return period



return period = 1 / exceedance probability

return level - return period - largest event 1859



- empirical observation: return level $s = 3735$ m return period 187 y
- GEV estimate for RP 187 y: 3657 m (3486 m to 3840 m)
- GEV estimate for RL $s = 3735$ my: 4313 y (52 y to ∞ y)

$\rightarrow$ return period estimates difficult - return level estimates O.K.