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Improving wide-area DEMs through data fusion - chances and limits

Konrad Schindler

Photogrammetry and Remote Sensing, ETH Zürich

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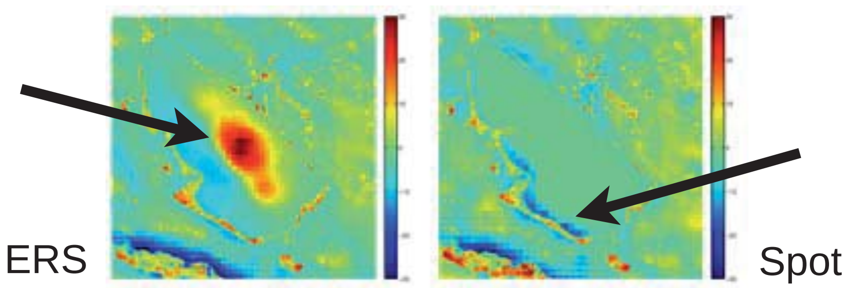
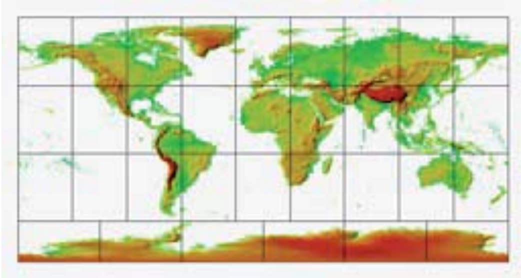
How to get a DEM for your job?

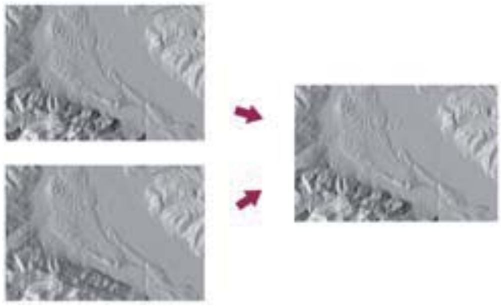
- for small projects (or rich people)
  - contract someone to collect elevation measurements
  - generate your own DEM tailored to your needs
- for large projects
  - check what DEMs are available for your project area
  - choose one of them and hope it is good enough
  - **or, fuse two or more of them to get a better one**



Agenda

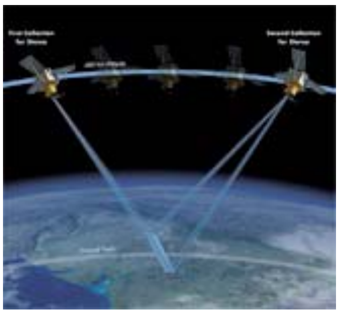
- Examples of large-scale DEMs
  - widely-used available models
  - characteristics, limitations
- DEM fusion
  - mathematical recipe: 2 examples
  - influence weights - the crunch point
- Experimental results
  - test site: Thun / Switzerland
  - gains and limitations of fusion

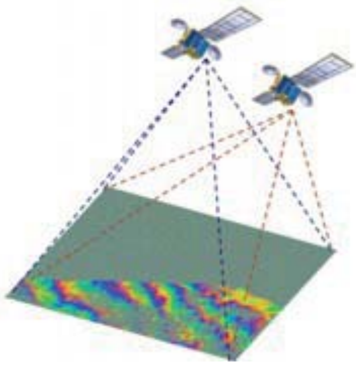




Available DEMs

- Here: limitation to large-scale DEMs
  - coverage: national / continental / global level
- Acquisition technologies
  - airborne LiDAR
  - multi-image matching
  - SAR interferometry
  - (map digitisation)





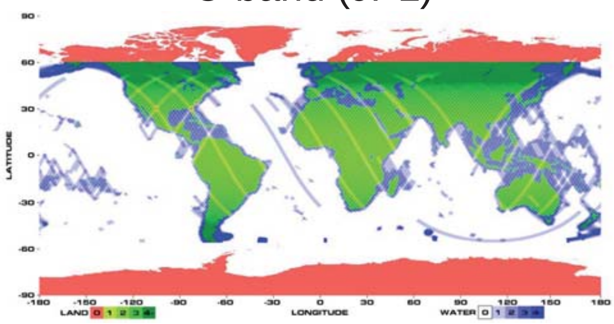
Wide-area DEMs

	LiDAR	image matching	SAR
accuracy	0.1 - 1.0 m	0.1 - 100 m	0.5 - 100 m
observation	DSM and DTM	DSM only	DSM (and DTM)
handicap	(clouds)	clouds, darkness	---
from space	no	yes	yes, predominantly
cost	$$$	$	$
coverage	few (small) countries	global	global

SRTM

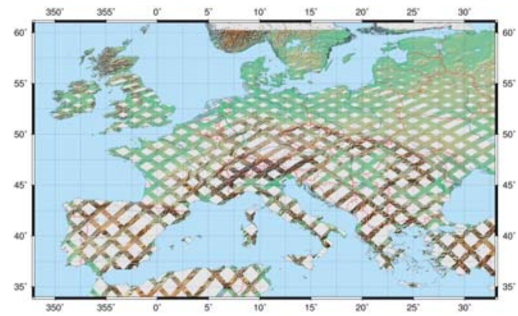
- Shuttle RADAR topography mission
  - acquired Feb 2000 with single-pass InSAR
  - available for free, widely used

C-band (JPL)



spacing	XY-error @90%		Z-error @90%	
	abs	rel	abs	rel
90 m / 30 m	20 m	15 m	16 m	10 m

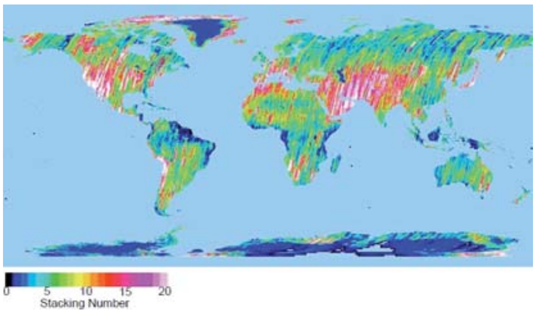
X-band (DLR)



spacing	XY-error @90%		Z-error @90%	
	abs	rel	abs	rel
30 m	20 m	15 m	16 m	6 m

ASTER GDEM

- Advanced spaceborne thermal emission & reflection radiometer
  - acquired 1999-2009, along-track stereo at 760-860 nm VNIR
  - available for free
  - systematic errors (cloud masking, DEM merging, over-smoothing)



spacing	XY-error @90%		Z-error @90%	
	abs	rel	abs	rel
≈30 m	25 m	---	17 m	---

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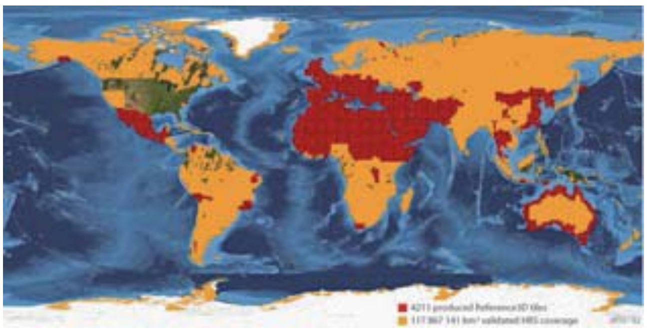
SPOT Reference3D

- SPOT-5
  - acquired since 2002, along-track stereo at 480-700 nm panchromatic
  - still not completely processed, coverage steadily increasing
  - cost ≈10 Euro / km^2



DEM (+Ortho) available

validated data

spacing	XY-error @90%		Z-error @90%	
	abs	rel	abs	rel
≈30 m	15 m	8 m	10-30 m	5-28 m

NEXTmap

- Intermap Technologies Inc.
  - airborne SAR (X-band) DSM (+ DTM by filtering)
  - cost ≈30 US$ / km^2
  - coverage: Western Europe, USA, Indonesia, ...

spacing	XY-error @90%		Z-error @90%	
	abs	rel	abs	rel
5 m	2 m	---	1-3 m	---

Others

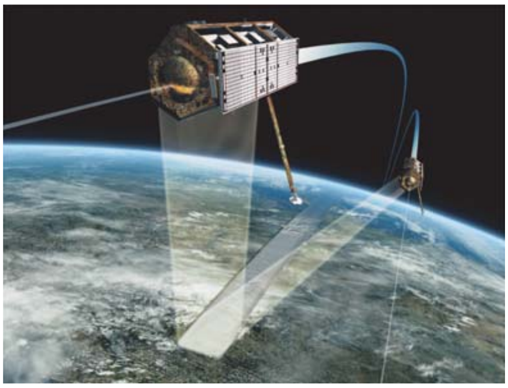
- ERS
  - tandem interferometry with ERS-1 and ERS-2
  - some countries (Switzerland, Great Britain, Egypt, ...)
  - main aim not DEM production
  - not always publicly available

- VHR satellites
  - matching of hi-res images (IKONOS, WorldView 1, Quickbird)
  - no large-scale models

IKONOS HI-DEM

Next Generation

- TanDEM-X
  - acquisition 2010-2012 by tandem interferometry
  - planned coverage: 100% land masses
  - cost ???



spacing	XY-error @90		Z-error @90%	
	abs	rel	abs	rel
≈12 m	10 m	3 m	10 m	2-4 m

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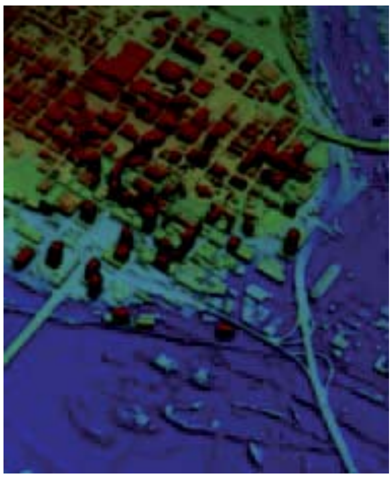
Next Generation

- Global DEMs from aerial photogrammetry?
  - cannot predict the future, but ingredients are there

- Example: Microsoft Global Ortho Project
  - coverage: 2010-2012
    USA, Western Europe
  - 3-yearly updates promised
    in populated areas

  - will such models be made available?
  - at what cost?



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DEM Fusion

- Several DEMs → redundancy
  - How to get a better DEM?
  - **note**: not considering mosaicking / hole-filling here
- In the ideal world
  - get all raw measurements, and all sensor models
  - estimate optimal DEM jointly from all observations
- The next best thing
  - cannot get raw data, only DEMs
  - use them as noisy observations to estimate a better DEM

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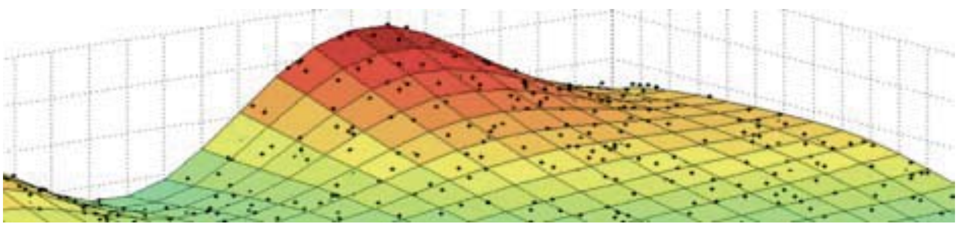
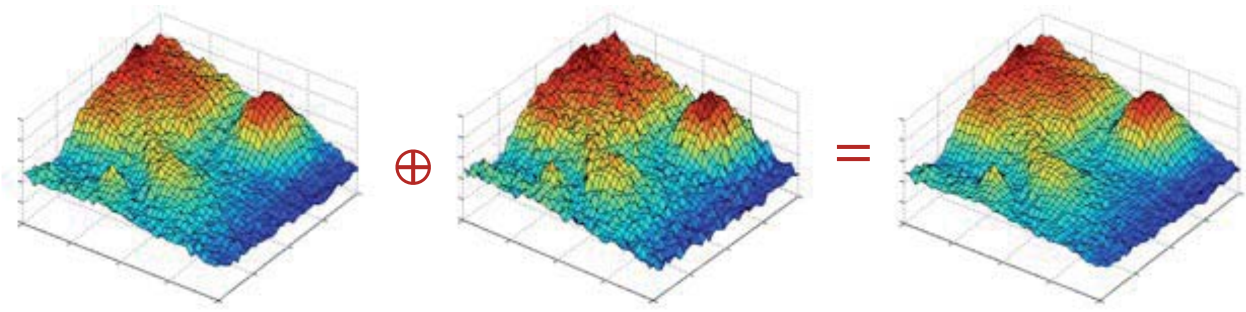
DEM Fusion

- Version 1 - your favourite surface fitting
  - treat raster points of input DEMs as “mass points”
  - ... **but** then one needs to know the correlations between them due to the original DEM estimation
- Version 2 - directly merge surfaces
  - treat input DEMs as (non-parametric) surfaces
  - find a new surface represented by the same samples
  - ...per-point fusion, thus need only per-point accuracies



Weighted Averaging

- The obvious (and most wide-spread) solution
  - given two DEMs and their accuracies
  - fuse by weighted averaging
  - weights from error propagation: $Z_{new} = \frac{\sigma_B^2}{\sigma_A^2+\sigma_B^2} Z_A + \frac{\sigma_A^2}{\sigma_A^2+\sigma_B^2} Z_B$
  - **note**: inputs need to be resampled to the same grid



$\sigma = 20$ $\sigma = 30$ $\sigma = 17$

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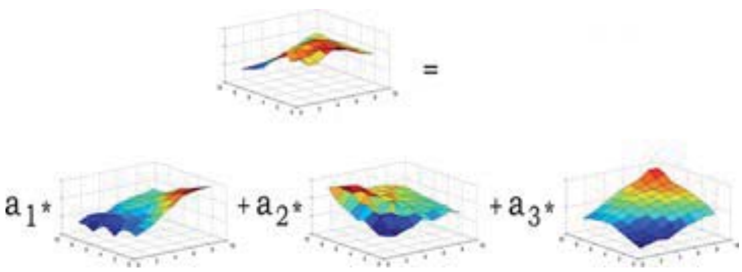
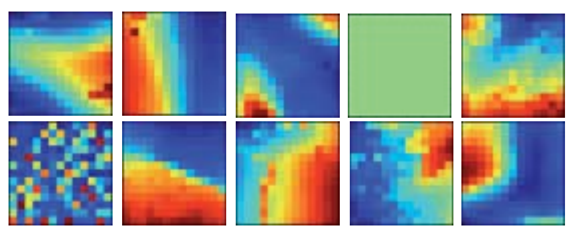
Sparse Representation

- Potential weakness of weighted averaging
  - sensitive to blunders, systematic artifacts
- Alternative fusion algorithm
  - work with DEM **patches** instead of single height values
  - represent local terrain shape as **sparse** sum of basis patches
  - learn the basis from ground truth terrain data
  - hope that the prior information suppresses implausible shapes





Fusion Weights

- Theory
  - weights are proportional to the accuracy
  - error propagation for 2 direct observations of 1 unknown

$$w_A = \frac{\sigma_B^2}{\sigma_A^2 + \sigma_B^2} \qquad w_B = \frac{\sigma_A^2}{\sigma_A^2 + \sigma_B^2}$$

- What is given in practice
  - per-point accuracy ... ***rarely***
  - accuracies for a few slope classes ... ***sometimes***
  - a global accuracy ... ***most often***

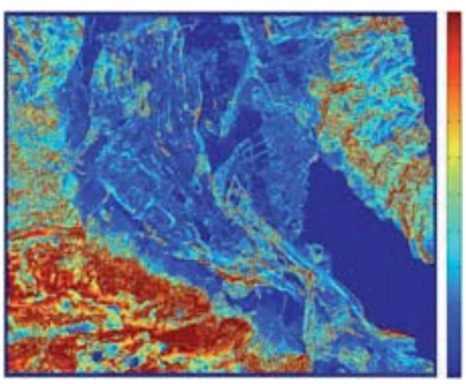
weights / error maps are the Achilles heel of most fusion methods

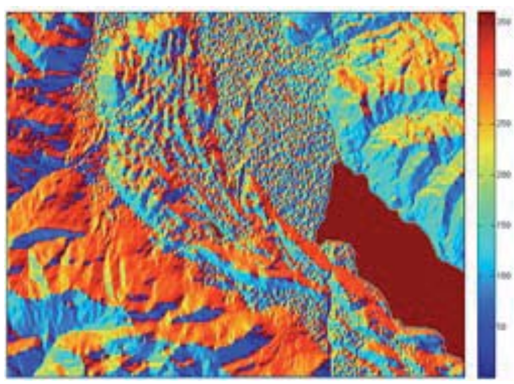
Estimating Weights

- Can we infer useful weights from local DEM properties?
  - **input**: slope, roughness, orientation, (land cover)
  - **output**: expected accuracy of a certain DEM

$$\sigma_Z = f(slope, roughness, aspect, \ldots)$$

  - learn from training data with ground truth (e.g. build histograms)





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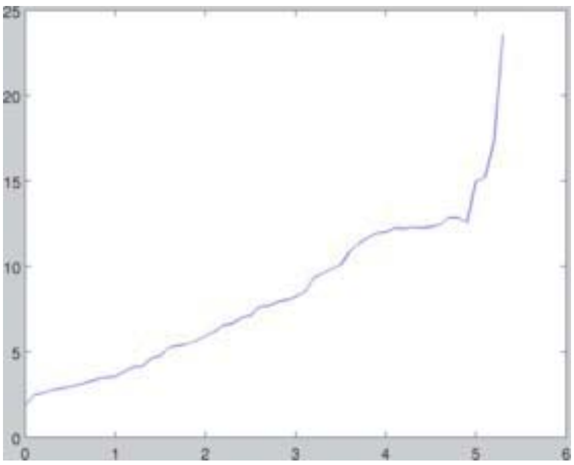
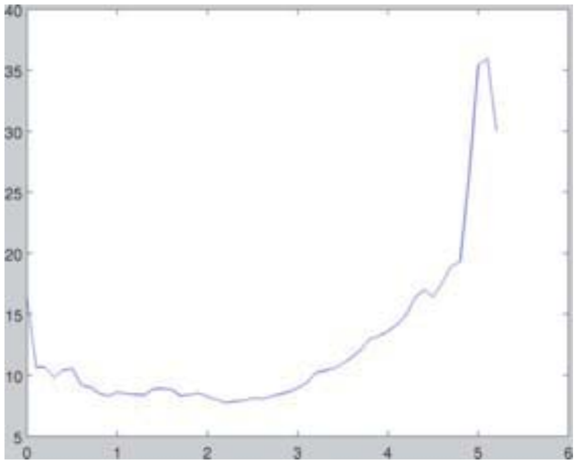
Estimating Weights

- Roughness (entropy)



SRTM (InSAR)



ASTER (stereo)

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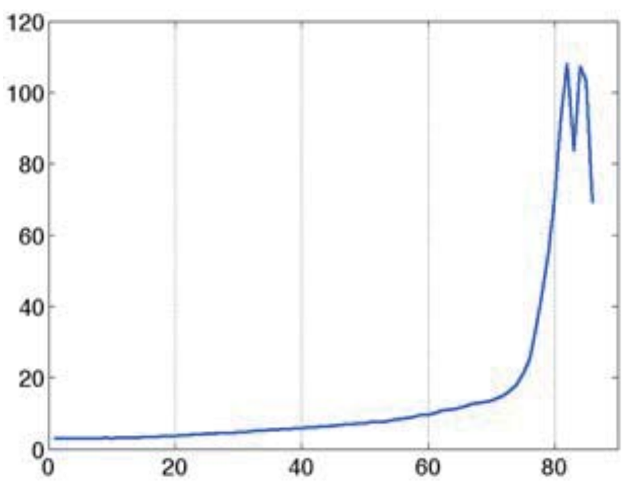
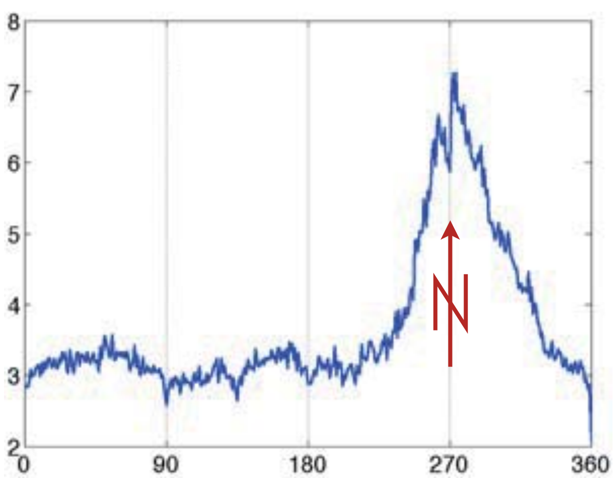
Estimating Weights

- Slope, aspect



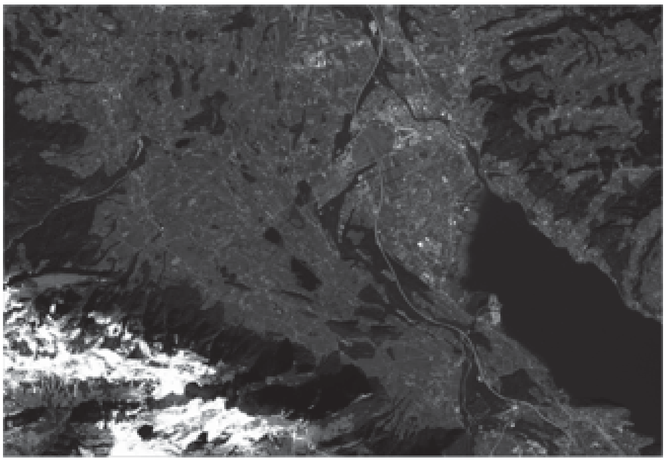
slope (SPOT)

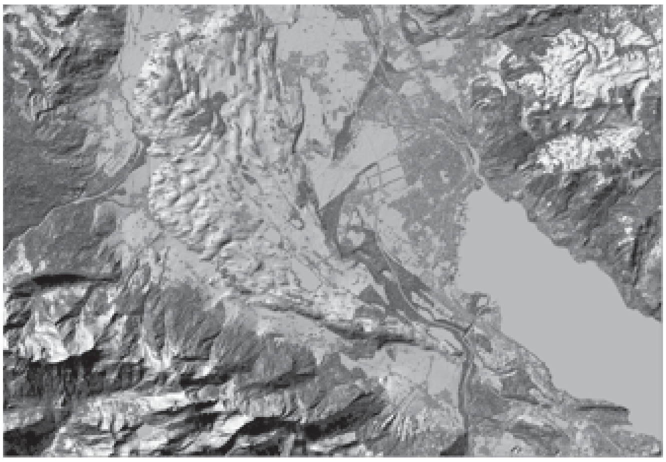


aspect (SPOT)

Results

- Test site: Thun / Switzerland
  - terrain from flat river valley to steep alpine slopes
  - land-cover: lake, city, agriculture, forest, ...





Results

- Test with several DEMs
  - SRTM-C, 90 m
  - ASTER GDEM, 30 m
  - SPOT Reference3D, 30 m
  - ALOS PALSAR L-band (by sarmap s.a.), 15 m
  - ERS C-band (by sarmap s.a.), 25 m

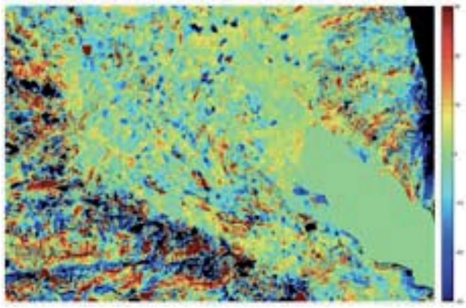
- Ground truth
  - airborne LiDAR (by Swisstopo)
    2 m resolution, ≈2 points / m^2, $\sigma < 0.5 / 1.5$ m

- All DEMs co-registered

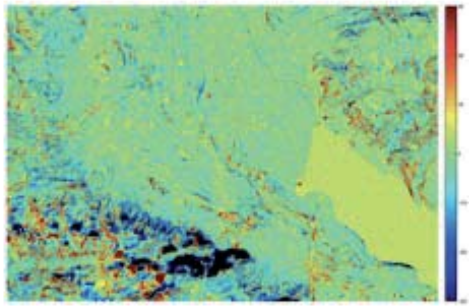
Results

- Fusion ALOS - SPOT

ALOS



SPOT



	mean	RMSE	MAD	max
ALOS	-1.0 m	19.3 m	6.6 m	280.6 m
SPOT	-1.6 m	15.4 m	4.4 m	349.1 m
Fusion SR	-1.0 m	10.9 m	4.2 m	205.1 m
Fusion WA	-1.0 m	10.9 m	4.1 m	202.8 m

theory:

σ = 12.1 m

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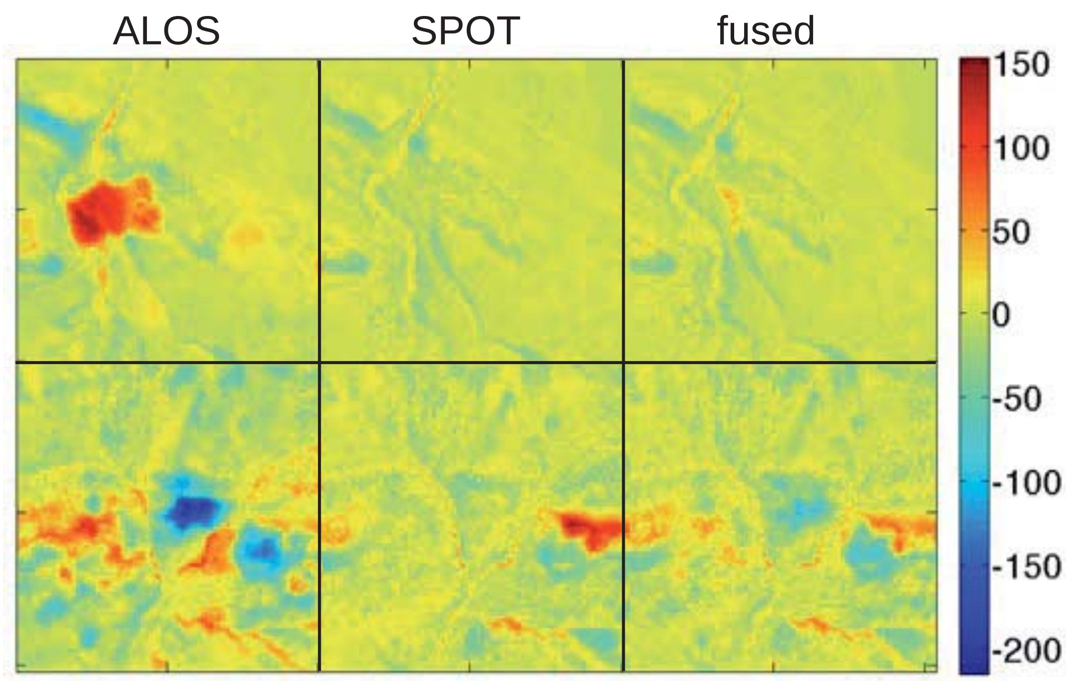
Results

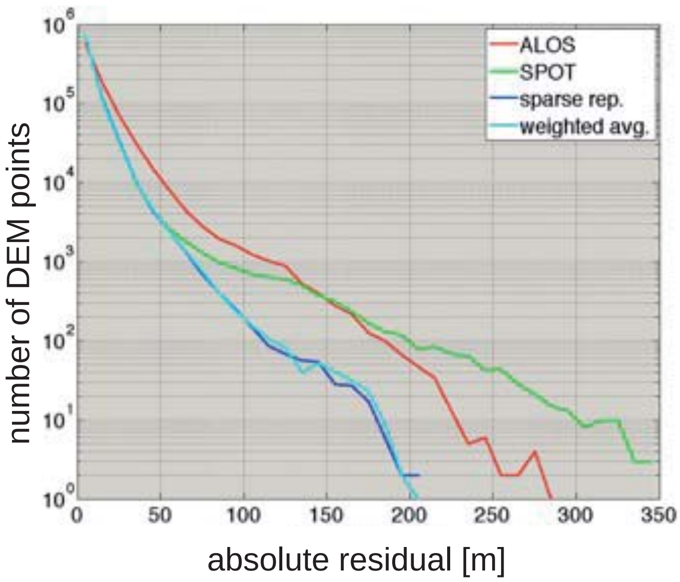
- Examples



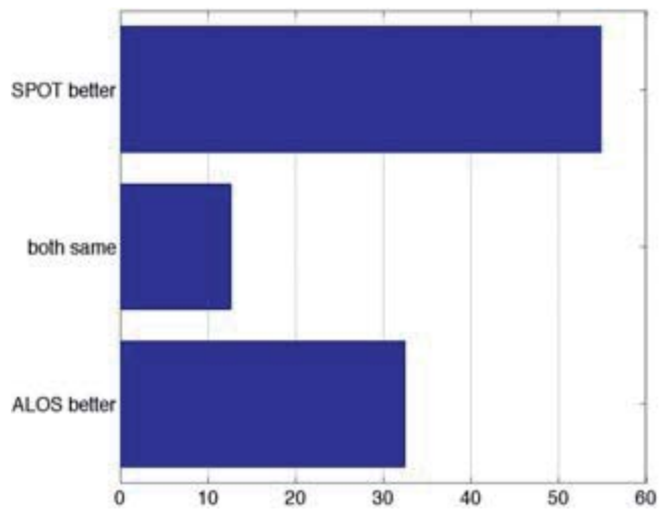
Results

- Error analysis

residual distribution



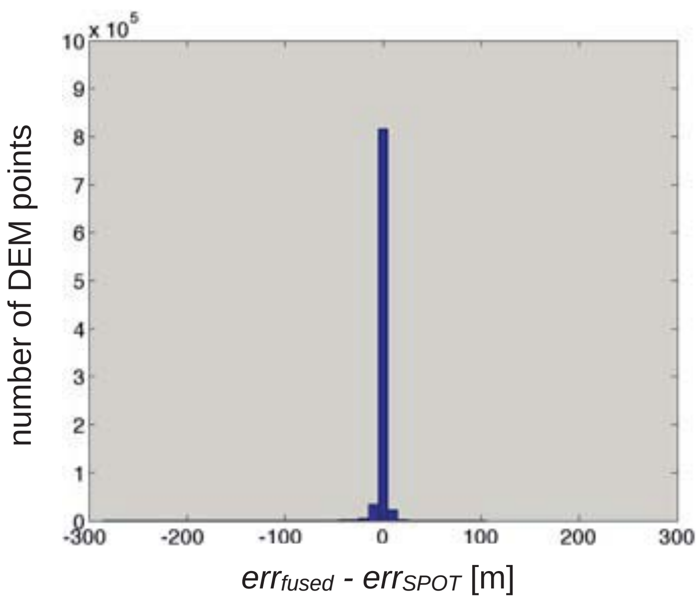
relative quality (rounded to 2m)

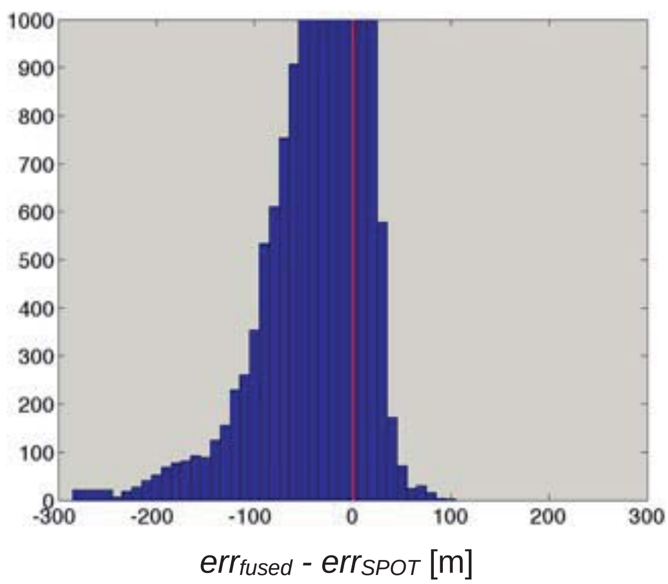


Results

- Error analysis

improvement over SPOT

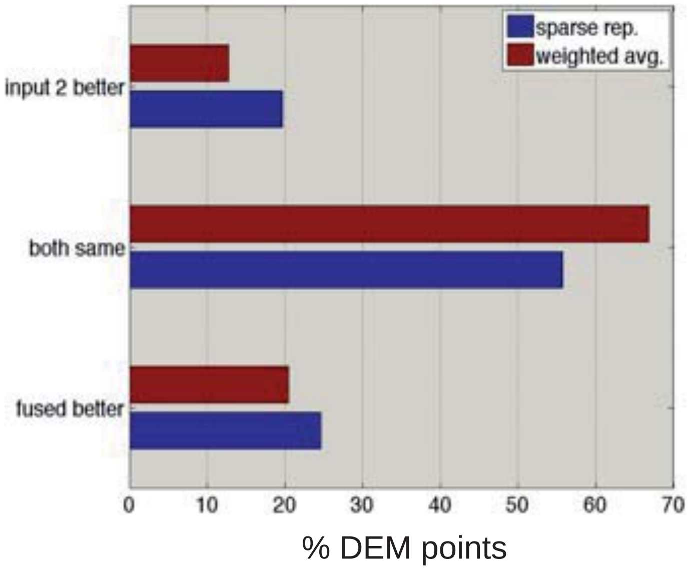




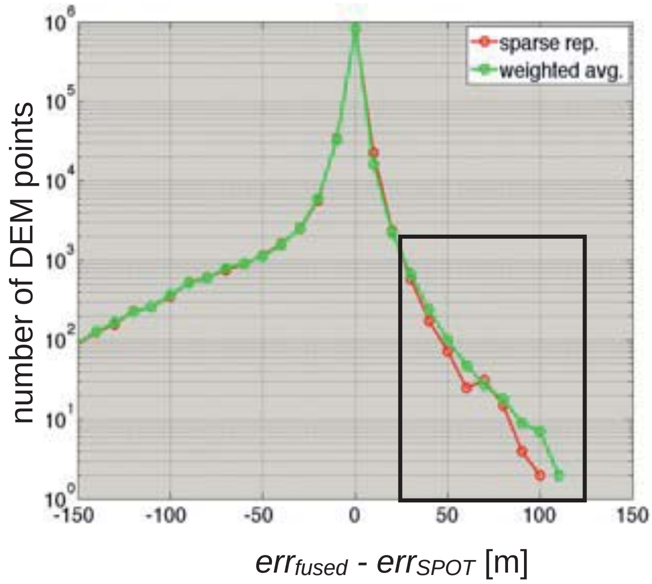
Results

- Weighted Average vs. Sparse Coding

improvement / deterioration



magnitude of changes



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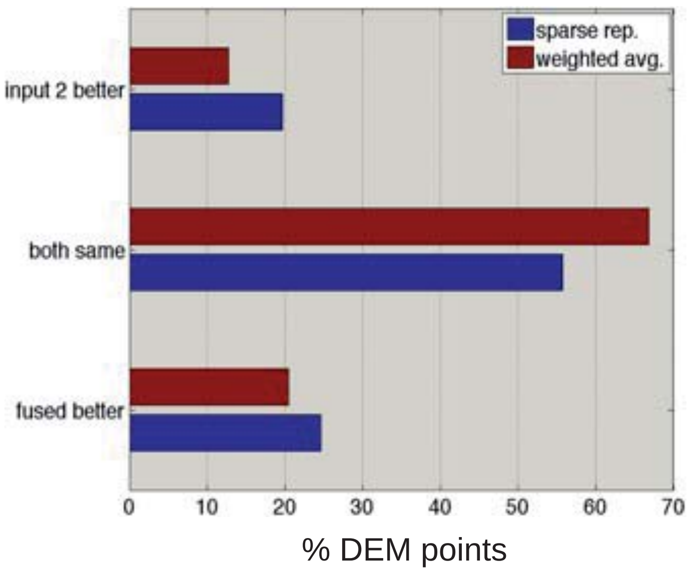
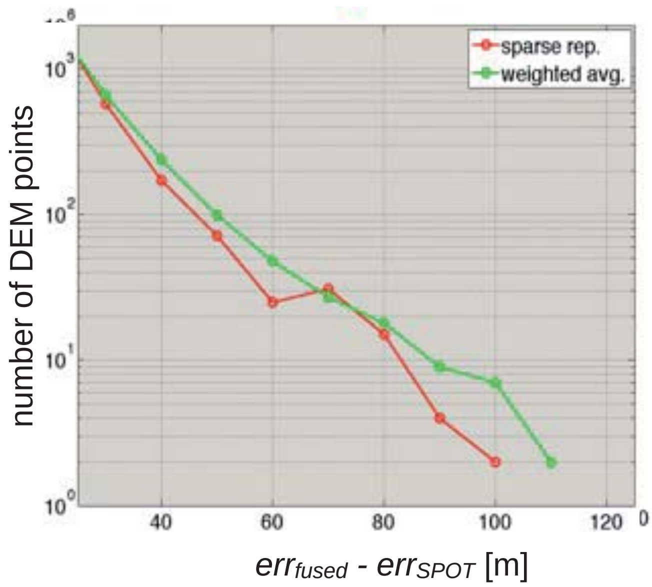
Results

- Weighted Average vs. Sparse Coding

improvement / deterioration

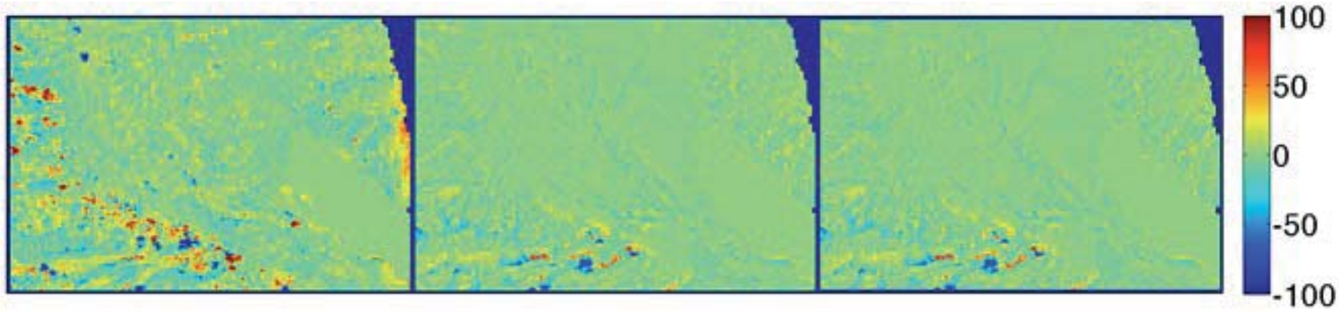


magnitude of changes



Results

- Fusion ALOS - ERS
  - big difference in accuracy, same modality: no improvement (even using per-pixel σ^2 from SAR processing)



	mean	RMSE	MAD	max
ALOS	-1.0 m	19.3 m	6.6 m	280.6 m
ERS	0.1 m	10.8 m	3.1 m	159.2 m
Fusion SR	0.1 m	10.7 m	3.1 m	156.8 m
Fusion WA	0.1 m	10.7 m	3.1 m	159.3 m

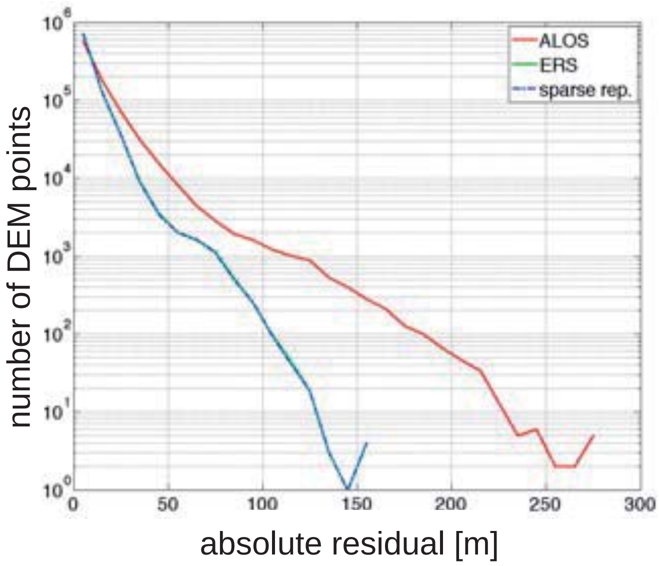
theory:

σ = 9.4 m

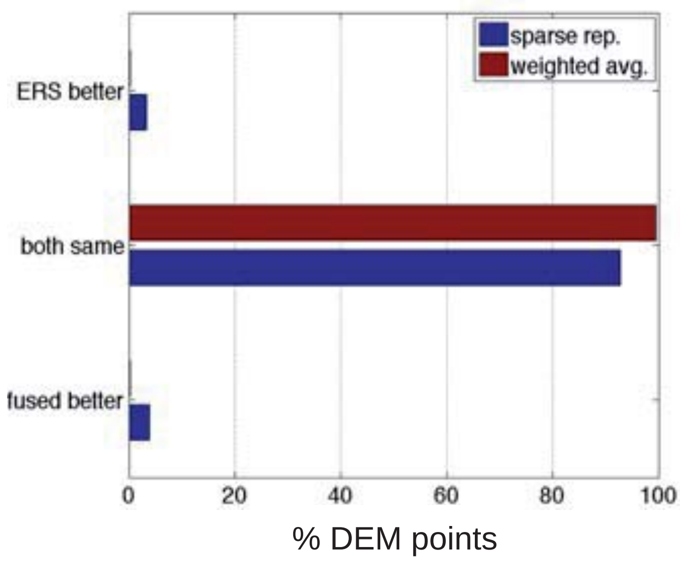
Results

- Fusion ALOS - ERS

residual distribution



improvement / deterioration



Discussion

- Large-scale DEMs have significant errors
  - locally often above claimed specifications
  - always large, spread-out blunders (>100 m)
- Fusion of DEMs reduces the errors
  - improvement near expected values
  - ...but that is sometimes rather moderate ☹
- Main effect is mitigation of blunders
  - complementary sensors better
- Open questions
  - influence of previous processing (smoothing etc.)?
  - what is a “better” DEM? e.g. preserve watersheds...

Thank you! Questions?

- Cast listing

Haris Papasaika-Hanusch

Manos Baltsavias

Stefan Schütz