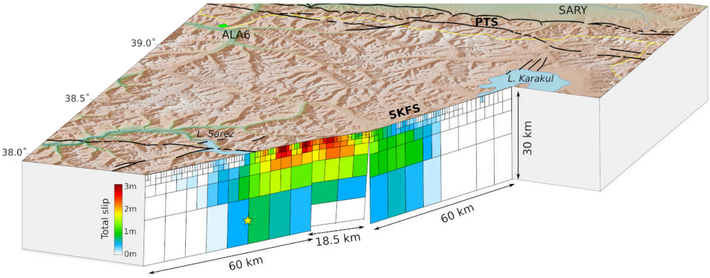


Slip model of the 2015 M7.3 Sarez earthquake 2015

Earthquake Source Modeling

From geodetic observations to distributed slip models

CATENA
CLIMATIC AND TECTONIC NATURAL HAZARDS IN CENTRAL ASIA

Federal Ministry of Education and Research

CLIENT II
International Partnerships for Sustainable Innovations

Sabrina Metzger

GFZ
Helmholtz-Zentrum POTSDAM

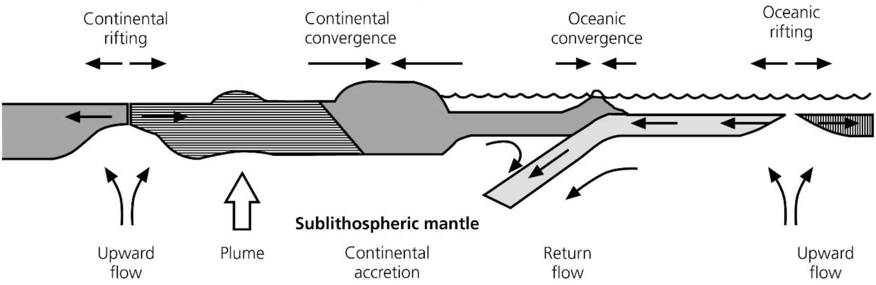
Surface deformation caused by earthquakes

After the 1906 San Francisco earthquake (Bancroft Library, USGS)

Shallow earthquakes move the surface over large areas. The surface displacement is proportional to the static moment $\mathbf{M_0} = \mu \cdot \mathbf{A} \cdot \mathbf{D}$
(μ rigidity, **A** rupture area, **D** mean fault slip)

G.K. Gilbert (USGS photographic library)

Interaction between mantle, crust, oceans and atmosphere

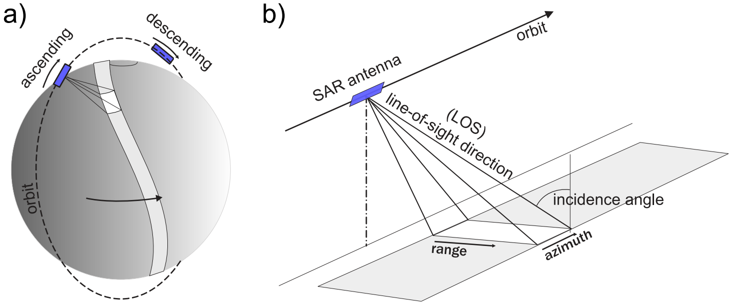


Source: Stein & Wysession (2003), "Introduction to Seismology, Earthquakes and Earth Structure" (find more figures of this schoolbook available here)

Aim of geodetic modeling:

Simulate the kinematics of the crust that best represent our **observations** from the surface by the use of **source models** embedded in an appropriate **medium**.

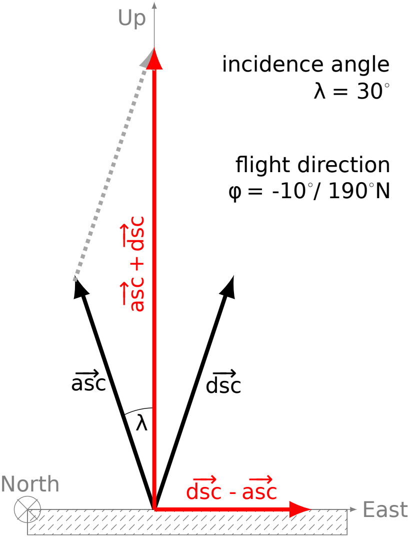
Ascending vs. descending orbit



- The orbit of radar satellites is inclined by $\sim 10^\circ$N
- The antenna is right-looking (incidence angle $\sim 30^\circ$)
- Normalized line-of-sight (LOS) direction in ENU:

$$\hat{n}_{asc} = \begin{pmatrix} -\cos\phi \sin\lambda \\ \sin\phi \sin\lambda \\ \cos\lambda \end{pmatrix} \approx \begin{pmatrix} -0.4 \\ -0.1 \\ 0.9 \end{pmatrix}, \text{ and } \hat{n}_{dsc} \approx \begin{pmatrix} 0.4 \\ -0.1 \\ 0.9 \end{pmatrix}$$

Combining ascending and descending data



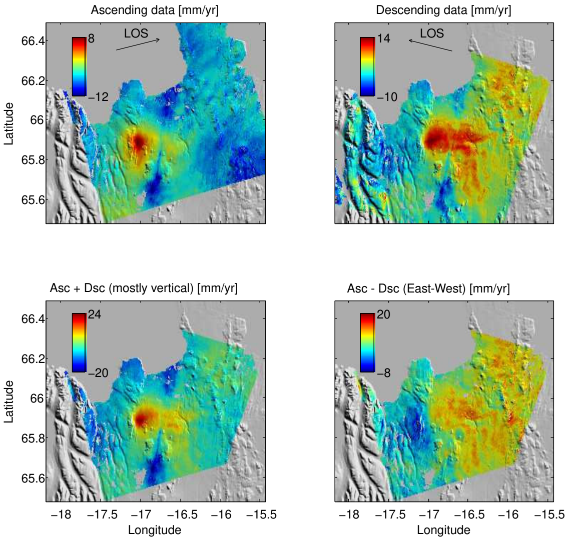
- East-West component:

$$\hat{n}_{dsc-asc} = \begin{pmatrix} -1.0 \\ 0.0 \\ 0.0 \end{pmatrix}$$

- Vertical component (plus minor N-S):

$$\hat{n}_{dsc+asc} = \begin{pmatrix} 0.0 \\ -0.1 \\ 1.0 \end{pmatrix}$$

Example from North Iceland



- Combine ascending and descending InSAR data
- Volcanic signal

→ mostly uplift

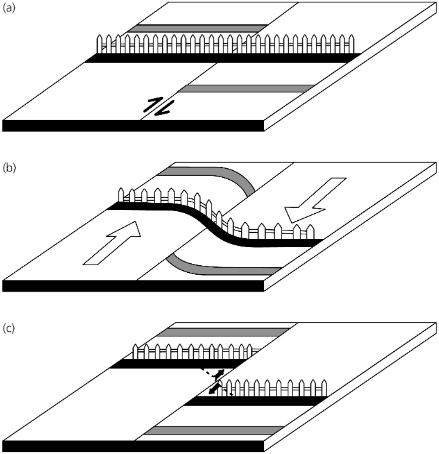
- Plate-motion

→ mostly horizontal

S. Metzger, PhD Thesis, 2012

The seismic cycle

Bird's view



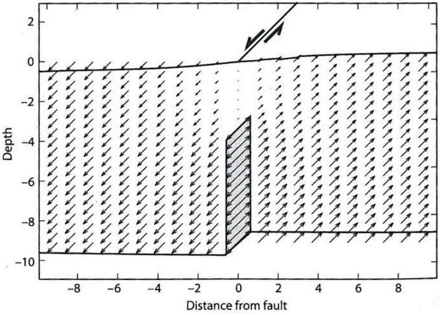
Stein & Wysession, 2003

a) Full relaxed status at T_0
b) Fault loading: interseismic state
c) Fault unloading: co-seismic rupture and post-seismic relaxation

The seismic cycle

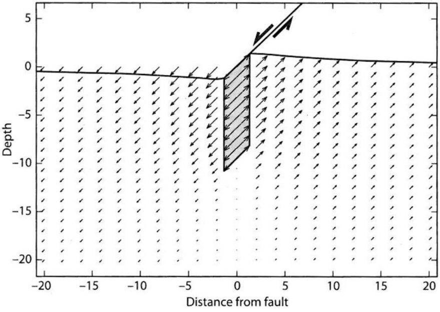
Side view

Loading state



Unloading state

Segall, 2010



Assumptions:

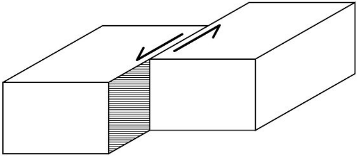
- Segment depth: $x - \infty$ meter
- Slip: milimeters
- ΔT =years

Assumptions:

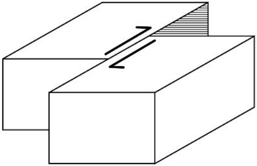
- Segment depth: $0 - x$ meter
- Slip: meters
- ΔT = seconds

Fault slip types

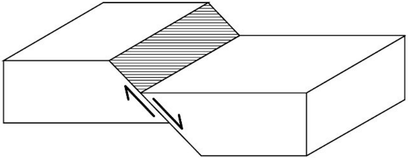
λ: rake angle, i.e., direction of slip on plane



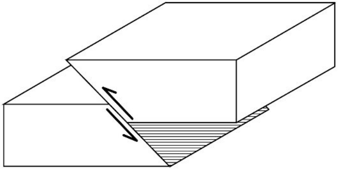
Left-lateral strike-slip fault
($\lambda = 0°$)



Right-lateral strike-slip fault
($\lambda = 180°$)



Normal dip-slip fault
($\lambda = -90°$)

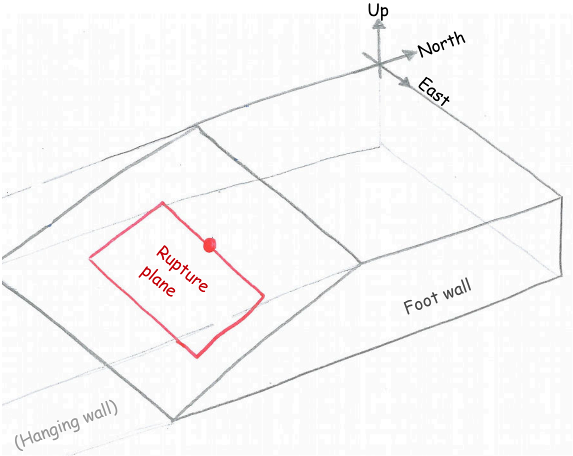


Reverse dip-slip fault
($\lambda = 90°$)

Stein & Wysession, 2003

Rectangular Dislocation after Okada (1985)

Rupture plane and slip defined by 9 parameters "*m*"



Dimension

1. length [km]
2. width [km]
3. depth [km]

Orientation

4. dip from hor. [°]
5. strike from North [°]

Location

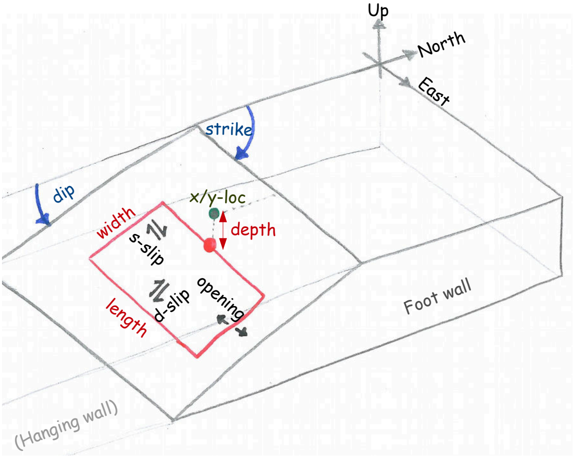
6. x/East [km]
7. y/North [km]

Slip

8. strike slip [m]
9. dip slip [m]
10. opening [m]

Rectangular Dislocation after Okada (1985)

Rupture plane and slip defined by 9 parameters "m"



Dimension

1. length [km]
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4. dip from hor. [°]
5. strike from North [°]

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6. x/East [km]
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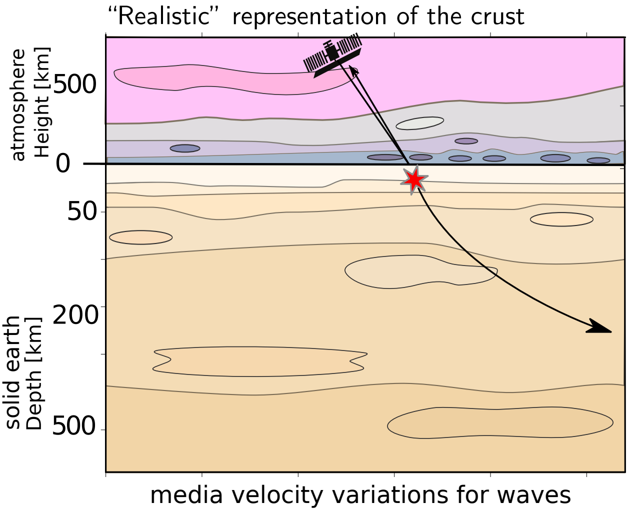
Slip

8. strike slip [m]
9. dip slip [m]
10. opening [m]

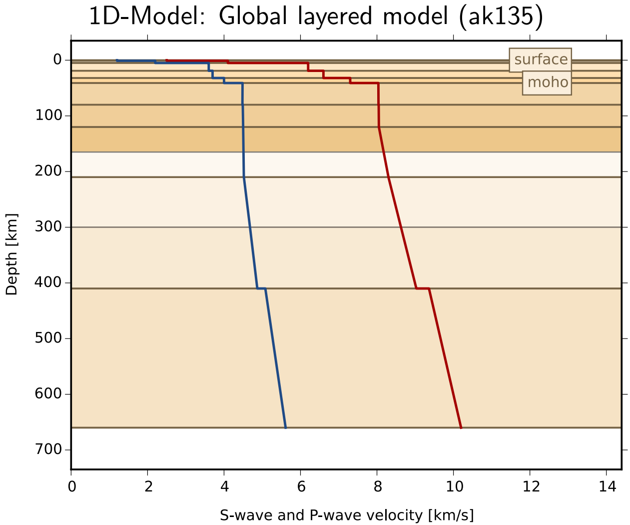
Earth model

Representation of the Earth's crust



Earth model

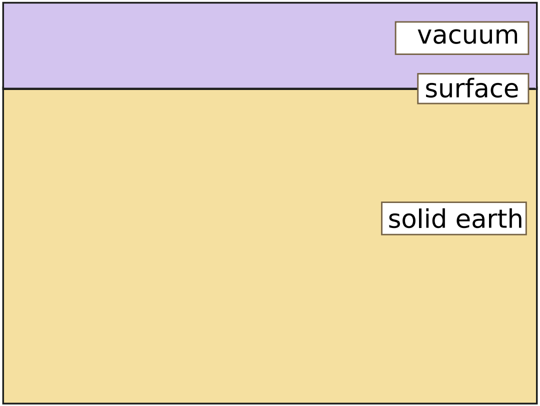
Representation of the Earth's crust



Earth model

Representation of the Earth's crust

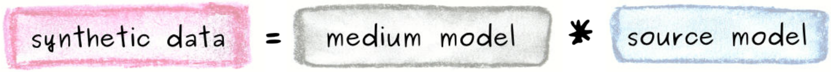
0D-Model: Elastic half space

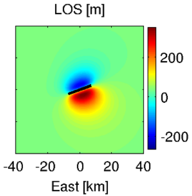


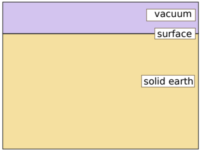
Most convenient model for upper crust earthquakes. Subduction earthquakes require an additional visco-elastic layer.

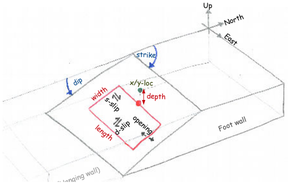
Green's functions "G"

"System response" to given slip in a given medium. ("G" is basically a set of physical equations.)









Forward models

$d_{\text{synth}} = G(m)$

- **predict** surface response d_{synth} for any rupture parameters m
- Used in **non-linear** problems

Inverse models ("Least squares")

$m = (G^T G)^{-1} G^T d_{\text{obs}}$

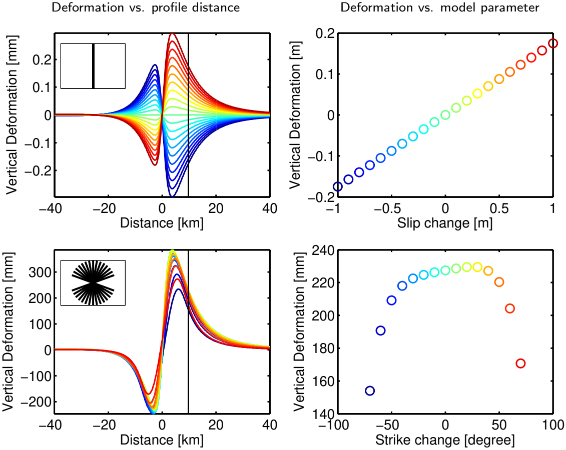
- **infer** rupture parameters m from any given surface response d_{obs}
- Used in **linear** problems

Linear vs. non-linear problems

Examples

Varying fault slip
Surface response is linearly dependent

Varying fault strike
Surface response is non-linearly dependent



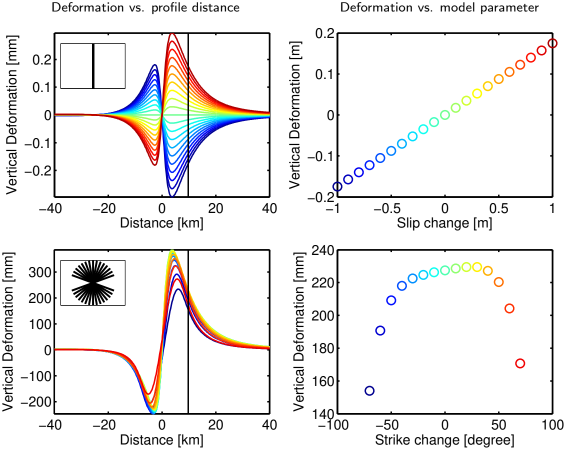
Known fault geometry ⇒ linear problem ⇒ Inversion
Unknown fault geometry ⇒ non-linear problem ⇒ Direct search

Linear vs. non-linear problems

Examples

Varying fault slip
Surface response is
linearly dependent

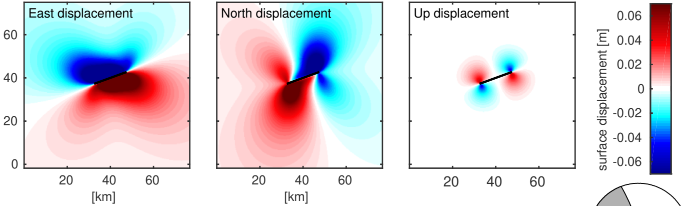
Varying fault strike
Surface response is
non-linearly dependent

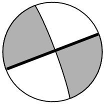


Known fault geometry ⇒ linear problem ⇒ Inversion
Unknown fault geometry ⇒ non-linear problem ⇒ Direct search

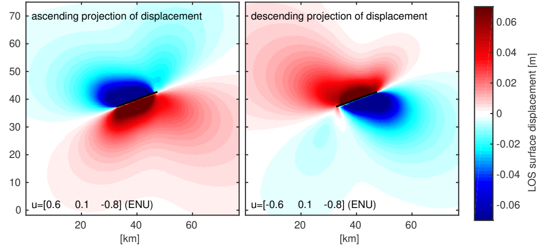
Forward model

Strike-slip earthquake





Projection to Line-of-sight of InSAR



Dimension

1. length: 15 km
2. width: 10 km
3. depth: 0.5 km

Orientation

4. dip: 90°
5. strike: 70°

Location

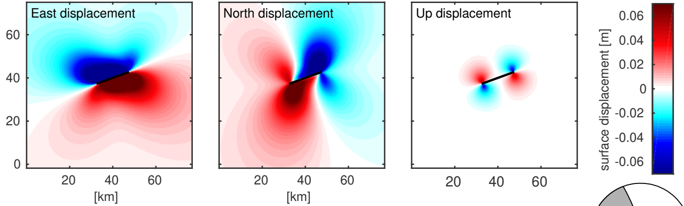
6. x/East: 40 km
7. y/North: 40 km

Slip

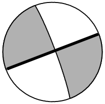
8. strike slip: -0.6 m
9. dip slip: 0 m
10. opening: 0 m

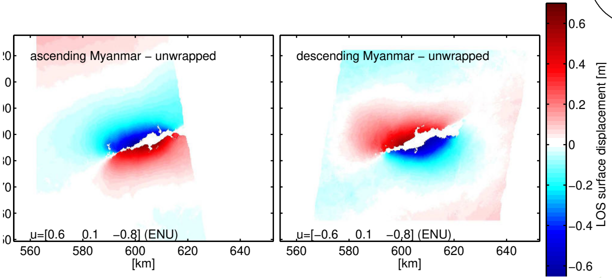
Forward model

Strike-slip earthquake



Projection to Line-of-sight of InSAR





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Slip

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9. dip slip: 0 m
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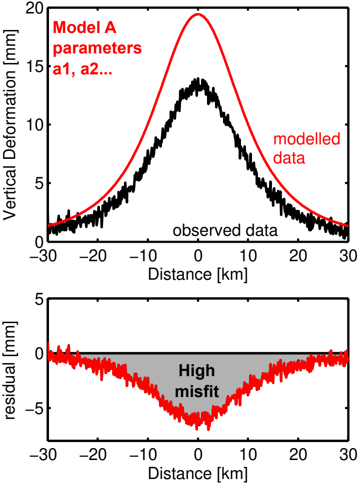
Direct search

Finding best-fit model parameters by minimizing the "misfit-function"

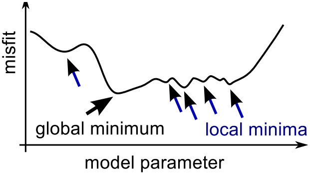


(Lecture material S. Metzger and H. Sudhaus)

Optimization algorithms

Find best-misfit for N model parameters

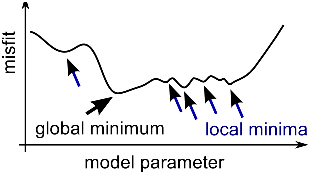
Misfit for one parameter



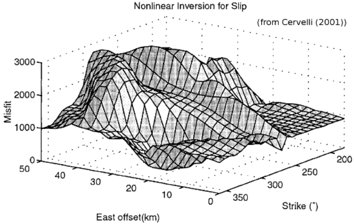
Optimization algorithms

Find best-misfit for N model parameters

Misfit for one parameter



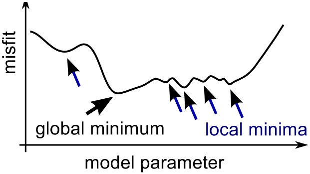
Misfit two parameters



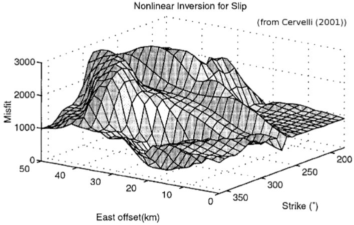
Optimization algorithms

Find best-misfit for N model parameters

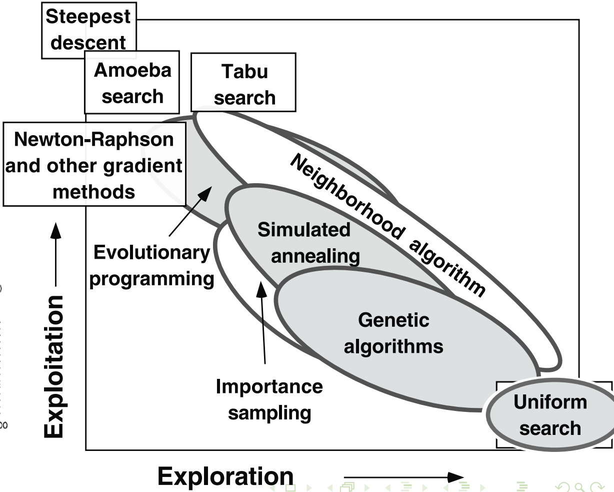
Misfit for one parameter



Misfit two parameters



Different optimization algorithms

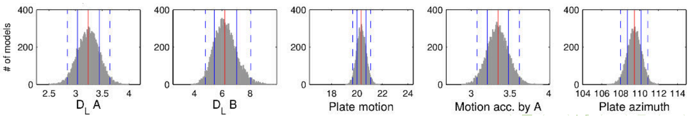


Error propagation

How do data uncertainties influence the model?

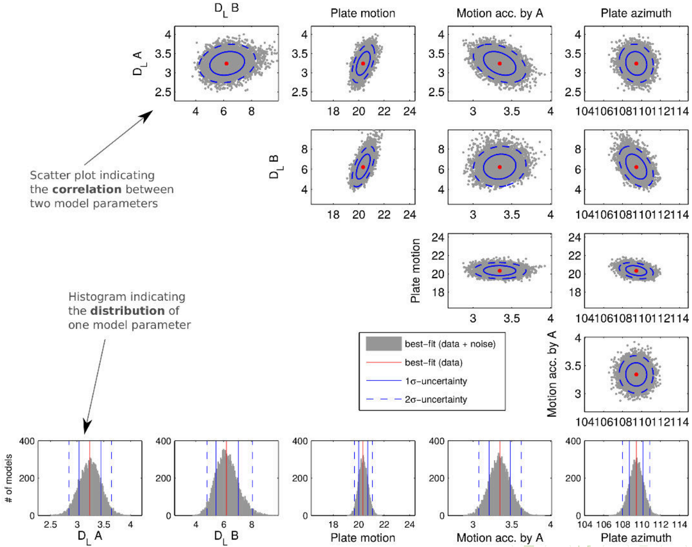
- Apply data weights before calculating the mis-fit: Good data points obtain high weights and thus must be fit better than poor data points
- Data error propagation: Realize ∼1000 best-fit models with modified input, e.g.
  - add random data noise (scaled by the individual data uncertainties)
  - exclude random data subsets (boot-strapping)

⇒ Best-fit model parameters become distributed (below). Poorly constrained model parameters appear more distributed than well-constraint model parameters.

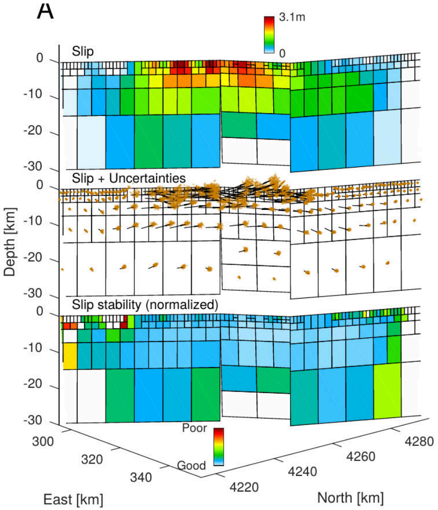


Model parameter correlation

Which parameter influence other parameters?



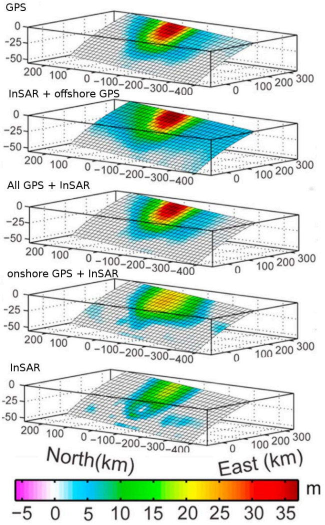
Advanced modeling



- combine multiple fault segments with different orientation
- segment size defined observation distance
- slip uncertainty based on data uncertainty

Metzger et al. (2017)

Do not trust a model!



2011 M9 Tohoku-Oki event; Feng & Jónsson, 2012

- A model is only *one* representation of the reality, how it *could* be.
- The model result depends on
  - quality and spatial distribution of input data (see offshore EQ example to the left)
  - model assumptions (elastic half-space!, rectangular dislocation!!)
- Kinematic models may not be physically plausible, i.e. they ask for a large vertical slip on a vertical plane.

⇒ Do not trust a model, always consider its assumptions and data/model uncertainties!

Take-home messages

- If several 1-dimensional InSAR observations with different look angles are combined they provide three-dimensional displacements.
- Earthquake slip models explain surface observations with kinematic processes in the crust. Rectangular dislocation models in a 1- or 2-layered medium are most popular.
- Best-fit model parameters are obtained by minimising the misfit between synthetic and observed surface deformation.
- If the model response is linear, the best-fit model parameters are obtained by least-square inversion. If it is non-linear, the whole model parameter space must be searched.
- Good models reflect data and model uncertainties.

References to open-source modeling software

- [Pyrocko]: Python-based seismologic software packages, but many tools are also usable for geodetic modeling, e.g.:
  - [Talpa]: Interactive static displacement modeling – play around with fault model parameters and see how the surface deformation looks like
  - [Kite]: InSAR displacement analysis and post-processing (data-subsampling and weighting)
  - [Beat]: Bayesian Earthquake Analysis Tool for slip model optimization
  - [Grond]: probabilistic slip model optimization for seismic and geodetic data.
- [GBIS] (Matlab): Geodetic Bayesian Inversion Software
- [disloc] (written in C): rectangular dislocation kernel, based on Okada (1985)
- Non-rectangular slip models (Matlab): Triangular and compound dislocation kernels that can also be used to model volume changes (e.g. volcanoes).
- Simulated annealing (Matlab): Matlab-code of Peter Cervelli (1998) (ask me!), that first samples the parameter space randomly and then favors samples near global minimum.