An evolutive linear kinematic source inversion

Inverting while recording: reducing time-space ambiguity

Sanchez-Reyes H. S.[1]
with Brossier R.[1], Cruz-Atienza V. M.[4], Métivier L.[1,3], Tago J.[2] and Virieux J.[1]

13th December 2018, 9:15 - 9:30

1. Institut des Sciences de la Terre, UGA, France
2. Facultad de Ingeniería, UNAM, Mexico
3. Laboratoire Jean Kuntzmann, UGA, France
4. Instituto de Geofísica, UNAM, Mexico

2018 AGU Fall Meeting

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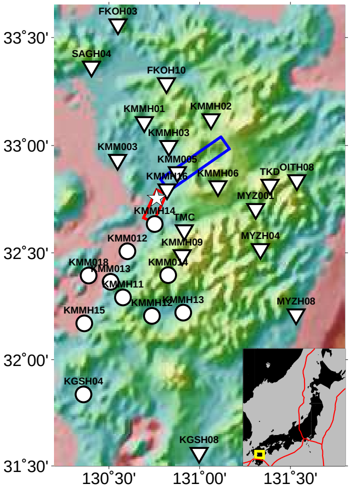
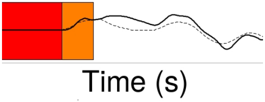
It is hard to follow the meeting when you can not see what is going on the screen!

2016 M_W7.0 Kumamoto earthquake



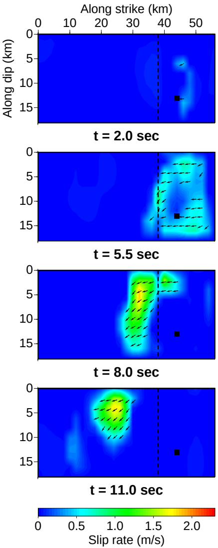
Inverting progressively increasing data time-windows



While still:

- respecting positivity
- enforcing causality
- including possible prior information

Inverted source history



Outline

Motivation

Methodology description (2016 M_w7.0 Kumamoto earthquake)

Conclusions and perspectives

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Motivation: time-space ambiguity

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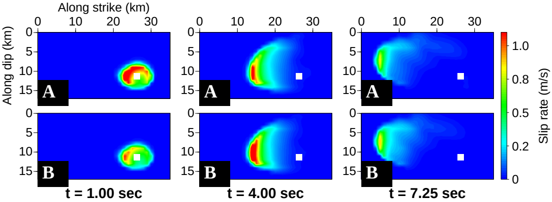
Conclusions and perspectives

Imagine two different rupture histories (**A** and **B**)!



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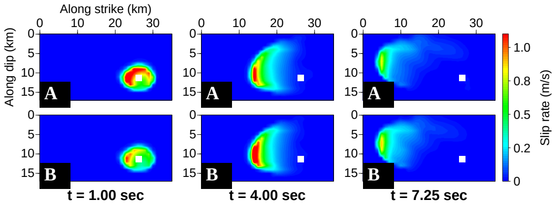
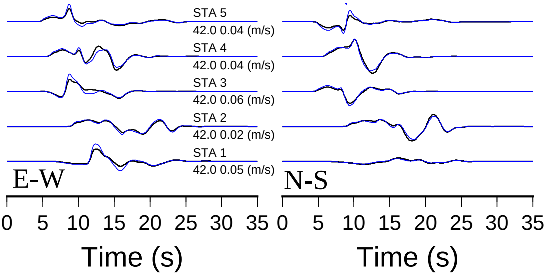


Which data sets are slightly different ($\leq$ 1Hz):

Rupture A vs Rupture B



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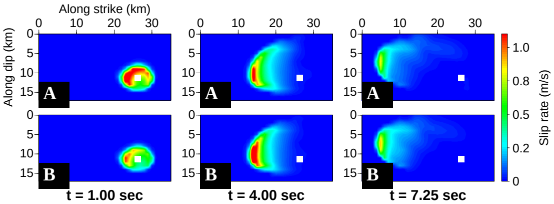

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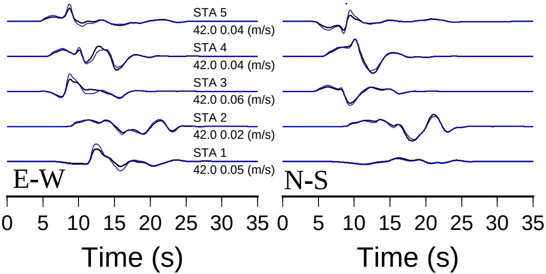
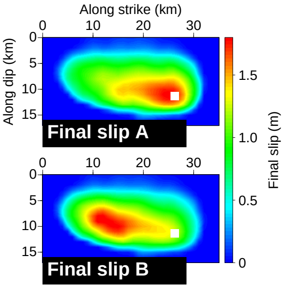


Different final slip distributions



Motivation:

Develop an inverse method able to reconstruct the correct source history by assimilating and inverting the data in a different way.

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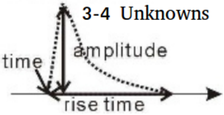
Non-linear



Few parameters per node:

- starting time
- duration
- max amp
- angle

Advantage:

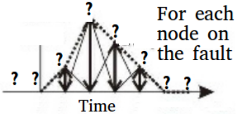
Explicit physical parametrization

Disadvantage:

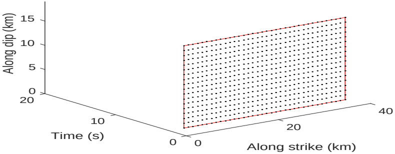
Strong assumptions impacting results

With drawbacks when assessing uncertainties

Linear



Search for time-space history (3D)



Disadvantage:

Large number of unknowns (tens of thousands)

Advantage:

Good for uncertainty assessment

☞ 1. Linear forward modeling:

$$\underbrace{\underbrace{\underline{d}}_{\textit{seismograms}} = \underbrace{\underline{\underline{G}}}_{\text{wave propagator}} * \underbrace{\underline{m}}_{\text{rupture model}}}_{\text{Linear relation}}$$

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☞ 2. L2 Norm misfit function:

$$\mathcal{C}(\underline{m}) = \text{Data misfit} + \overbrace{\begin{array}{c}\text{Model misfit}\\ \text{based on prior info}\\ \text{and rupture physics}\end{array}}^{\textbf{Very important}}$$

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3. Newton equation using data gradient & model gradient: $\underline{\gamma} = \underline{\gamma}_{data} + \underline{\gamma}_{model}$

$$\underbrace{\underline{\underline{H}}}_{\text{Hessian}} \underline{\Delta m} = - \underbrace{\underline{\gamma}}_{\textit{Gradient}}$$

Ingredients of this linear time domain formulation

☞ 1. Linear forward modeling:

$$\underbrace{\underline{d}}_{\textit{seismograms}} = \underbrace{\underline{\underline{G}}}_{\text{wave propagator}} * \underbrace{\underline{m}}_{\text{rupture model}}$$

Linear relation

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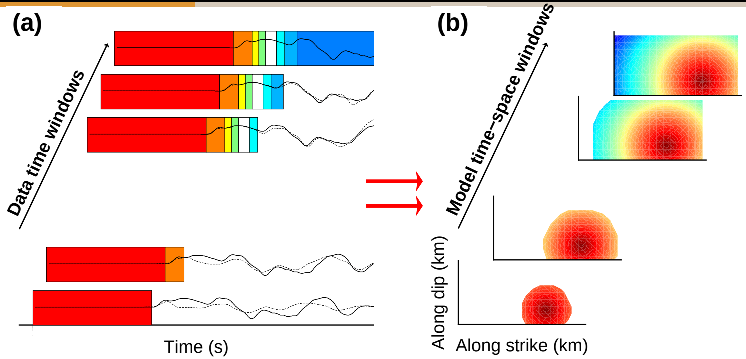
same kernel!

$$\underbrace{\underline{\underline{H}}}_{\text{Hessian}} \underline{\Delta m} = - \underbrace{\underline{\gamma}}_{\textit{Gradient}} \longrightarrow \underline{\gamma}_{data} = \underbrace{\underline{\underline{G}}}_{\text{wave propagator}} * \text{Data residuals}$$

Data assimilation and time-space model expansion



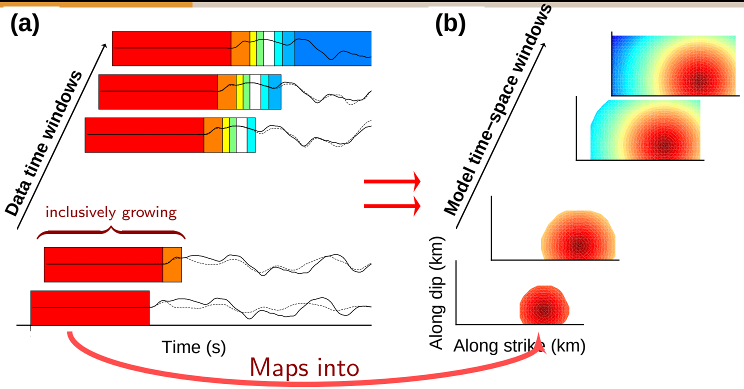
Assumptions:

- Previous calibration of data and model time-space windows.
- Requires a synthetic rupture for the calibration.
- Pre-computed Green functions.

Benefits:

- Rough prediction of wave packets to come!
- Only residuals need to be explained!
- Residuals map mostly into the new allowed rupture zone.

Data assimilation and time-space model expansion



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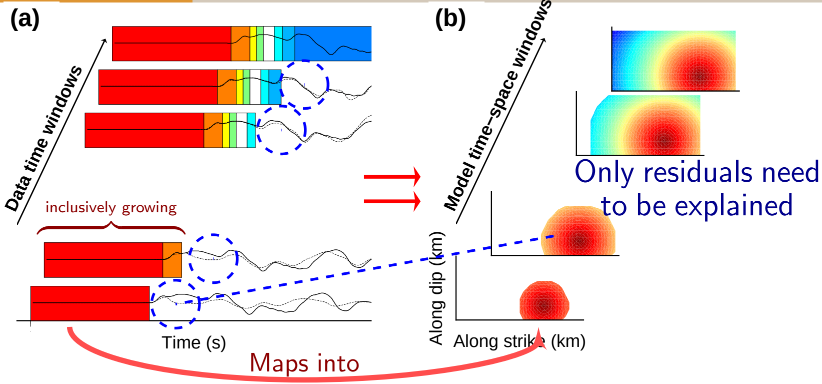

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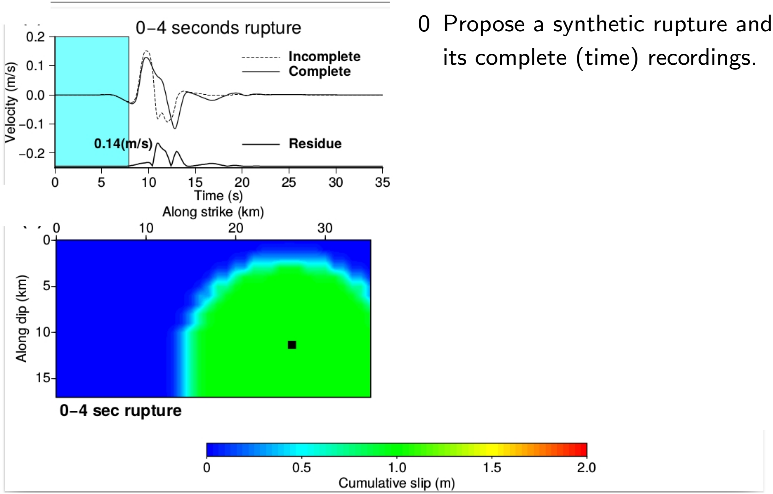
Time windowing pre-calibration is required

Given a source/receiver geometry it is possible to define our data time windows and time-space model growth using a simple synthetic rupture.



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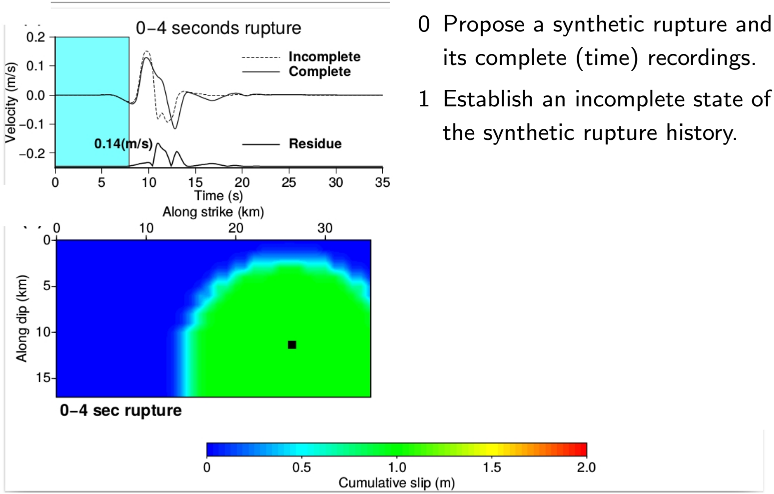

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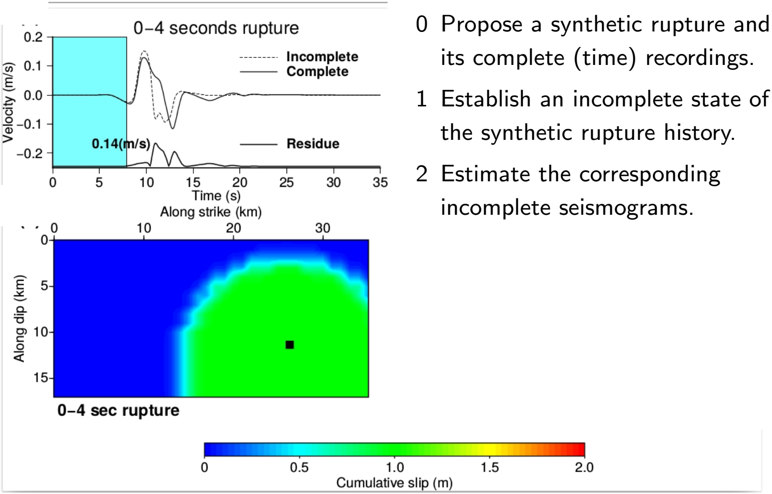

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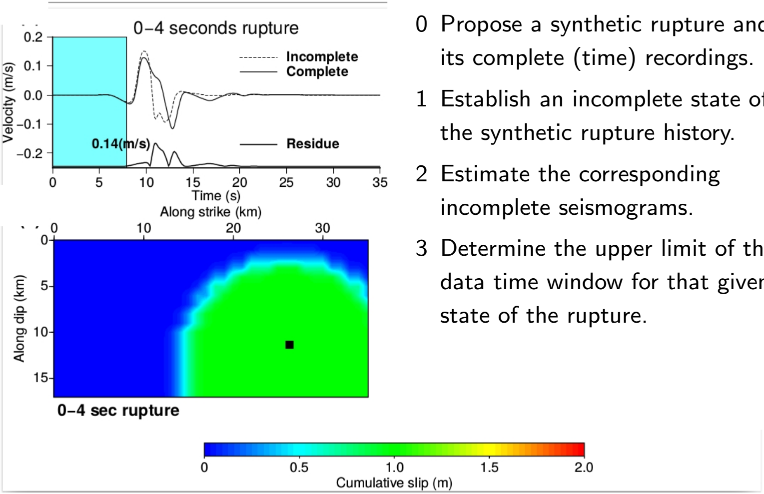

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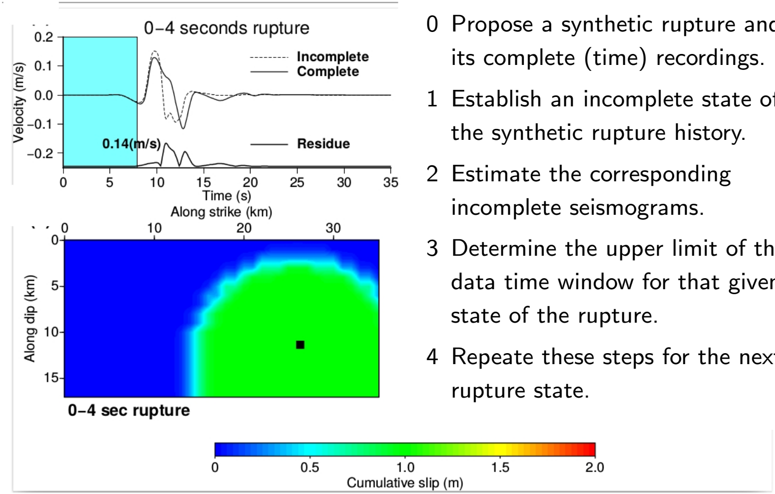

0 Propose a synthetic rupture and its complete (time) recordings.

1 Establish an incomplete state of the synthetic rupture history.

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3 Determine the upper limit of the data time window for that given state of the rupture.

4 Repeate these steps for the next rupture state.

Rupture physics are not yet included!

$$\mathcal{C}(\underline{m}) = \text{Data misfit}_{|_{t_0}^{t_1}}$$

Model regularization and gradient preconditioning ARE REQUIRED.

Data driven model preconditioning:

- Depth preconditioning to mitigate surface acquisition footprint.
- Gradient smoothing to enforce spatial coherence.

Model regularization:

- Upper and lower bounds of rupture velocity.
- Expected zones of minimum slip (fault edges).
- Min and Max slip rate bounds.
- Other prior information (rake angle).

$$\mathcal{C}(\underline{m}) = \text{Data misfit} + \overbrace{\text{Model misfit based on prior info and rupture physics}}^{\textbf{Very very important}}$$

Preconditioning and regularization can also evolve during the inversion!

Inversion results from previous data windows can be used to enhance our prior information.

This strategy helps to reduce the footprint of the regularization from the final results.

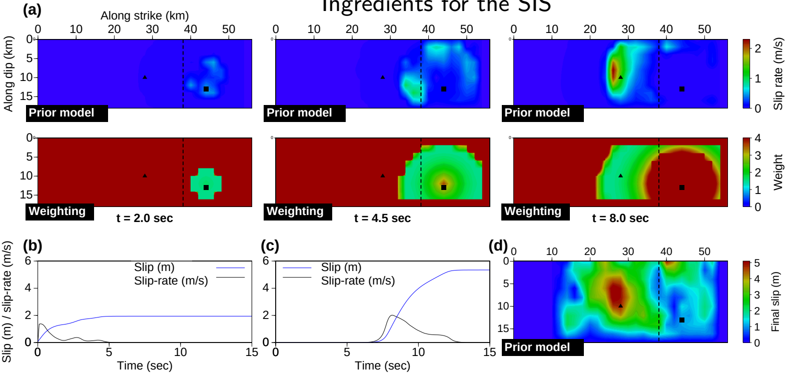
Standard Inversion Strategy (SIS): (**Traditional approach**)

- The full recordings are inverted.
- During the inversion, **NO EVOLUTION** of:

  ⟶ The prior model (reconstructed from Asano and Iwata (2016))
  (other prior model or information can be injected)

  ⟶ and its weigthing (defined based on physics and after several tests).

Ingredients for the SIS



Progressive Inversion Strategy (PIS): (**New approach**)

inspired by Kikuchi and Kanamori (1982)

- Progressively increasing data time windows are inverted.
- The prior model and its weigthing **EVOLVE** during the inversion.

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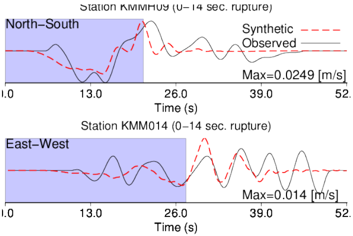

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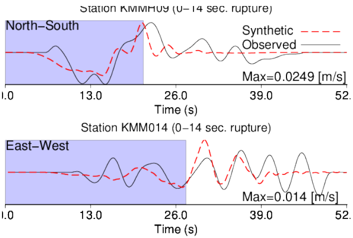
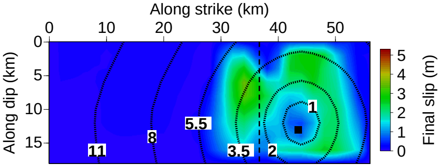
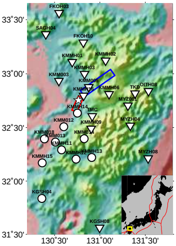


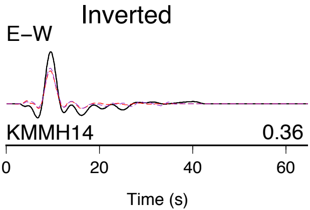
Cummulative slip after 6 seconds



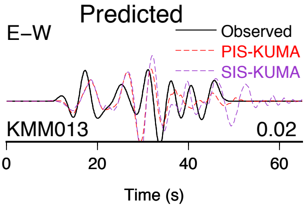
Such changes in the regularization help to reduce its footprint in our results.

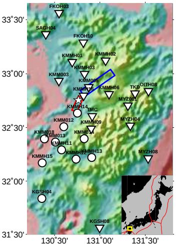


▽ 57 Recordings inverted



○ 33 Recordings predicted





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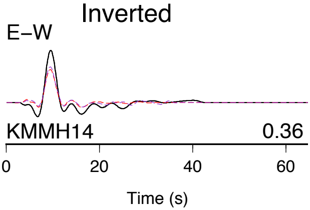
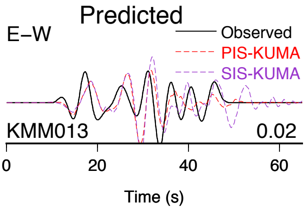
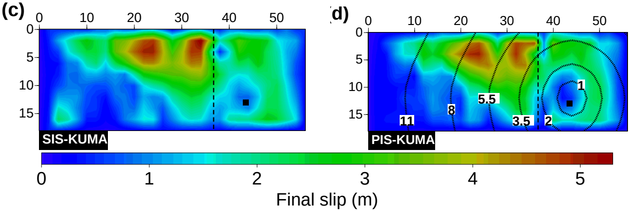
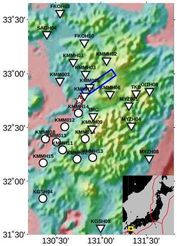






Standard full-time inversion (SIS) VS Progressive Inversion (PIS)



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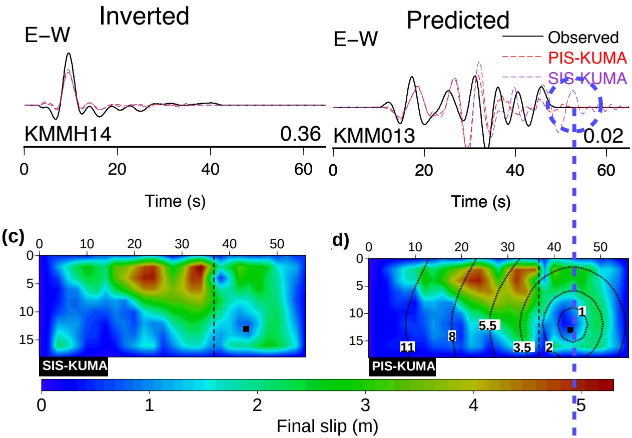
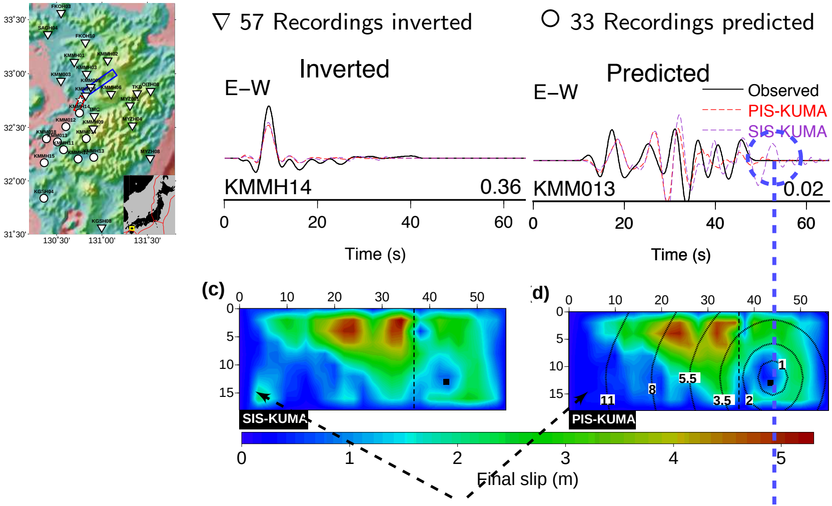


PIS predicts better



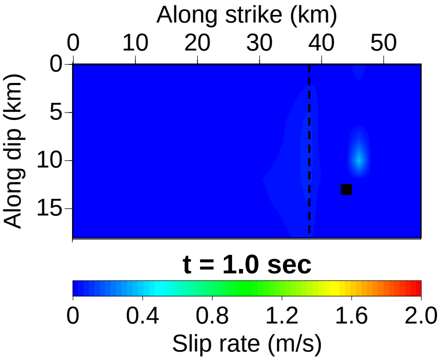
With the same misfit, SIS and PIS lead to different solutions!

PIS predicts better

Outline

Some important conclusions:

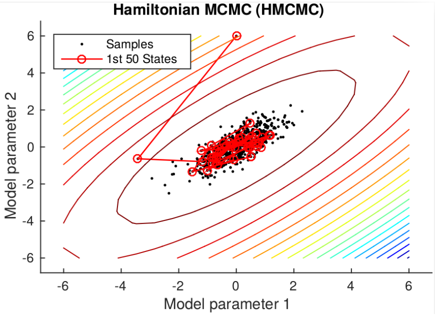
- ☞ Preserving the linearity of the forward problem:
  physics are enforced through model preconditioning/regularization rather than applying model-reduction strategies.
- ☞ Progressive inversion strategy reduces space/time leakage by honoring causality
- ☞ Uncertainty quantification easier with linear forward problem.



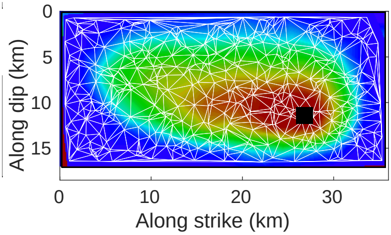
For assessing uncertainties:

- Hamiltonian MCMC (HMCMC): Possible, efficient and attractive.
- Sequential MCMC: Possible and able to handle data-assimilation.
- Reverse Jump HMCMC (RJHMCMC): Possible and very attractive.

How certain are our results?



According to the data, what is the best mesh to use?



Advert: If you want to read more about this work

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JGR

Journal of Geophysical Research: Solid Earth

RESEARCH ARTICLE

10.1029/2017JB015388

An Evolutive Linear Kinematic Source Inversion

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[1]Institut des Sciences de la Terre (ISTerre), Universite Grenoble Alpes, CNRS, Saint-Martin-d'Heres, France, [2]Facultad de Ingeniería, Universidad Nacional Autónoma de México, Mexico City, Mexico, [3]Laboratoire Jean Kuntzmann (LJK), Universite Grenoble Alpes, CNRS, Saint-Martin-d'Heres, France, [4]Instituto de Geofísica, Universidad Nacional Autónoma de México, Mexico City, Mexico, [5]Institut des Sciences de la Terre (ISTerre), Universite Grenoble Alpes, Saint-Martin-d'Heres, France

Key Points:
- An alternative linear inverse formulation for kinematic source reconstruction is presented
- Such formulation can invert progressively growing data time windows while spanning the model space
- Promising advantages of this method are found, thanks to the preservation of causality and sparsity

http://hugosanrocks.github.io/

Thanks for listening!

Immigrants are not "bad hombres"!!

ISTerre

Aki, K. and Richards, P. G. (2002). *Quantitative seismology, theory and methods, second edition*. University Science Books, Sausalito,California.

Asano, K. and Iwata, T. (2016). Source rupture processes of the foreshock and mainshock in the 2016 kumamoto earthquake sequence estimated from the kinematic waveform inversion of strong motion data. *Earth, Planets and Space*, 68(1):147.

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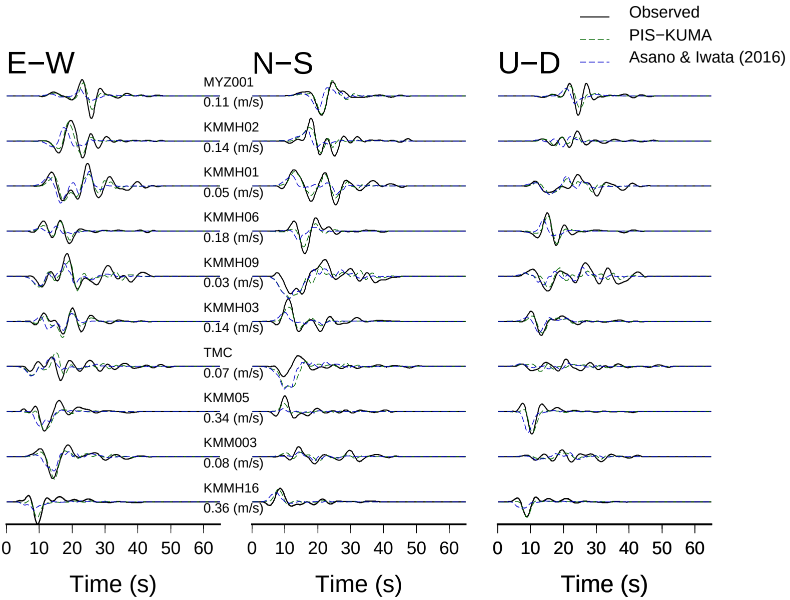
Sánchez-Reyes, H., Tago, J., Métivier, L., Cruz-Atienza, V., and Virieux, J. (2018). An evolutive linear kinematic source inversion. *Journal of Geophysical Research: Solid Earth*, 123.

Prior model (Asano & Iwata, 2016) misfit vs PIS results



PIS Workflow: How it works?