New ideas for earthquake source imaging systems: Networks of seismic arrays and Seismology from space

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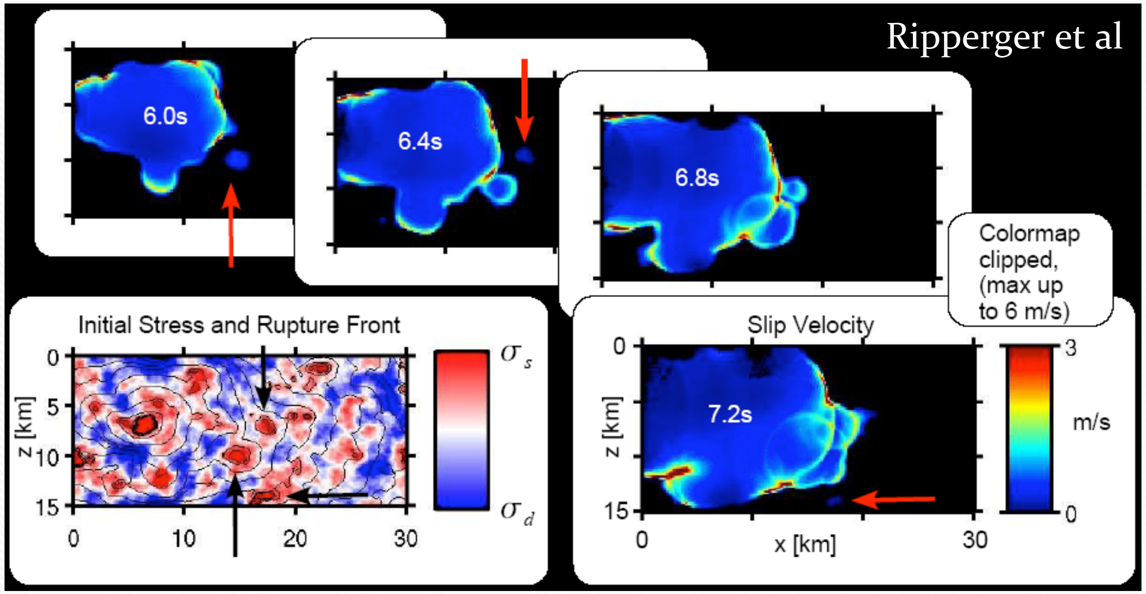
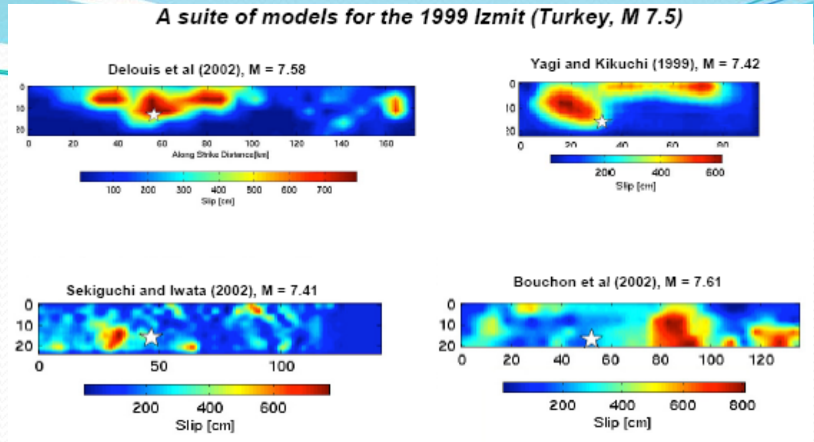
Some open questions about earthquake dynamics

- Earthquake source complexity: geometry and evolution of the rupture front, broad-scale heterogeneity, variability of rupture speed
- Pulse/crack rupture styles: how short are earthquake rise times?
- Fault rheology: which weakening mechanisms are dominant in real faults? Is rupture dominated by rheology or by heterogeneities?

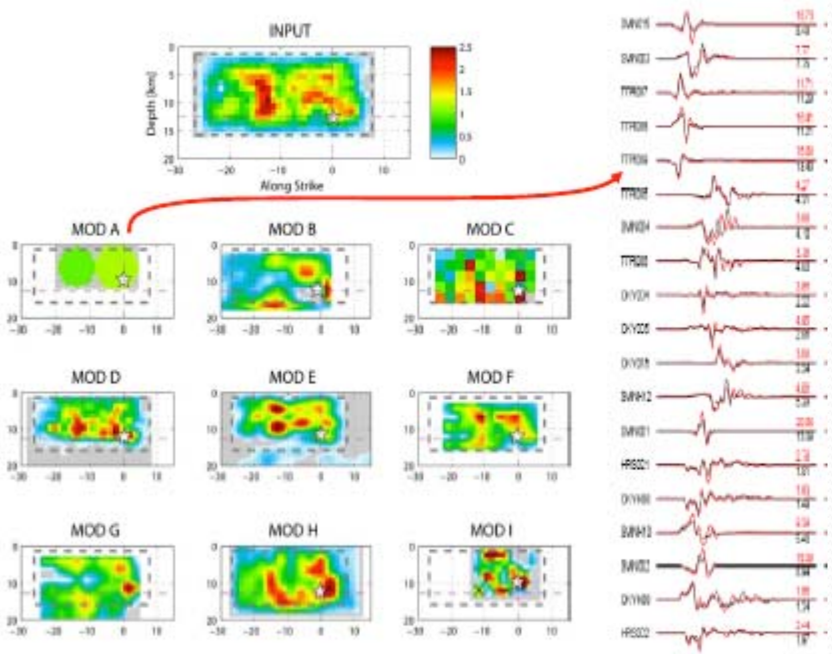


Source imaging today: Intrinsic limitations

- Source inverse problem: retrieve the **space-time distribution of fault slip** from seismological, geodetic, field data
- Due to our poor knowledge of the propagation media at small scales, seismic data is usually exploited in a **limited frequency band** (< 0.5 Hz)
- Data scarcity: **ill-posed inverse problem**, sensitive to regularization and data selection. Different teams often obtain very different models of the same earthquake.
- **Low resolution**: models suffer from limited spatial resolution (> 10 km).
  - Little detail about the friction law can be retrieved
  - Resulting slip models are notoriously heterogeneous but how much of that spatial variability is real?



SIV first blind test results (Mai et al)

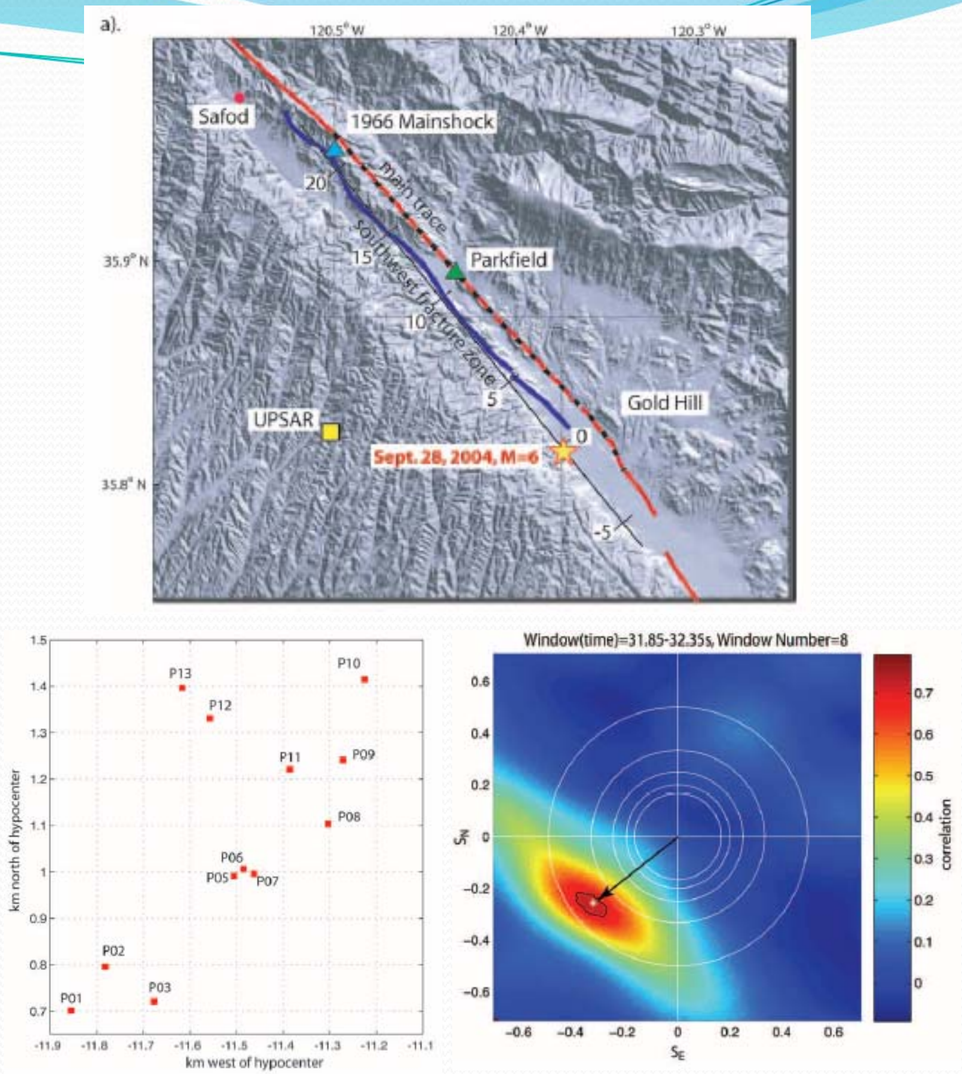


Source imaging today: emerging array techniques

- Seismic array = a compact cluster of stations with high waveform coherency

- Usual applications of regional and teleseismic arrays:
  - Monitoring nuclear explosions (CTB)
  - Non-parametric source imaging of very large earthquakes (back-projection)

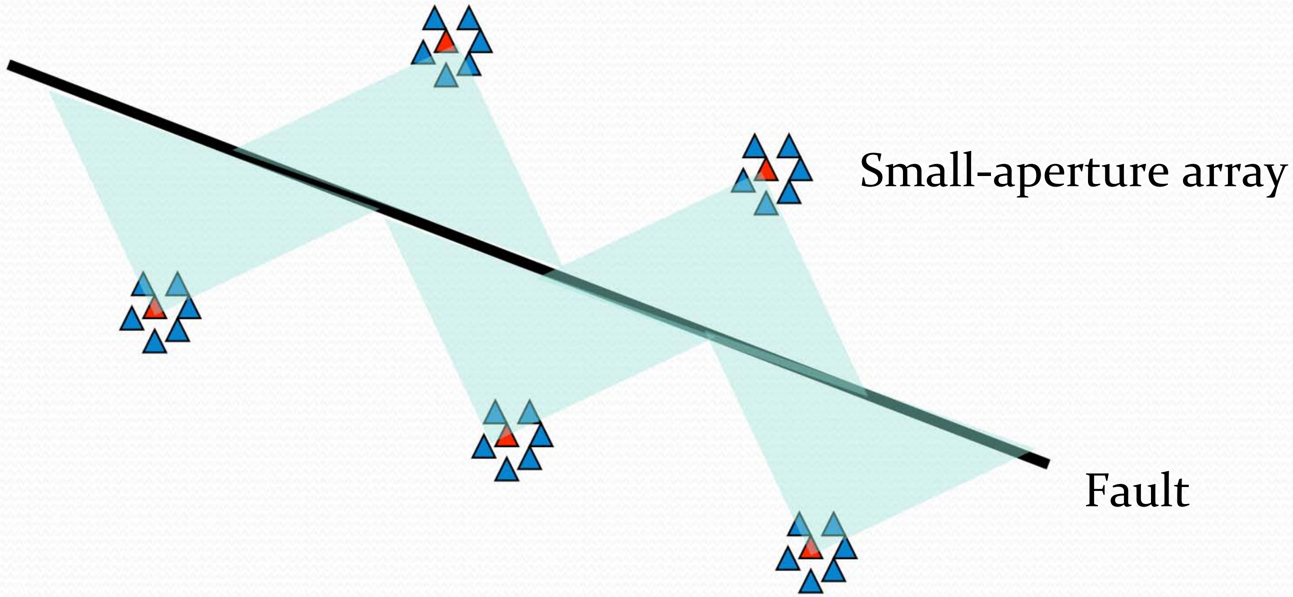
- Hi-frequency source imaging by a **small-aperture seismic array** close to the fault:
  - **Determination of direction of arrival** of hi-f strong phases and back-projection on the fault plane allows **tracking of hig frequency bursts from the rupture front**
  - **Directional filtering** allows simplification of the wavefield (enhance direct arrivals and filter out scattered phases) and focusing on a target fault spot



UPSAR array, Parkfield (Fletcher et al 2006)

Source imaging tomorrow: networks of arrays

- Goal: break the high-frequency barrier, reach sub-kilometric resolution in source imaging
- Proposal: a highly clustered seismic network made of multiple small-aperture arrays (seismic antennas)



Technical requirements

- Instrumentation:
  - Complete coverage of an M6.x earthquake source area (~50km long) with unknown hypocenter location over a >200km long region
  - Each array can image ~30km fault section
  - Overlap in array coverage improves robustness
  - Proper array resolution requires ~20 stations per array

  → Few 100s stations, low-cost MEMS accelerometers
- Logistics:
  - site selection and pre-planning
  - Real-time not required
- Array signal processing:
  - Multipath environment
  - Multiple non-stationary, wideband, correlated sources

Fig.5 determination of errors using ray theory

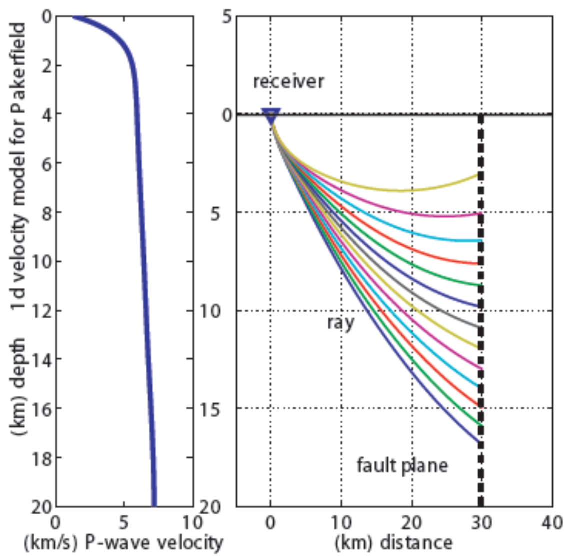
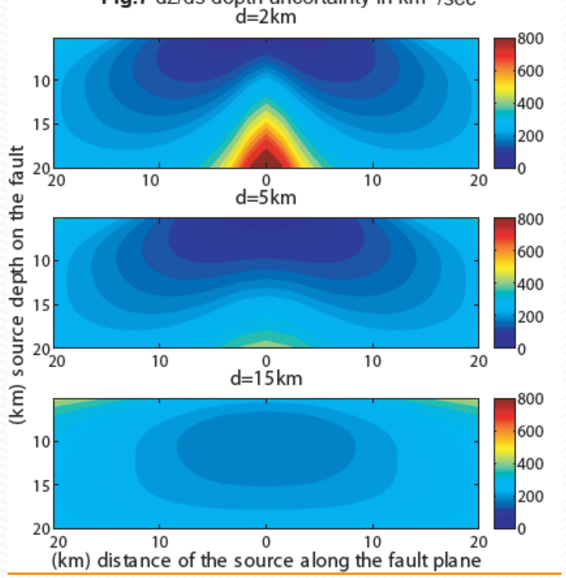


Fig.7 dz/ds depth uncertainty in km ^{2}/sec



Towards a space-based seismometer Preliminary Requirements

Topic	Requirements	Comments
Field of view	# 550X250 km	Main Shocks, California
	# 100X100 km	Aftershocks
Spatial Sampling	# 100 m	Aliasing of higher spatial fHz
Temporal Sampling	# 1 Hz	Ok for Mw>7 Poor for Mw<6 ?
Accuracy	# 1cm.s^{-1}	Dimensioned from sparse seismometers

Requirements may be adjusted to the limits and potential of dense video-imagery

An Optical Geostationary seismometer?

Instrument	Comments	"TRL"
Drones	Lack Field Of View	
Commercial airplanes	FOV, temporal sampling? To be investigated	
Stratospheric Balloons	Stability, FOV Alt 30km => FOV max 50km	
Low Earth Orbiter Medium Earth Orbiter	Repetitivity FOV # 1000km => 40 satellites	
Geostationary	Accuracy, Instrumentation?	
Radar	SAR temporal sampling low A Couple of Images a Day	
	Real aperture : Ultra large antennae	
Optics	Telescope size, FOV, large detectors, huge data volume Limited to Clear Sky…	?

An Opportunist Geostationary Optical Seismometer (objective : capture some events)?

Optical Signals from Earthquakes

Signals	Keywords	Geostationary Issues
Horizontal deformation of images	Video, Optical flow, Correlation, sub-pixel, Kalhman	Telescope size (resolution) Detection Data flow
Changes in topography	Lidar	Laser Energy
	Photoclinometry	Telescope size (Photometry)
Doppler shift (interaction with the atmosphere)	Incoherent Wind Velocimeters	Extremely small Doppler shifts (100 kHz) Very Complex Signal
Lightening	Tribology	Unreliable

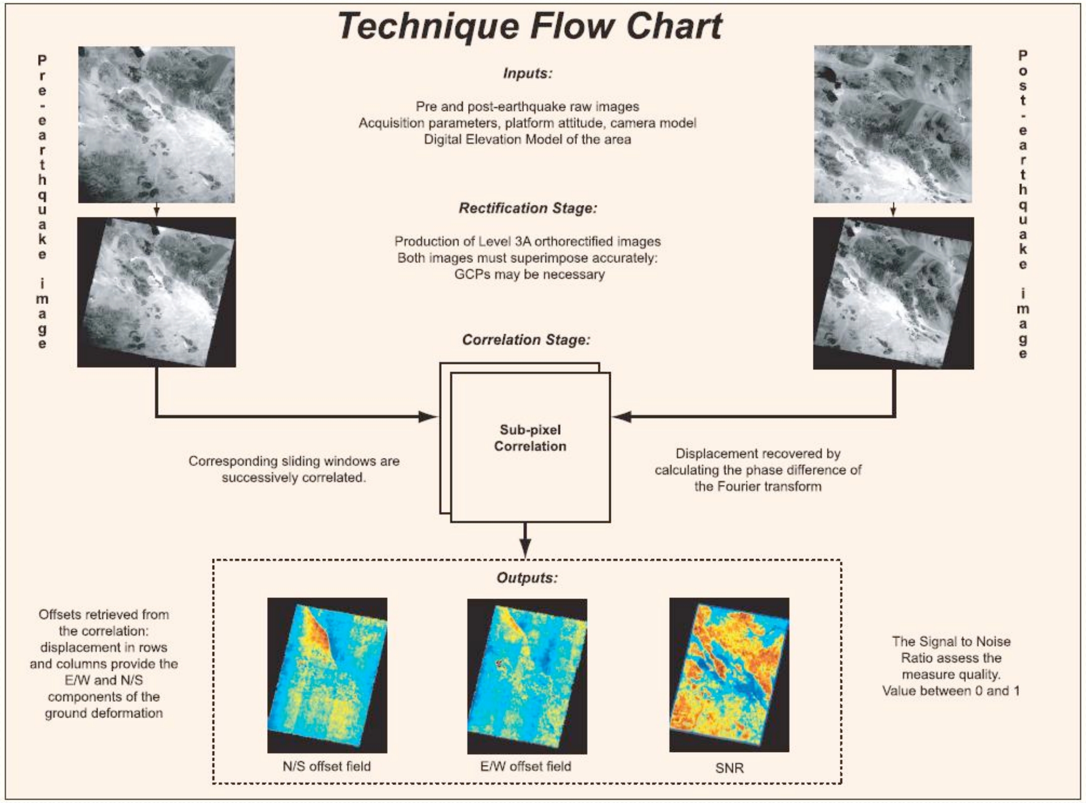
Two “Horizontal” Components

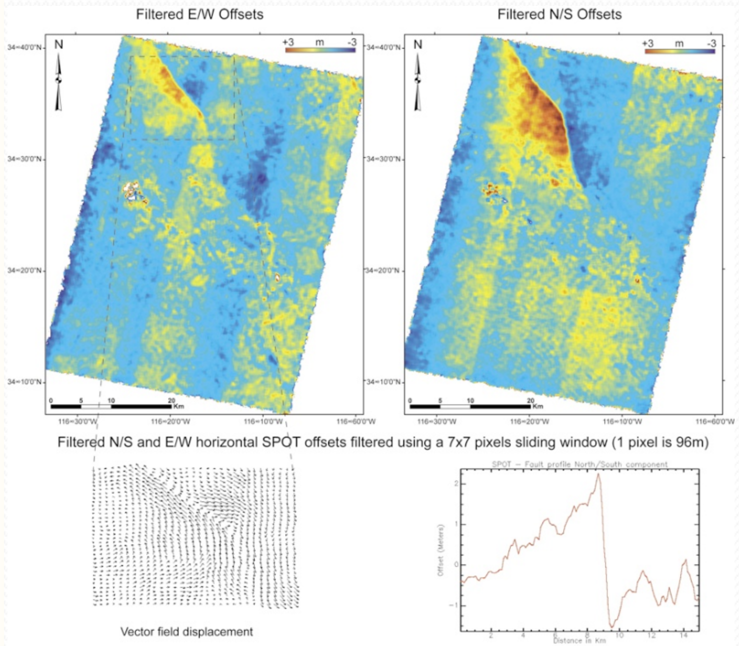
- Correlation, Optical flow. Limited to about $1/100^{th}$ (distribution of scatters, aliasing, SNR, CCD)
- Nyquist (2 pixels per Airy zone), no aliasing, back illuminated CCD, SNR=1000 (10^7 photons), r=0.1

FOV	Telescope	Nb_pixels (diffraction)	Data rate (read out)	Data Memory (100s)	noise (rms)
550X250 km Main shock Large FOV (1, LSST is 4)	**f4m**	7 billions		7 Tbits	6cm
	f10m	42 billions		42Tbits	2cm
100x100 km Aftershock	**f4m**	1 billion		1Tbits	6cm
	f10m	7 billions		7Tbits	2cm

- Integration time per pixel # 0.05s << 0.5s : The Fundamental Modularity of the Concept
- Data Storage Unit 7.2 Tbits (Hyperspectral)
- CCD 4 billions pixels (3.2 Gpix LSST, read out in <2s)
- ~ $1/100^{th}$? (Seism Simulations at $1/50^{th}$)

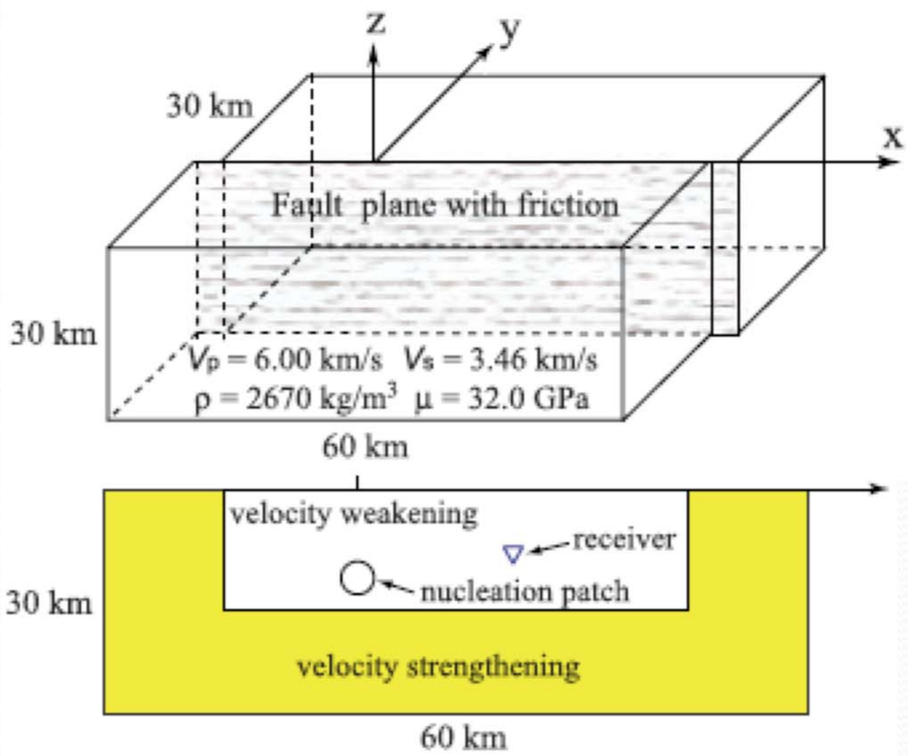
CosiCorr: sub-pixel horizontal deformation of optical images by cross-correaltion

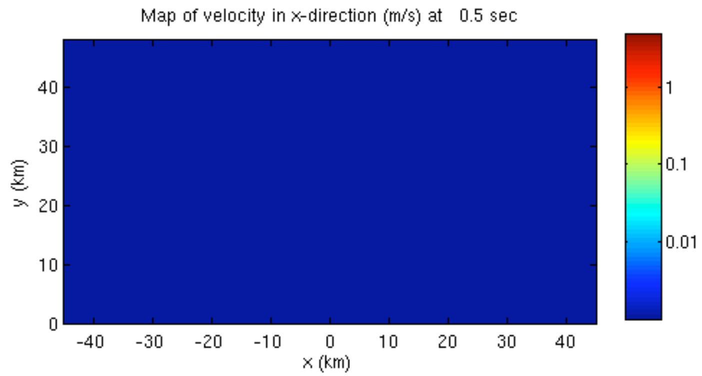


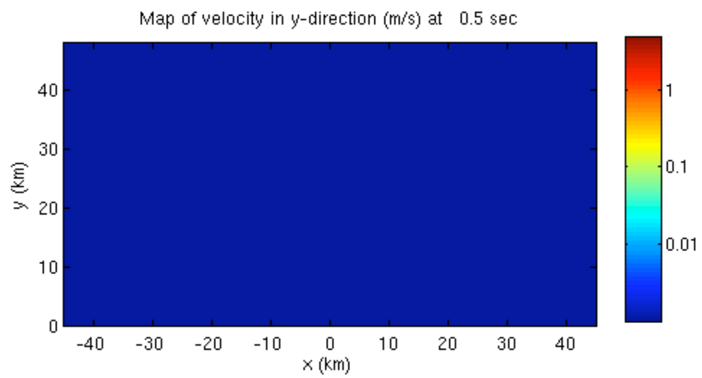


Example: Hector Mine earthquake

Synthetic test
Setup and Geometry



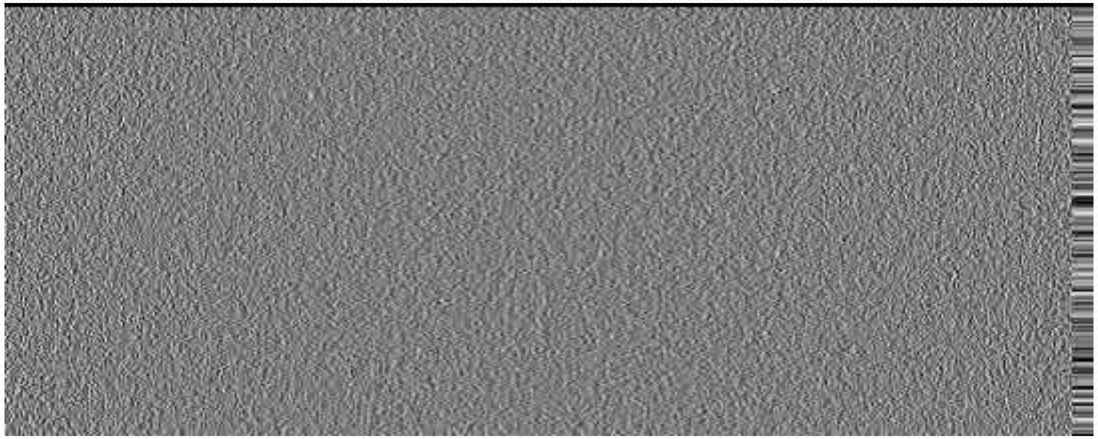




Kaneko et. al (2008) : SEM modeling of Ra

Model

Telescope f10.0m

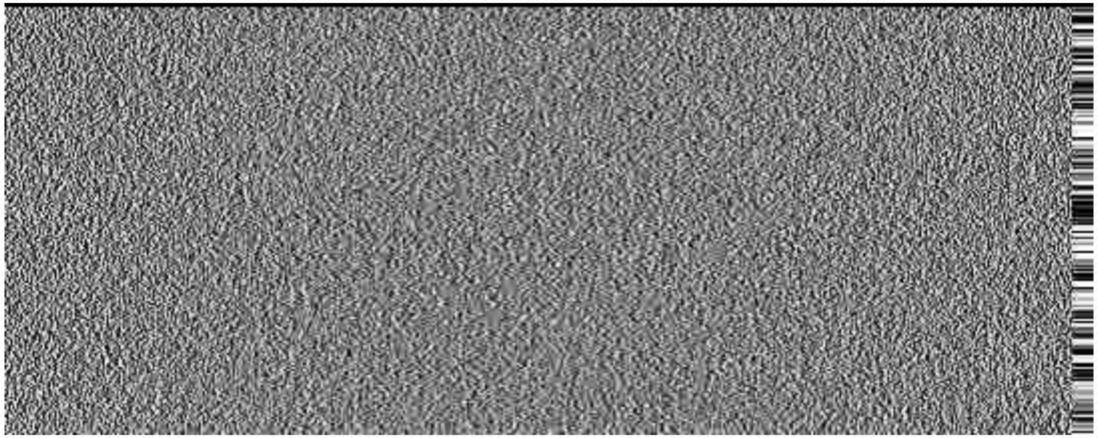


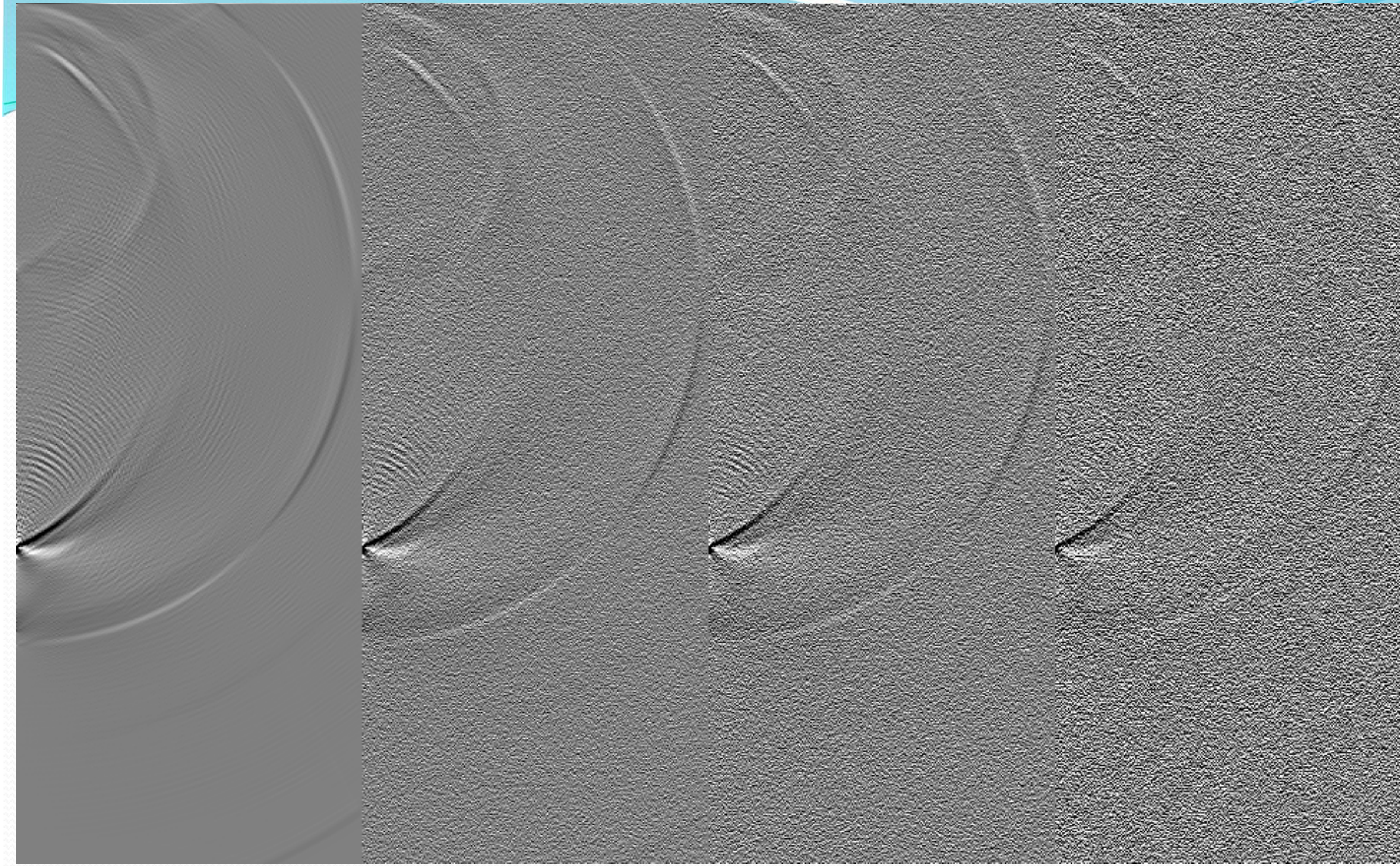
$$\frac{\partial v_x}{\partial x}$$

-0.1 S^{-1} 0.1

Accuracy 1/50th pixel

Telescope f4.0m





Modele f10.om f7.om f4.om

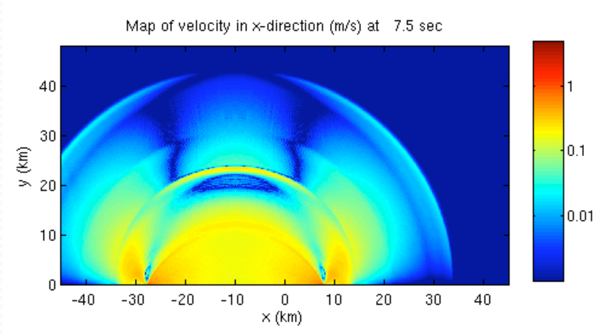
$$\frac{\partial v_x}{\partial x}(15s)$$

Inverse problem with dense data

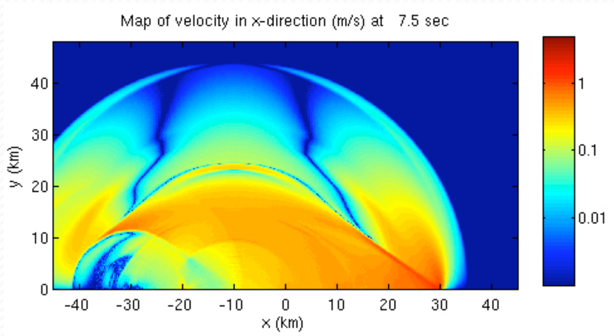
Some features of rupture are directly visible (without source inversion) in the wavefield, e.g. discriminating between sub-Rayleigh and supershear rupture speed

In theory, source reconstruction up to sampling frequency requires:
• Dense measurements with spatial sampling = wavelength
• coverage over a half-sphere surrounding the source

We are testing adjoint (time-reversal) source imaging



Sub-Rayleigh vs Super Shear

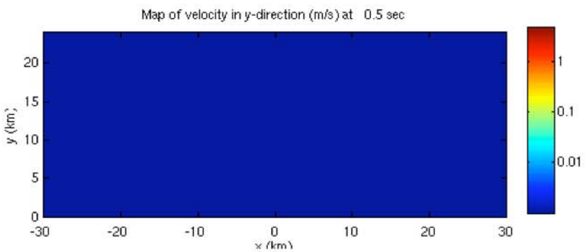


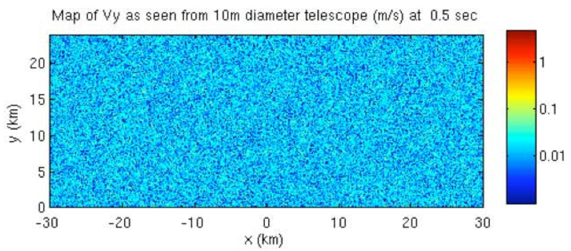
Summary

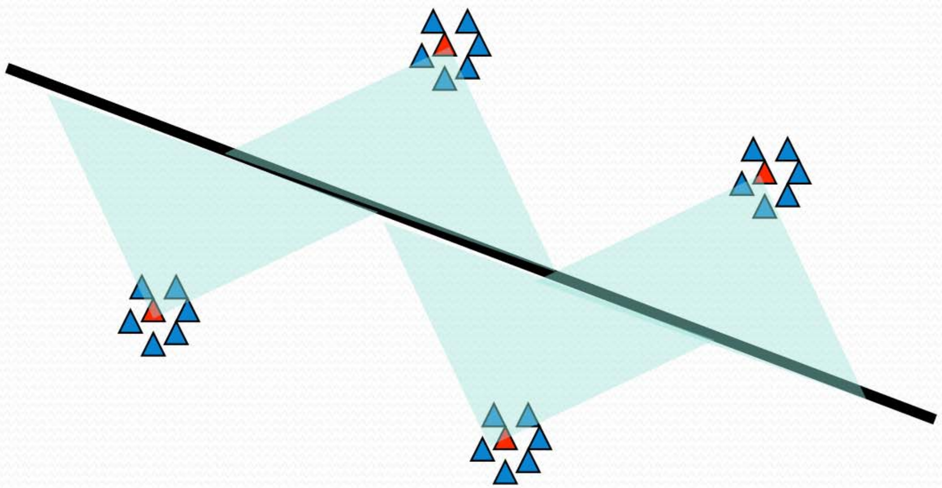
- Source imaging today has too low resolution to address key open questions about earthquake physics

  → Need to break the "high-frequency barrier"

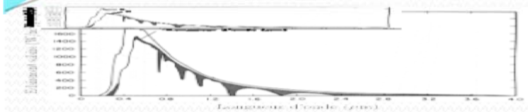
- Two potentially transformative proposals:
  - a clustered network of multiple small-aperture seismic arrays near the fault
  - Imaging seismic wavefield from space with a geostationary satellite 4m optical telescope



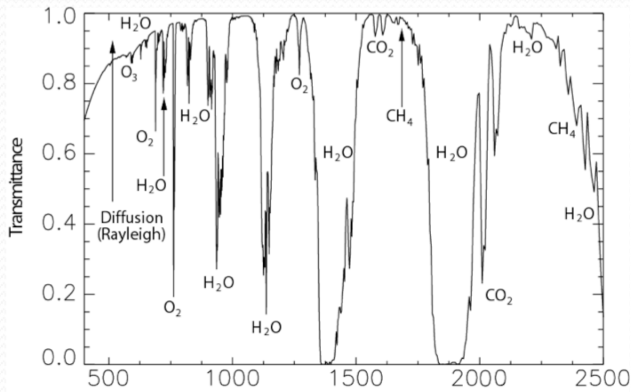




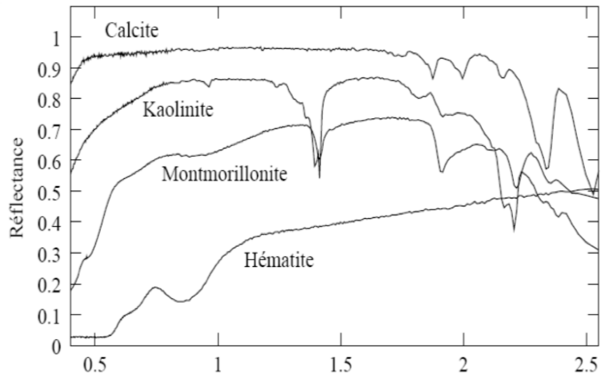
Photometry Essentials



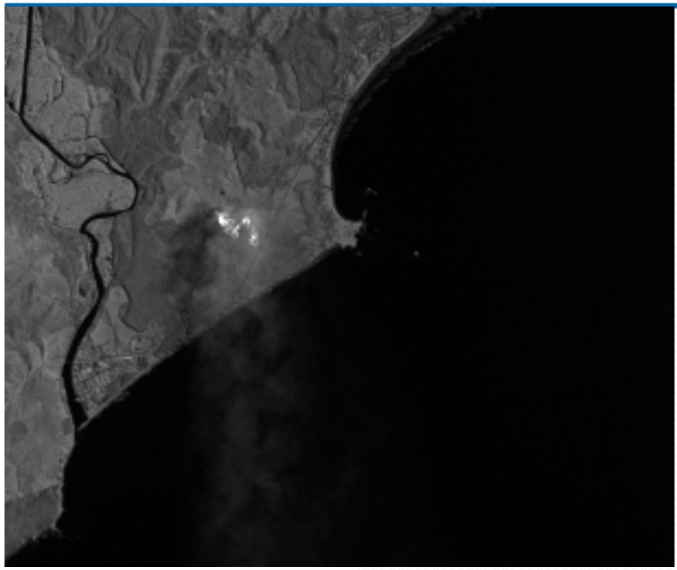
Wavelength (mm)
Sun Radiance



Wavelength (mm)
Atmosphere Transmittance



Wavelength (mm)
Ground Reflectance



Movie [0.4-2.5mm]

$$I = \frac{\pi L_{sun}\cos(\theta_{Sun})}{2\left(\frac{focal}{\emptyset_{telescope}}\right)^2} . T_{optics} T_{atm}^2 \cdot \frac{\rho}{1 - S\rho} . \Delta t . S_{detector} \cdot \rho_{quantic}$$

L:radiance, *r* : reflectance, *S* : atmosphere spherical reflectance

Photon Budget

Sun	Poisson		$\frac{dI}{I} = \sqrt{nb\_photons}^{-1}$
	Incidence		$\frac{dI}{I} \le 10^{-5}.s^{-1}$
Atmosphere	Steering (geometry)	Kolmogorov	Shift < few centimeters
	Dancing (geometry)		Blur < few centimeters
	Scintillation (photometry)	Rytov (weak fluctuation)	TBD $\frac{dI}{\sqrt{I}} << 1$
Ground	Bidirectional Reflectance Distribution Function	Nominal (near Lambertian, 1-100m)	$\frac{dI}{I} \approx 10^{-6}$
		Urban	TBD (high level), lightening damages, etc.
		Vegetation	TBD
		Shacked ground	TBD

The “Vertical” Component

- Photoclinometry $\partial I / I \approx \tan(\theta) d\theta$

•Accuracy possible up to [10^{-6}-10^{-5}]

•r=0.1, pixel size : 100m, integration time 0.25s, most unfavorable incidence angle # 10 degrees

FOV	Telescope	Integration time	noise (rms,rad)
550X250 km Main shock	f4m	0.25s	10^{-5}
	f10m	0.25s	$3\ 10^{-6}$

- Integration time per pixel # 0.25s : ¼ of the total light
- 10 m <> 4m, limitation from incidence angles

Conclusions

Optics-Geostationary : the optimal (only) solution to catch seism waves?
Telescope f4.0m seems OK. Larger telescope would be very challenging (no launcher, no telescope).
Horizontal and Vertical Components : 6cm rms-100m-1Hz. Better?
10% to 25% of light used, place enough for other applications.
Payload critical but ok (*stability*, data management, *energy*, *etc*.).
Need further investigations (atmosphere, moon light, meteorology, wide field telescope, geostationary environment, etc.).
Need from preliminary assessment by inverse modeling.