EARTHQUAKE EARLY WARNING

Aldo Zollo

RISSC-LAB - Dipartimento di Scienze Fisiche
Università di Napoli "Federico II"
http://www.rissclab.unina.it

With the main contribution of: C. Satriano, C. Martino, L. Elia, M. Lancieri, G. Iannaccone and RISSC Lab team

Outline

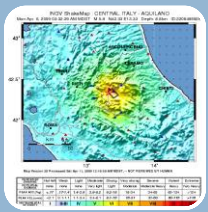
- ❑ Basic ideas and worldwide developments
- ❑ Network-based (regional) and stand-alone (on-site) systems
- ❑ Real-Time Location and magnitude estimation
- ❑ Example of implementation in southern Italy
- ❑ New developments: Integrated regional/on-site approach

Earthquake risk mitigation actions

EARLY-WARNING

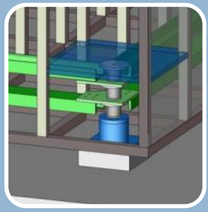
Observation

- Advanced seismic monitoring and control infrastructure



Modelling

- Simulation of realistic earthquake scenarios and ground motion prediction

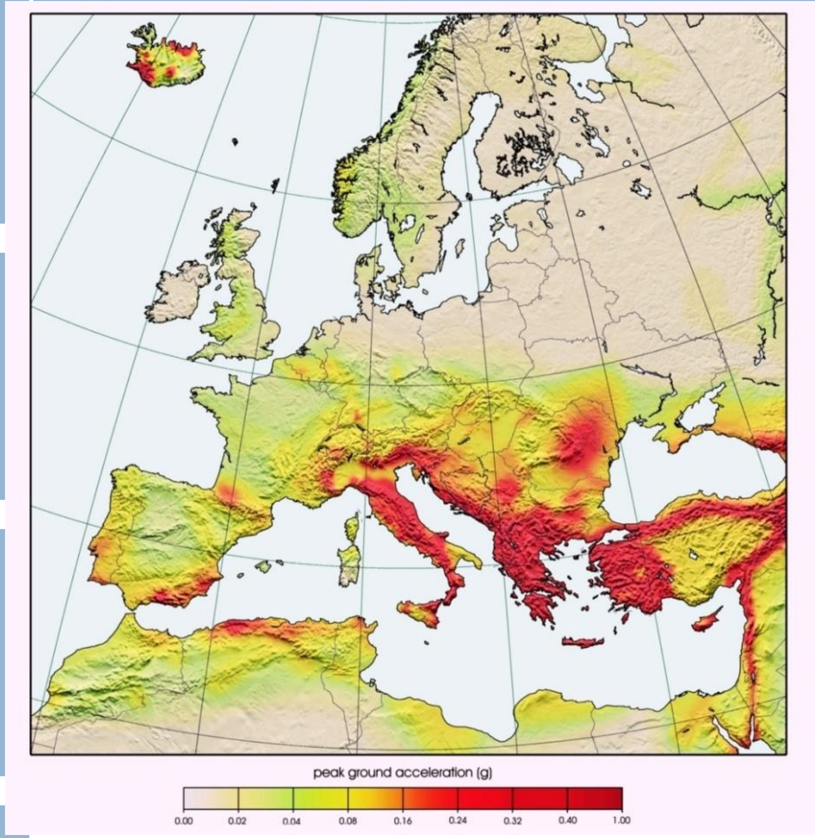


Earthquake engineering

- Design, construct and mantain structures to resist at earthquake actions

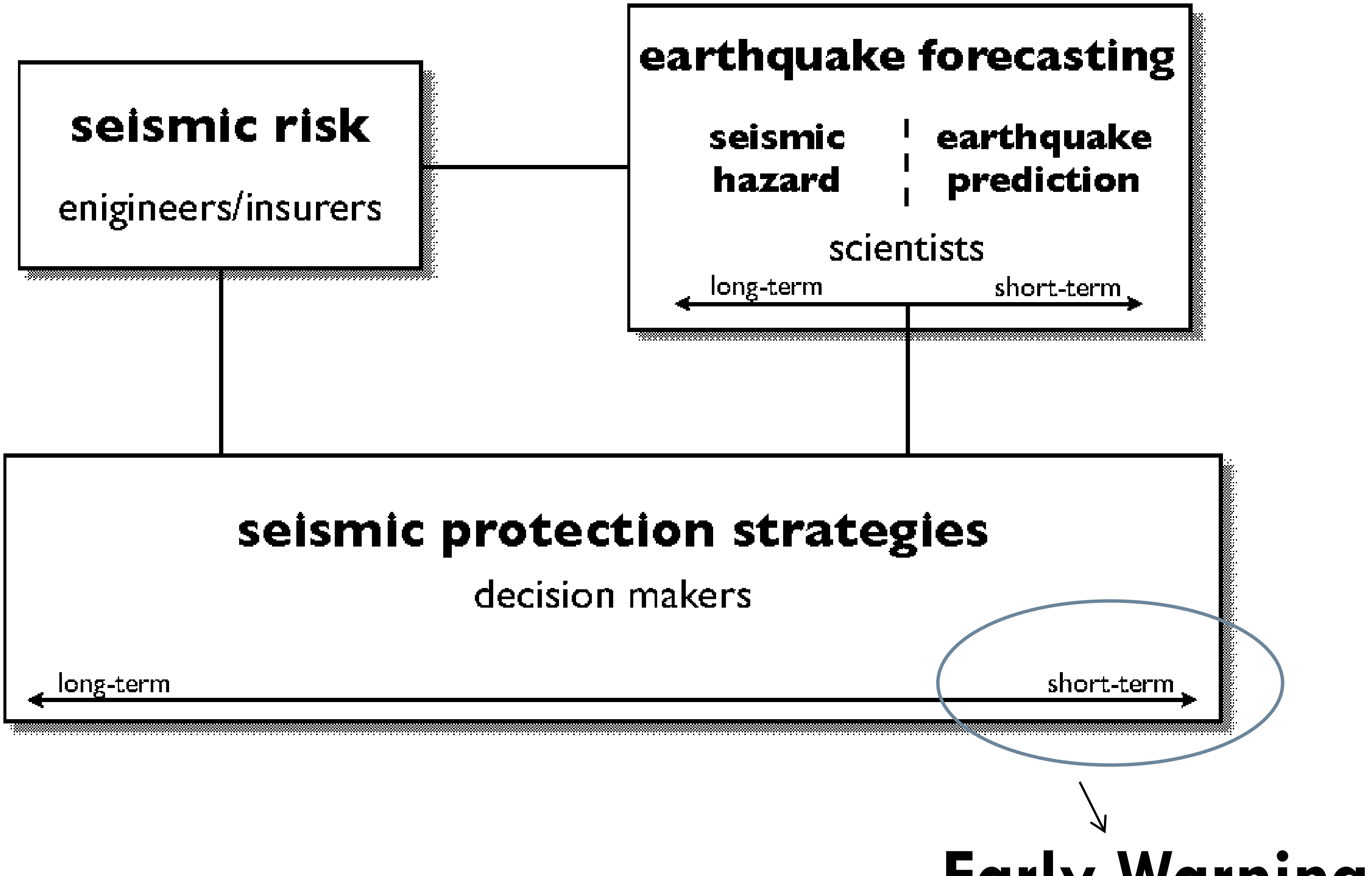
Education

- Information and awareness activities addressed to population in high seismic risk areas



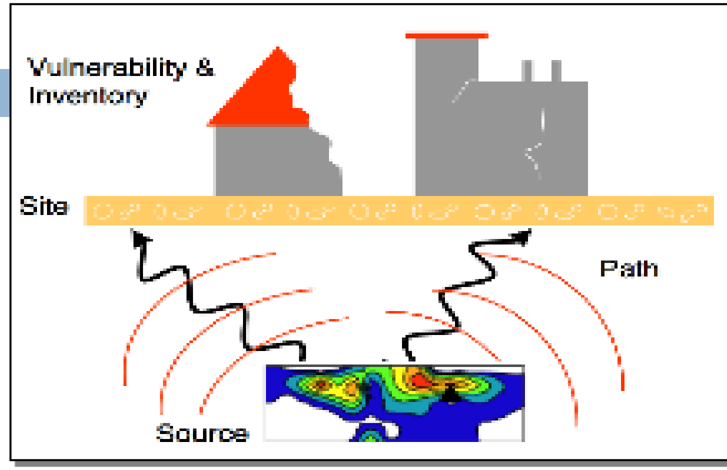
Seismic hazard map of the Mediterranean region (Jimenez et al., 2003

Time scales of seismic risk mitigation strategies



Redrawn after Snieder & Van eck, 1997

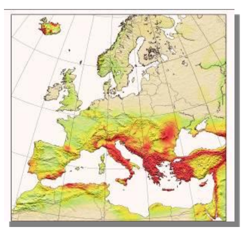
European Projects Related to Early Warning



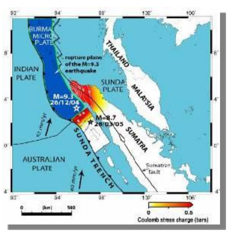
Earthquake

SHARE - NERIES

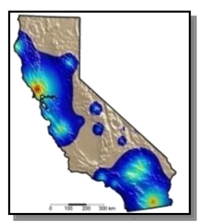
SAFER – TRANSFER
SEAHELLARC - NERIES



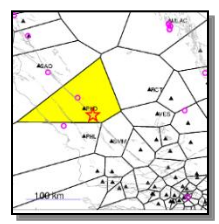
Long-term Hazard Mapping



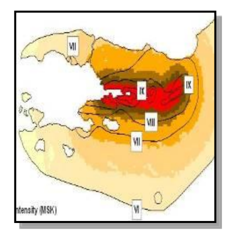
Long-Term Forecasting



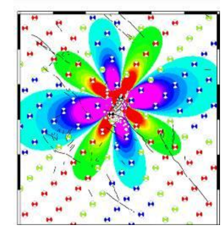
Short-Term Forecasting & Prediction



Early Warning



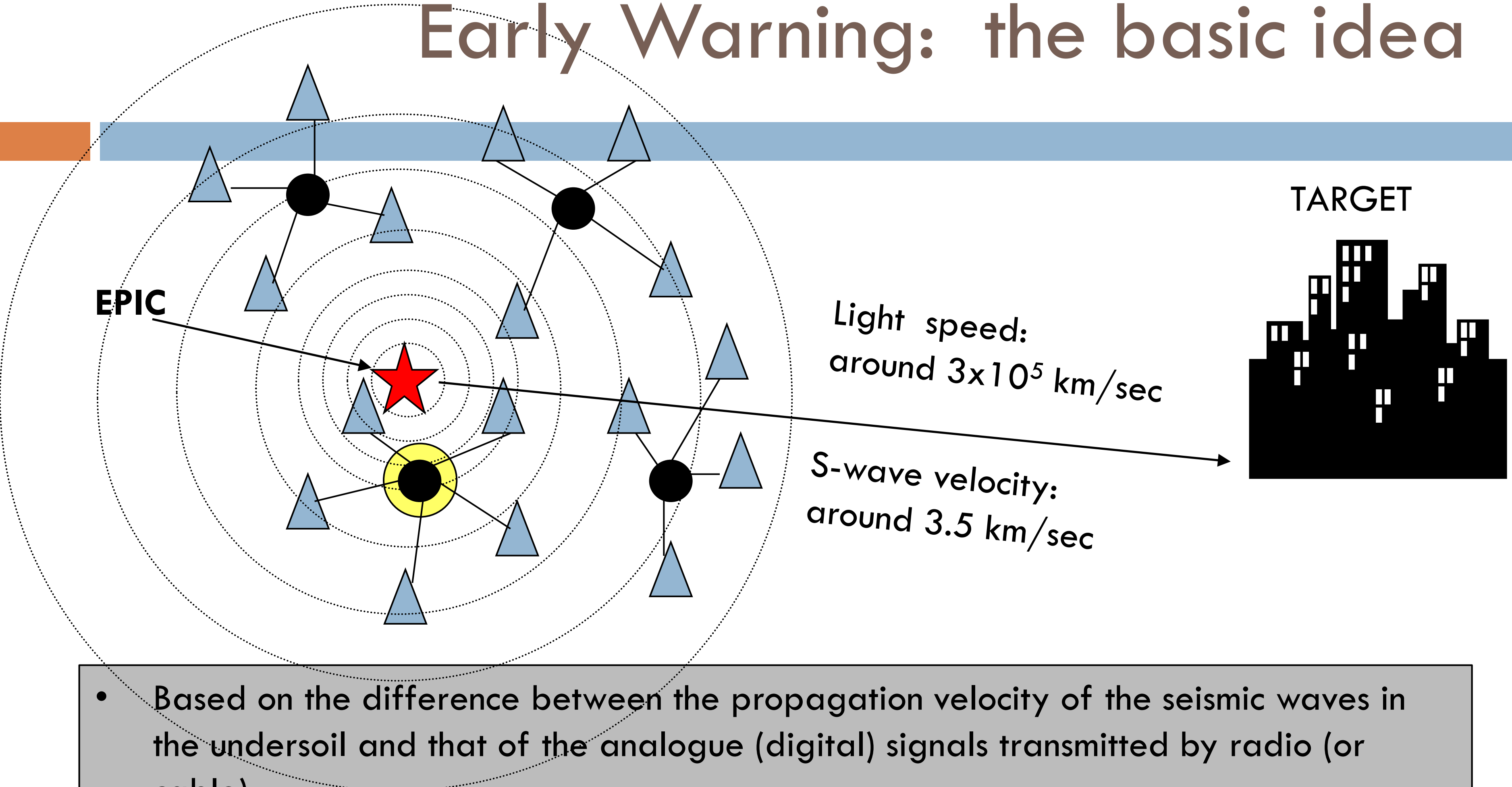
ShakeMaps &Rapid Loss Assessment



Aftershock Hazard

decades **years** **days** **0** **seconds** **minutes** **days/ months**

Early Warning: the basic idea



- Based on the difference between the propagation velocity of the seismic waves in the undersoil and that of the analogue (digital) signals transmitted by radio (or cable)
- As a function of the distance from the source area of a strong earthquake, the information about its location and magnitude can reach a site that is "potentially at risk" from **a few seconds to tens of seconds** before the arrival of the largest amplitude seismic waves.

The pioneering idea of Early Warning by Dr.Cooper, 1868

Fig. 13.1 The concept of the first detection system by Dr. Cooper.

When an earthquake triggered the detectors, an electric signal would be sent by telegraph to San Francisco. This signal would then ring a big bell in City Hall to warn citizens that an earthquake had occurred. Unfortunately, Cooper's scheme was never implemented.

Japan Railways Company, Japan, late sixties

In late sixties, the Japan Railways company started to operate an EW system, based on the acceleration threshold

In 1984, UrEDAS, Urgent Earthquake Detection and Alarm System slows down or stop train before seismic shaking

(Nakamura,1988).

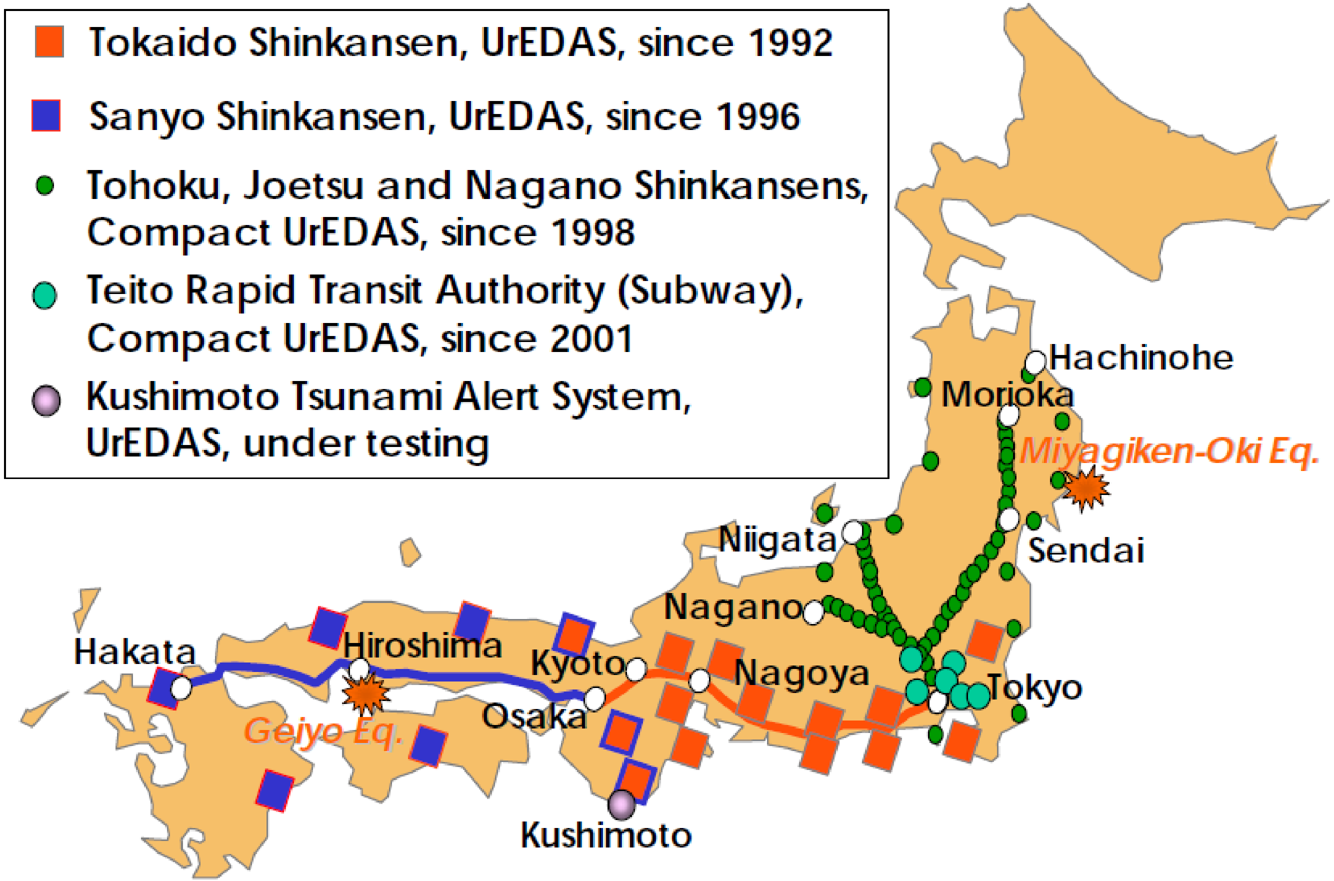
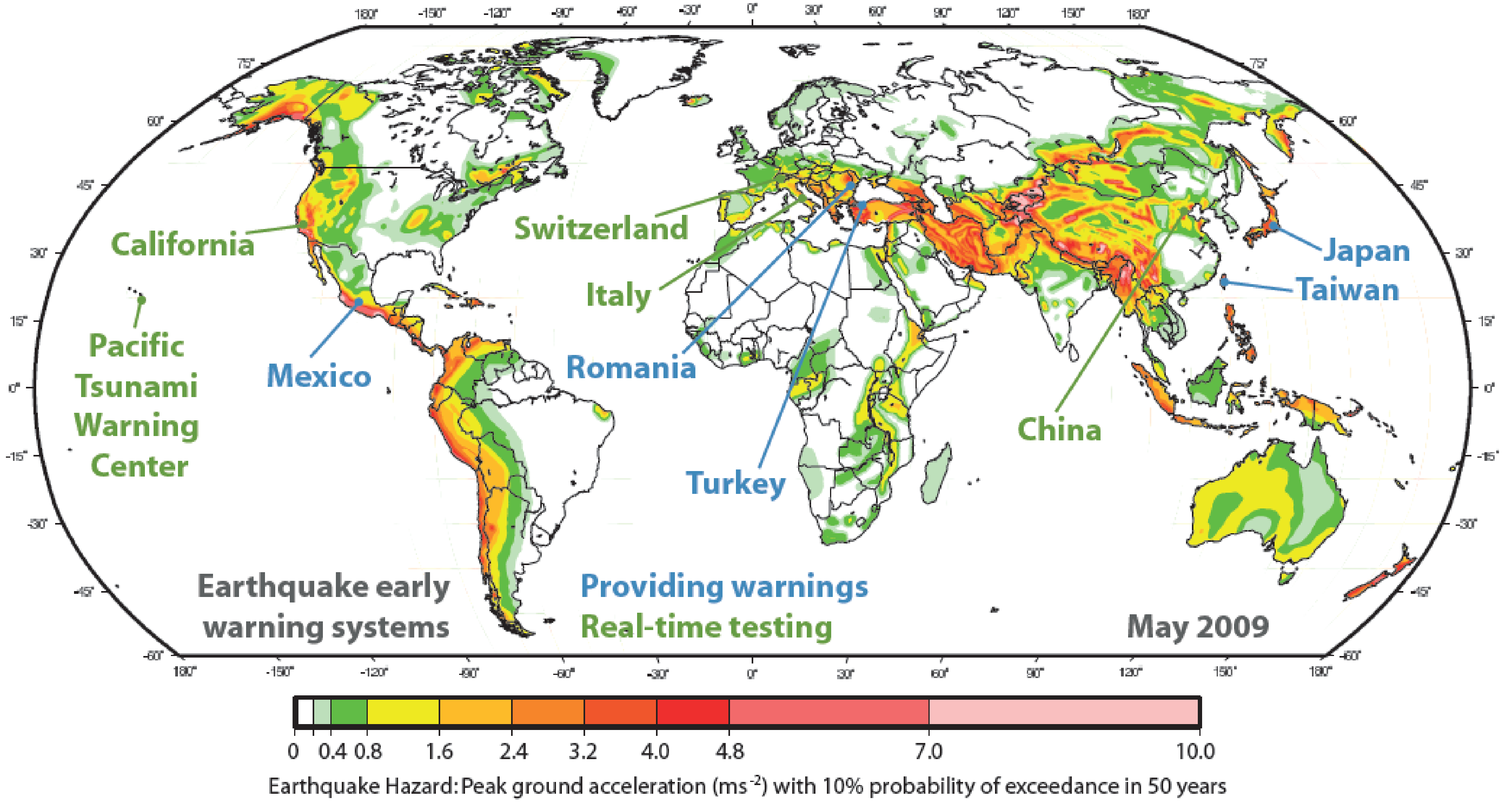


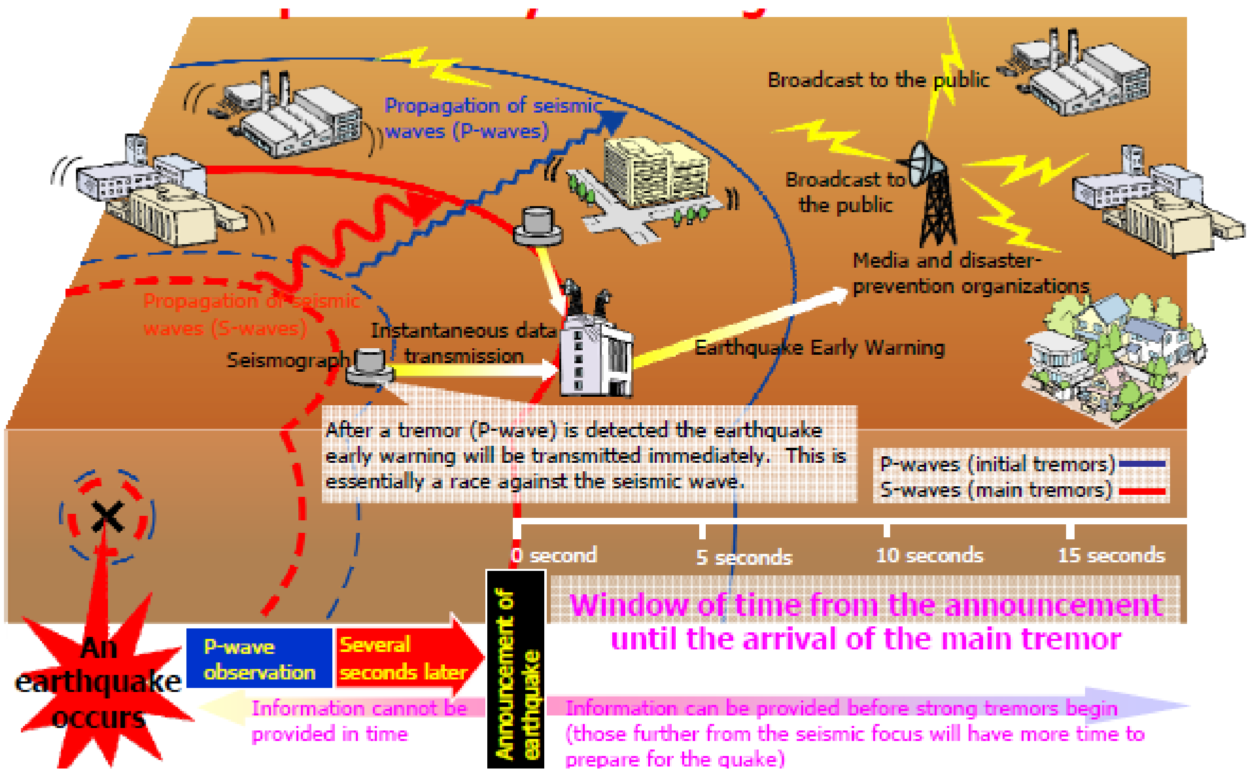
Figure1 The distribution of UrEDAS and Compact UrEDAS in Japan

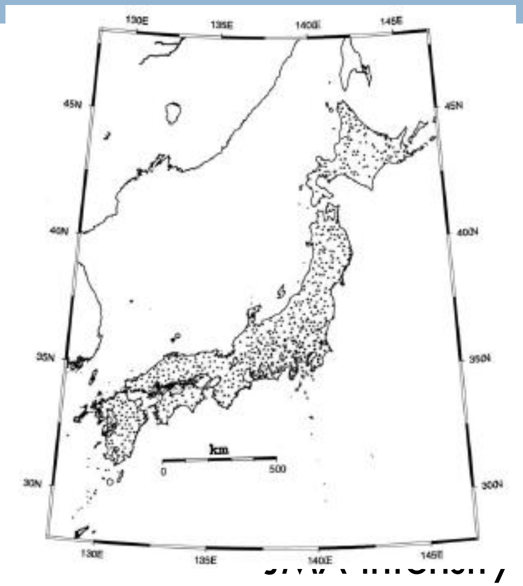
Worldwide Early Warning Systems

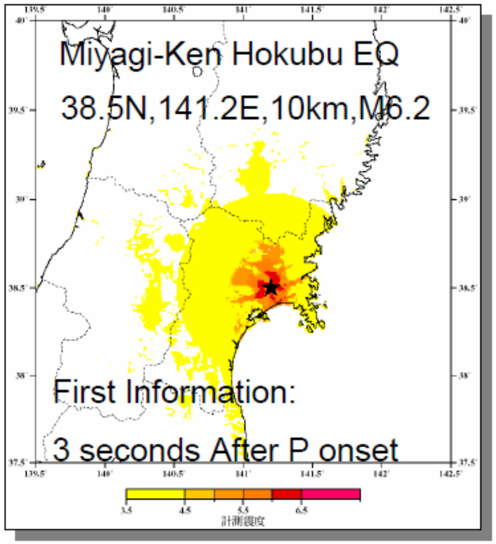


From Allen et al., 2009

The Japan Meteorological Agency Early Warning System in Japan





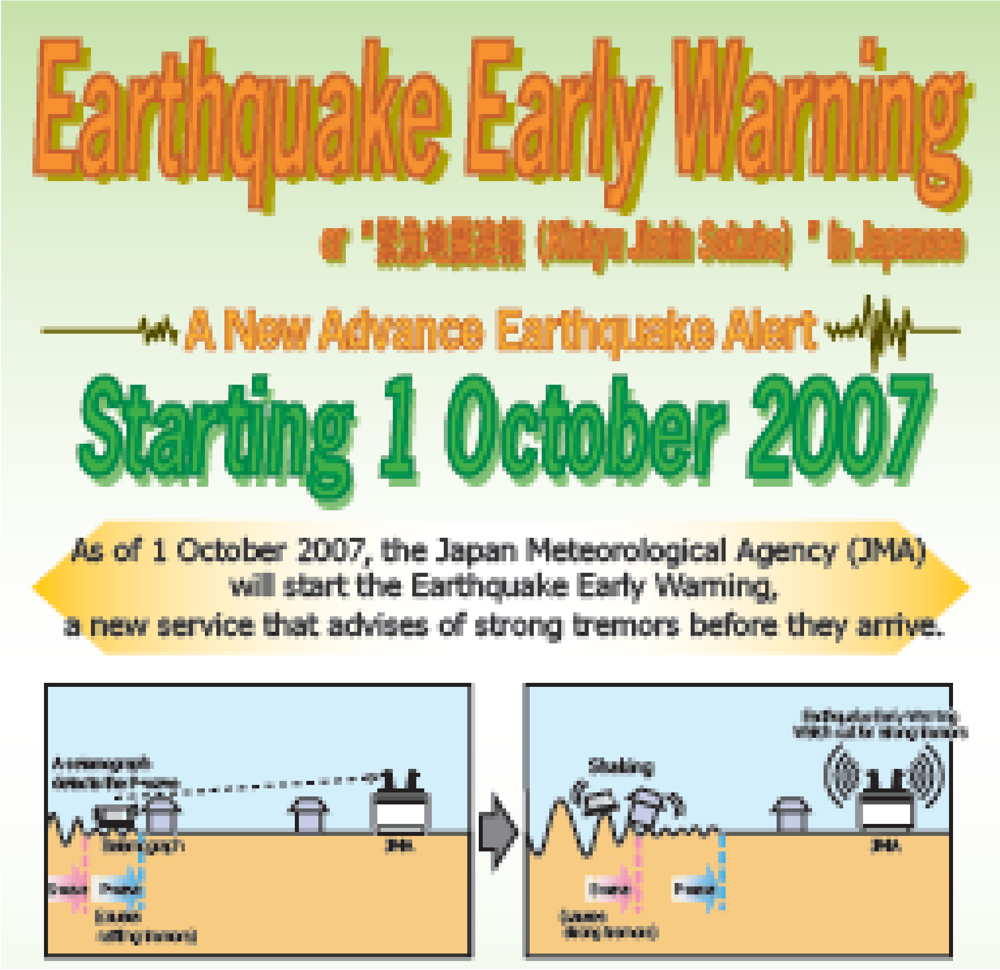


Early-Warning broadcast has started in Japan on October,2007

October 2007 to March 2009: 11 earthquakes for which a public warning was issued and/or shaking intensity 5-lower or greater was observed.

Two missed alarms when the maximum predicted intensity was 4 but 5-lower was observed. Three false alarms when intensity 5-lower was predicted but only 4 was observed

The largest event was the onshore 14 June 2008 M 7.2 earthquake. The first public warning was issued 4.5 s after the first detection and was updated 18 s later.



http://www.jma.go.jp/jma/en/Activities/eew.html

Current applications

Utilities

Power (fire prevention), gas

Industry

Hazardous chemicals, chip manufacturers, eye surgeons

Construction

Site safety, (active control buildings)

Transportation

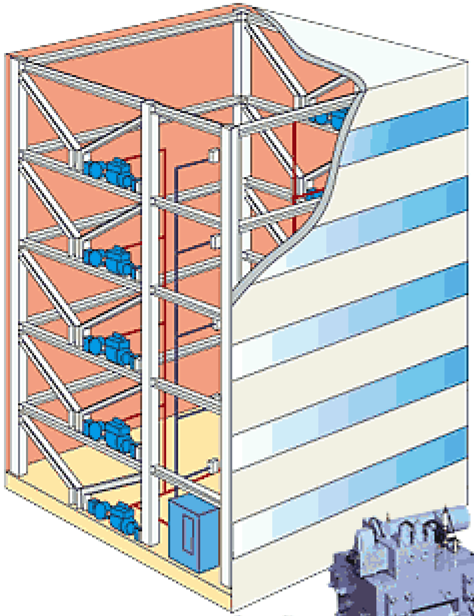
Airports, rail and subway, bridges

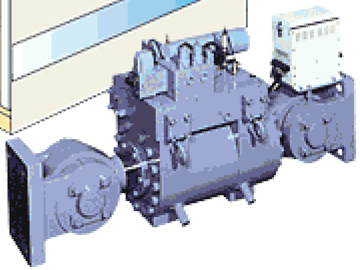
Response community

Fire departments, rescue teams, government

Personal protection

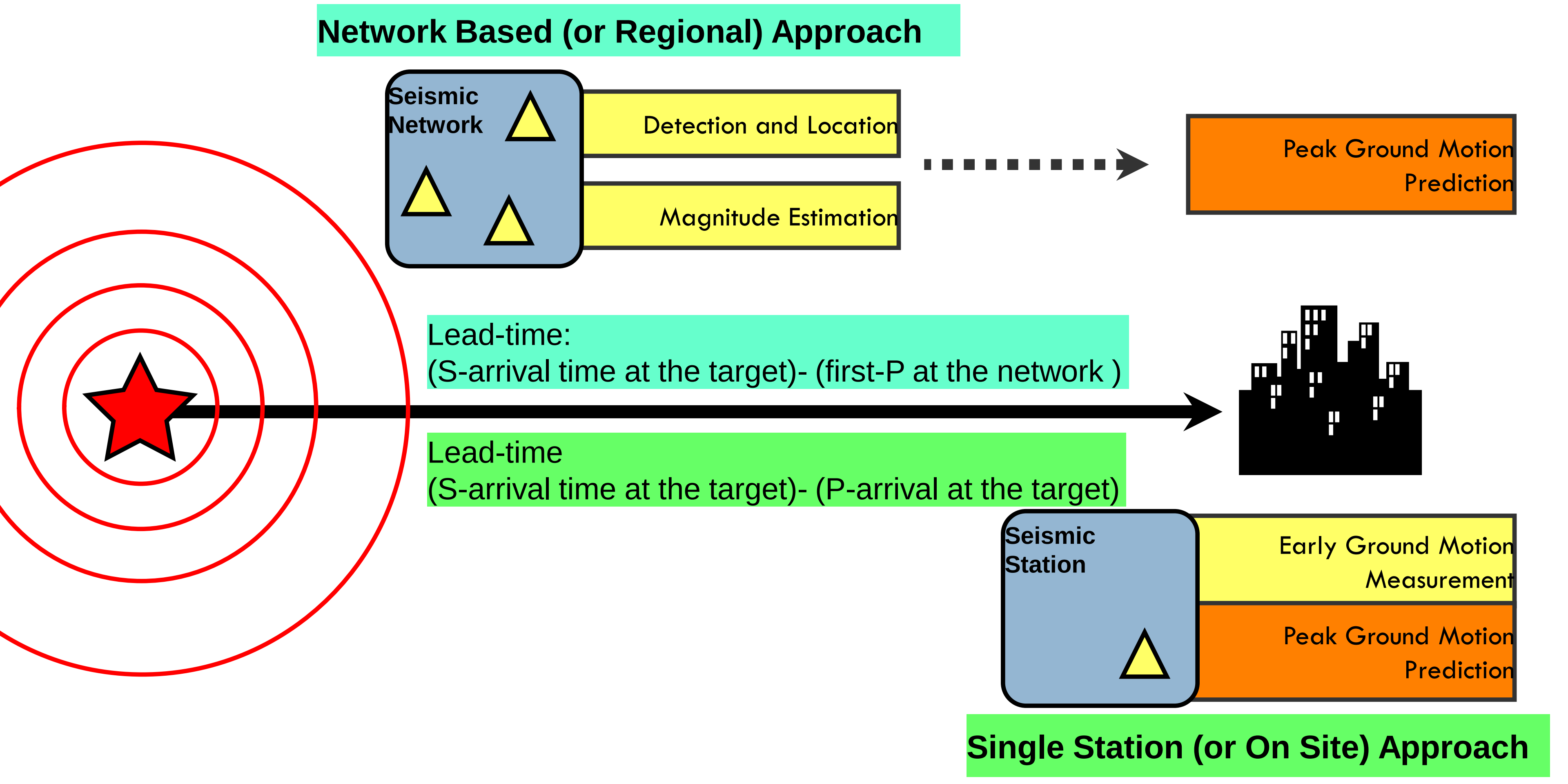
Schools, housing complexes (evacuation), hosing unit (preparation)





Earthquake Early Warning Systems

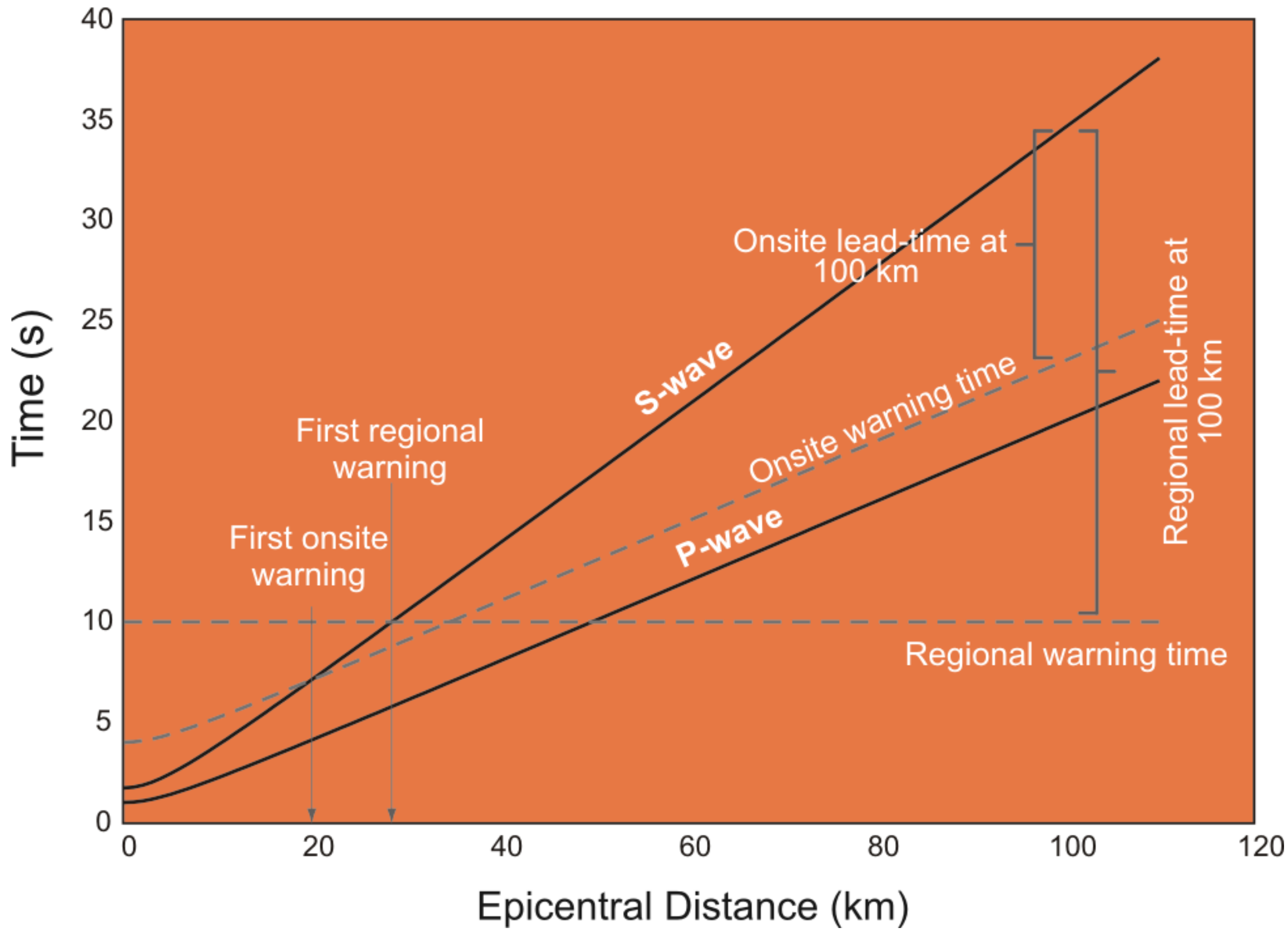
Objective: To estimate in a fast and reliable way the earthquake's damage potential



Warning- and Lead-times for regional and on-site systems

The expected lead-time of “Regional“systems increases with distance and it is about twice than for “On-site” systems.

On-site systems can provide fast warning to targets close to the epicenter .



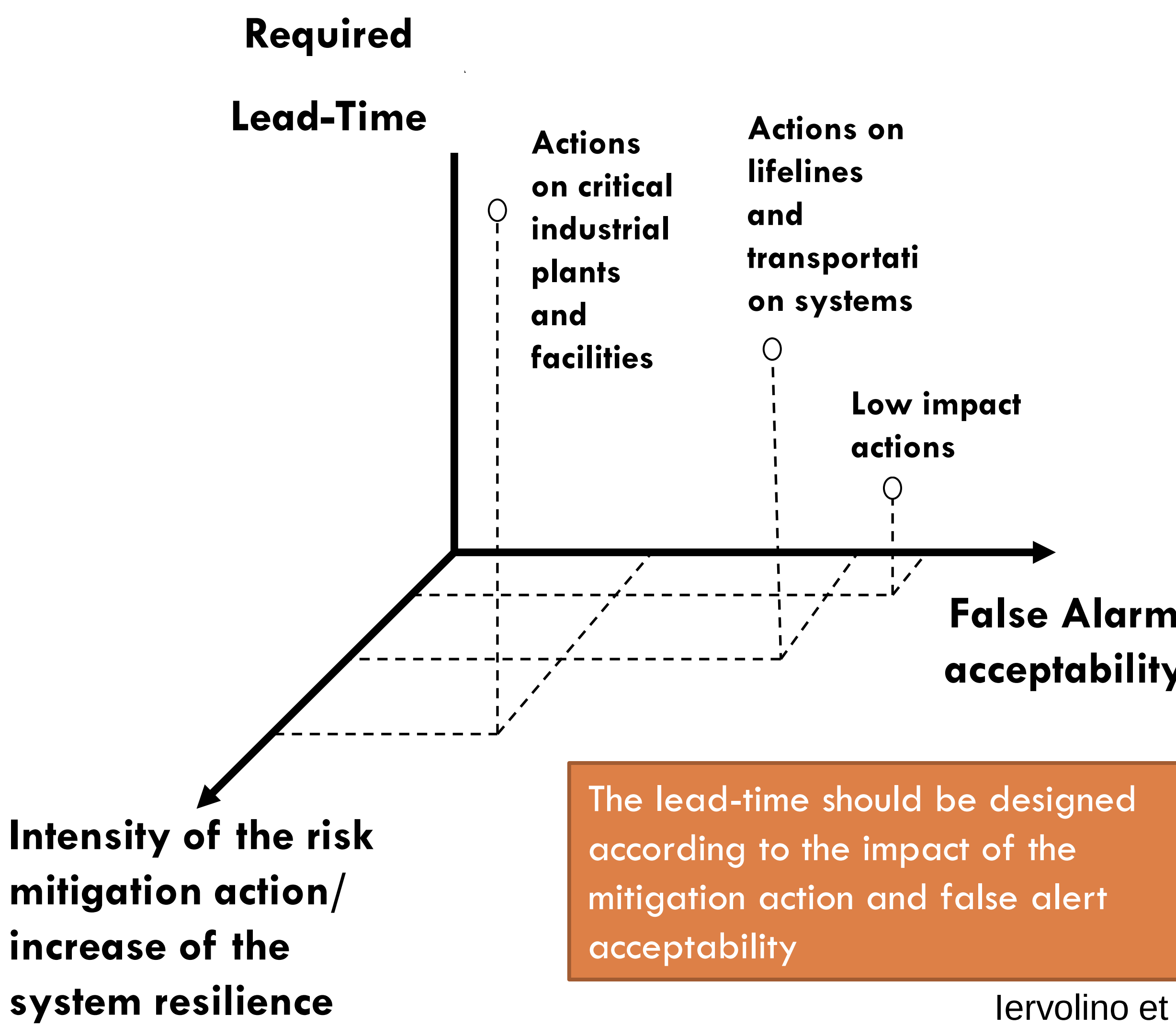
Lead-Times vs Mitigation Actions

Three classes of actions:

1/ low impact (stop elevators, children under the desk,..)

2/ medium impact: actions on lifelines (shut-off gas/electric supply, stop or slow down train,

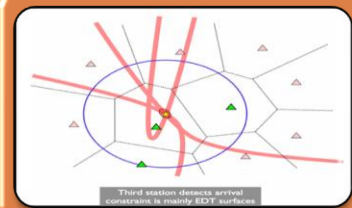
3/high impact: shut-off large industrial plants, as nuclear, electro-thermal, chemical



The lead-time should be designed according to the impact of the mitigation action and false alert acceptability

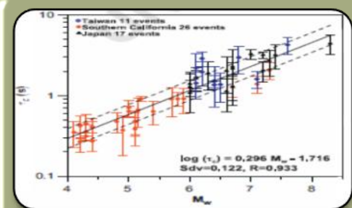
Iervolino et al., 2007

Output of a Regional Early Warning System



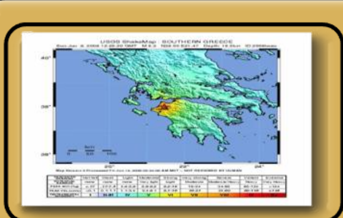
Location

- A conceptually simple problem, with techniques that are standard or are being developed; high precision



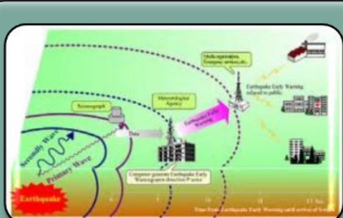
Magnitude

- A conceptually difficult problem; empirical regressions on complex observational measures; low accuracy



Peak ground motion at the target site

- Well established problem; critically dependent on accuracy of attenuation law; simplified assumptions about the source and propagation models

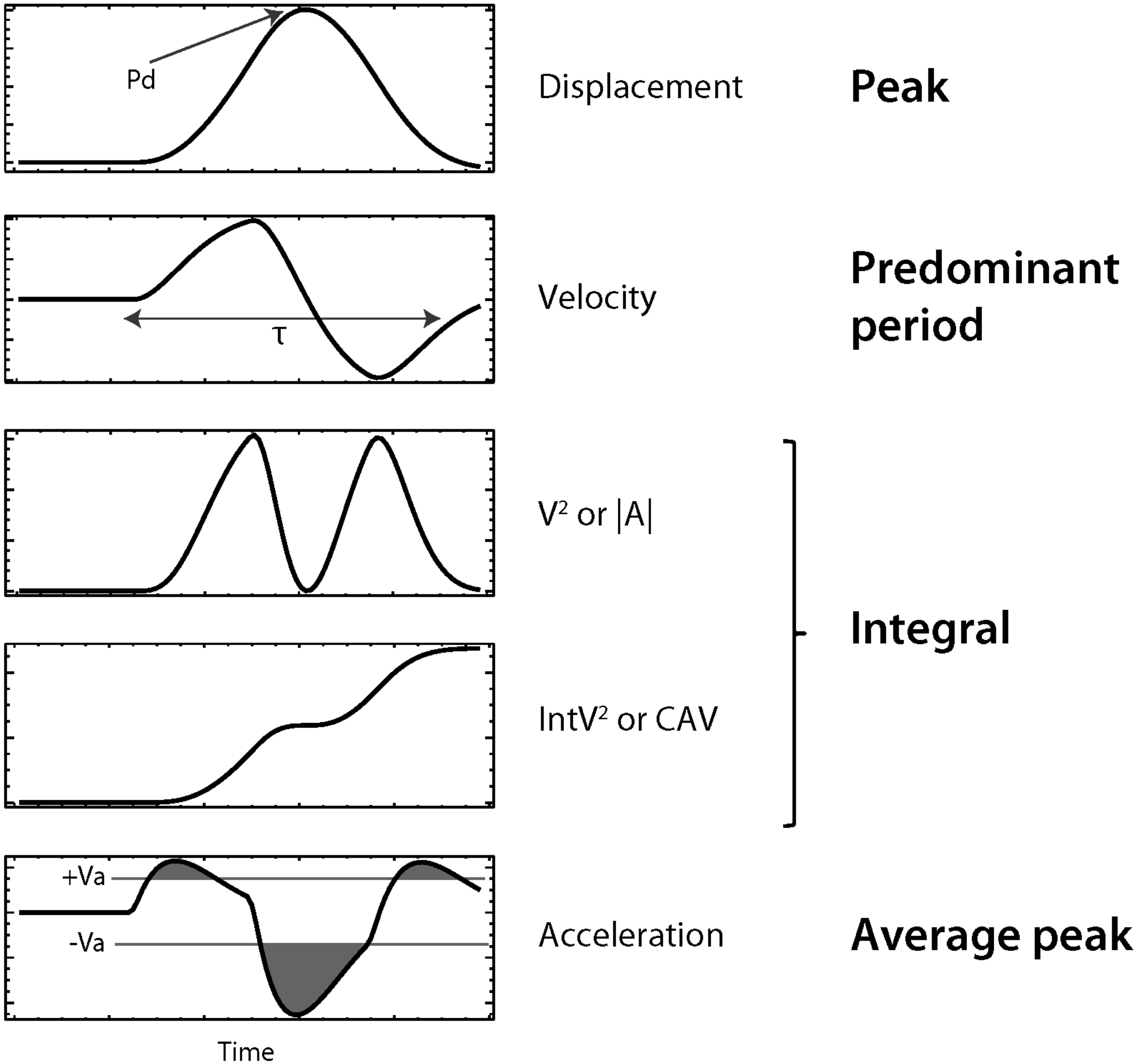


Alert notification

- Critically depends on uncertainties related to source parameter and peak motion estimation,.It must be designed according to the target application, probabilistic evaluation of missed/false alarms

Observed Physical Quantities for EW

The parameters used for real-time earthquake size determination : period parameters (e.g. τ_p and τ_c , mainly measured on velocity and displacement records , respectively), peak measurements (e.g. Pd, on displacement signals), integral quantities (e.g. CAV and IV2, measured on acceleration or velocity records) and peak levels (e.g. Va, measured on the acceleration).

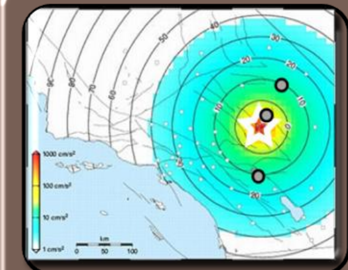


Real-time location

Basic concepts

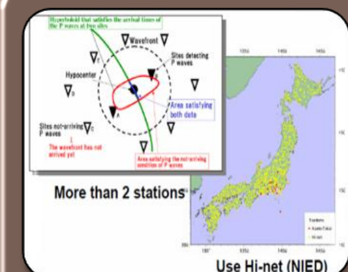
- Information from the stations that have not yet recorded the event
- Tracing and intersections of the isocrone surfaces
- Probabilistic estimation of the earthquake location as a function of time (evolutionary approach)

Real time eqk location: Different approaches



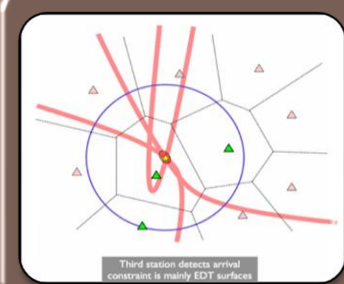
E-larms (Allen et al.)

- Initial epicenter is fixed at the first triggered station
- As first-P is recorded at other stations the epicenter is fixed at the baricenter of the recording stations
- No depth information



Horiuchi (Horiuchi et al, 2005)

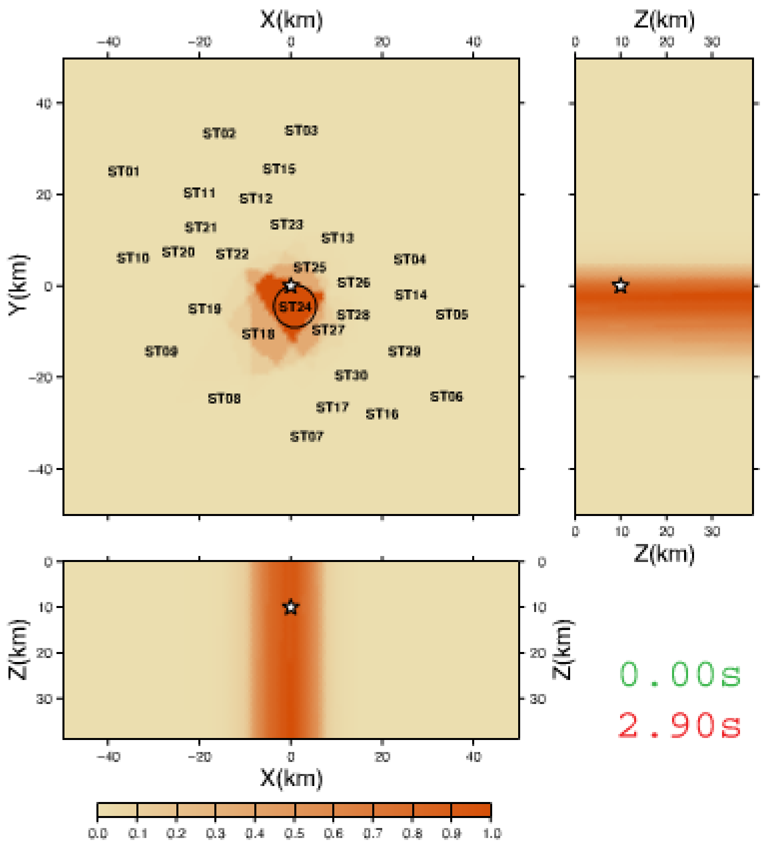
- Minimum two stations
- Trace the equal differential time surface between stations
- Intersect with the volume defined by not-yet recorded stations



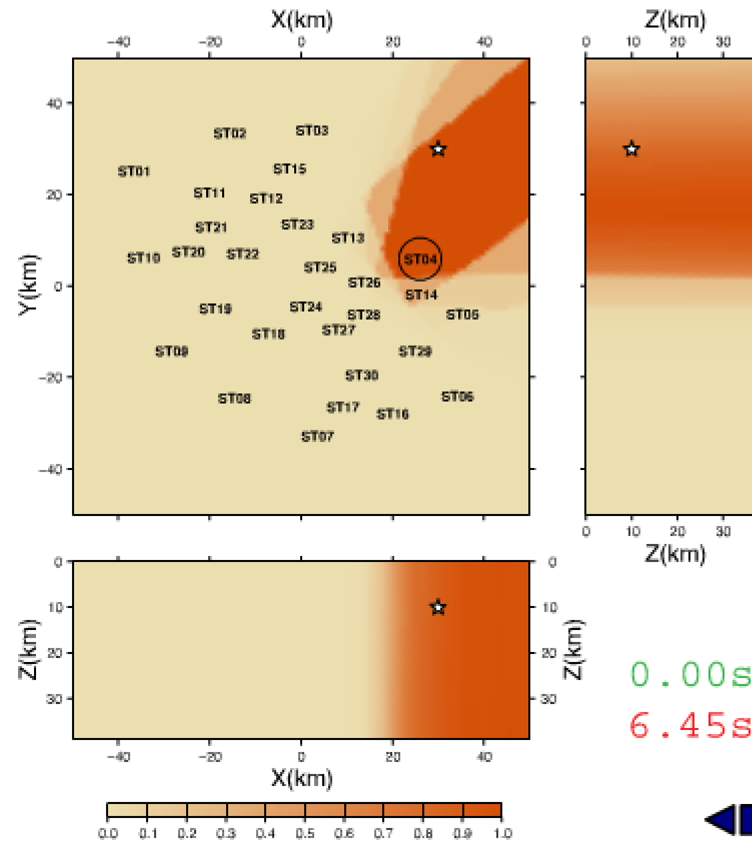
RTLOC (Satriano et al.,2008)

- Use 1 station, evolutionary, probabilistic
- Define Voronoi volumes for location with 1 station
- As the time increases use information from not-yet –arrived data to constrain the voronoi volume shape

RTLOC - Synthetic Simulation



Earthquake location probability



Earthquake location probability

Seconds from first trigger

Seconds from earthquake Origin Time

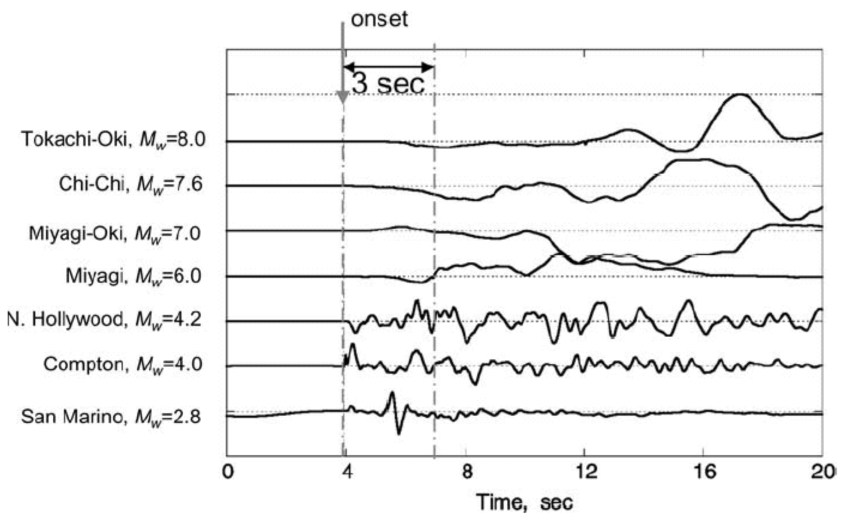
Triggered stations

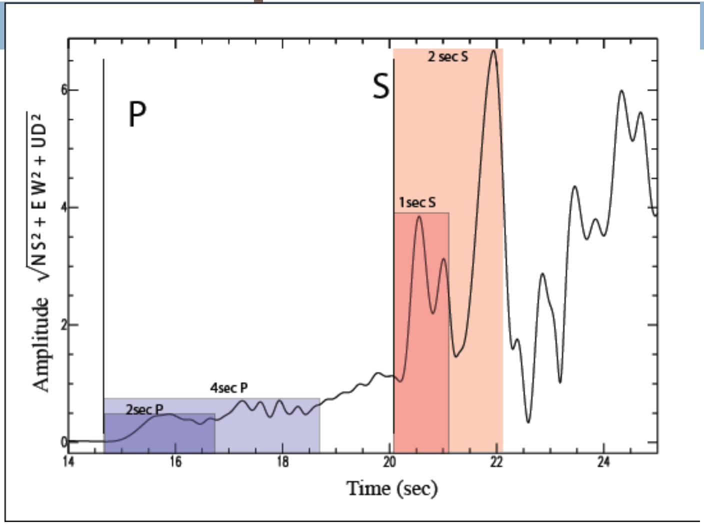
Real Time Magnitude

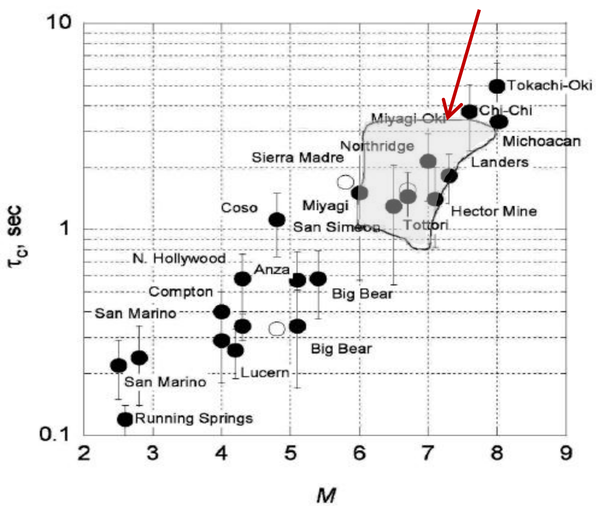
Basic Concepts

- Use of information carried out by early P- and S-waves recorded at a dense, high dynamics network deployed in the source area of earthquakes
- Determine empirical regression laws between real-time measured ground motion parameters (dominant period, peak displacement) and magnitude
- At each time step after first P, evaluate the magnitude using an evolutionary approach and combining P and S information at all recording stations

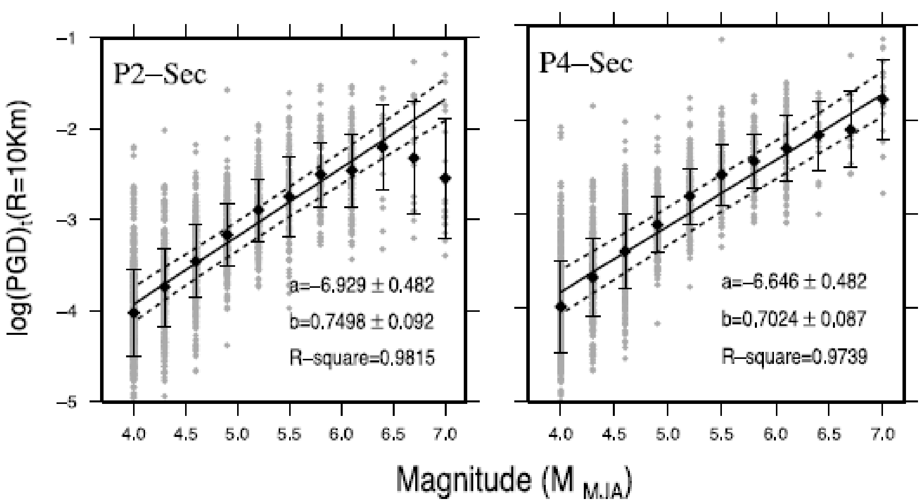
Peak displacement & Period parameter







Predominant period



Displacement Peak

Standard Approach

- P-phase detection (use only P)
- Measurement of τ and/or Pd on a 3(4) sec window after the first-P arrival
- Magnitude estimation through empirical relationships
- Average estimation using at least 4 stations
- Evolutionary estimation adding new data

A Bayesian, evolutionary approach

Lancieri & Zollo, JGR, 2008

$$f\left(m|\underline{d}\right)=\frac{f\left(\underline{d}|m\right)f\left(m\right)}{\int_{M_{MIN}}^{M_{MAX}} f\left(\underline{d}|m\right)f\left(m\right)dM}$$

Probability density function (PDF) of magnitude given the observed P-, S-peak data vector $\underline{d}=\{d_1,d_2,\ldots,d_N\}$ at time T

Prior PDF of magnitude derived from the Gutenberg-Richter law

$$f\left(m\right):\begin{cases}\dfrac{\beta e^{-\beta m}}{e^{-\beta M_{\min}}-e^{-\beta M_{\max}}} & M_{\min}\le m\le M_{\max}\\ 0 & m\notin\left[M_{\min},M_{\max}\right]\end{cases}$$

$$f\left(\underline{d}|m\right)=\prod_{i=1}^{\nu}\frac{1}{\sqrt{2\pi}\,\sigma_{\log(d)}\,d_i}\,e^{-\frac{1}{2}\left(\frac{\log(d_i)-\mu_{\log(d)}}{\sigma_{\log(d)}}\right)^2}$$

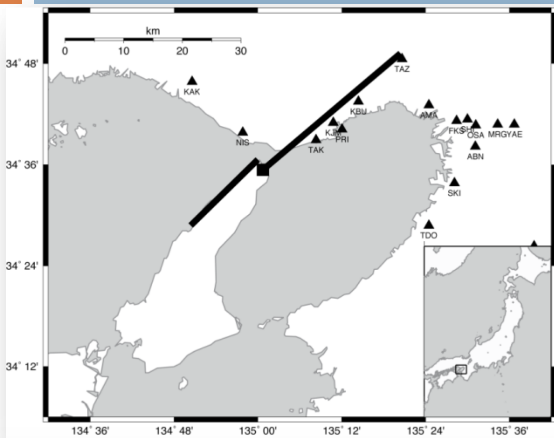
PDF of observed data given M:

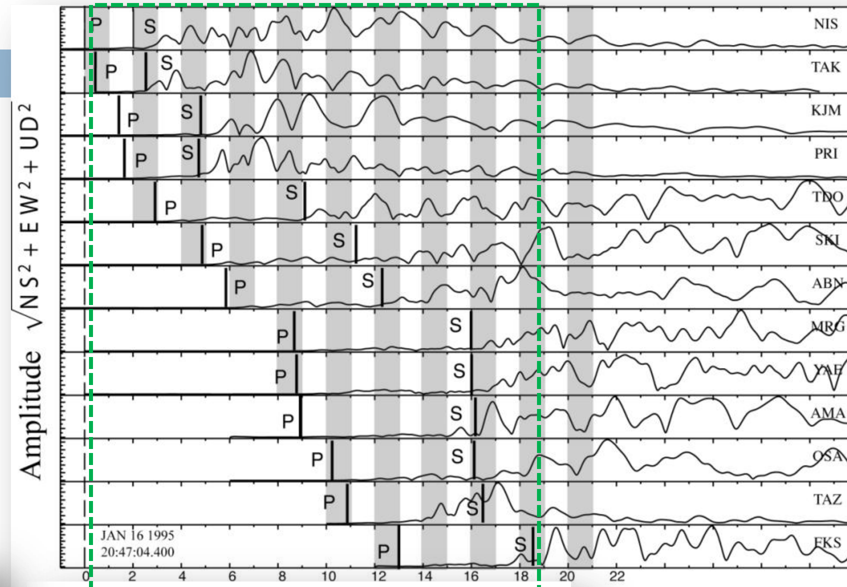
Hypotheses on data:

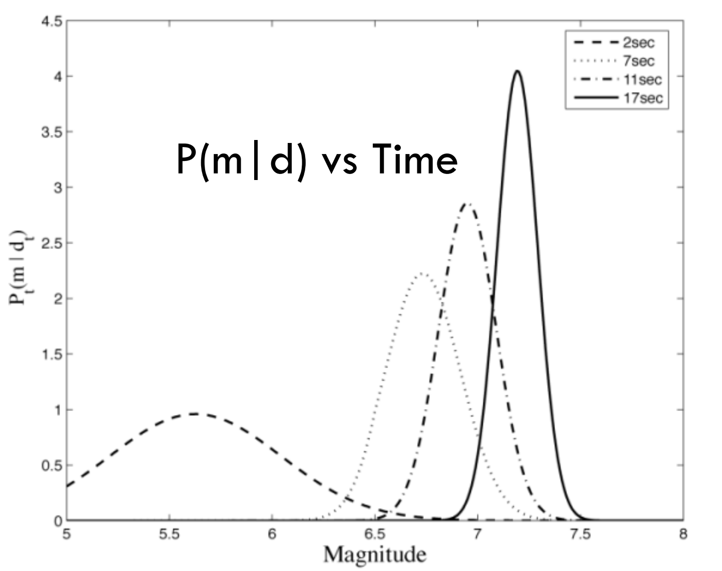
- are stochastically independent
- follow a log-normal distribution with

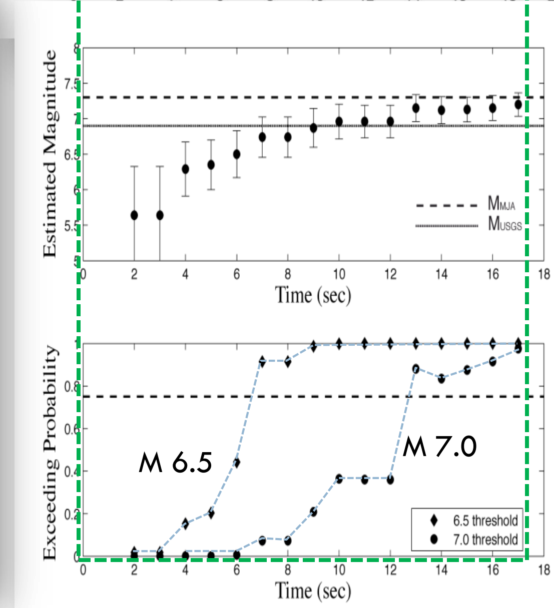
mean μ and st.dev σ

Offline application: The1995 Kobe Eqk (M=7.3)







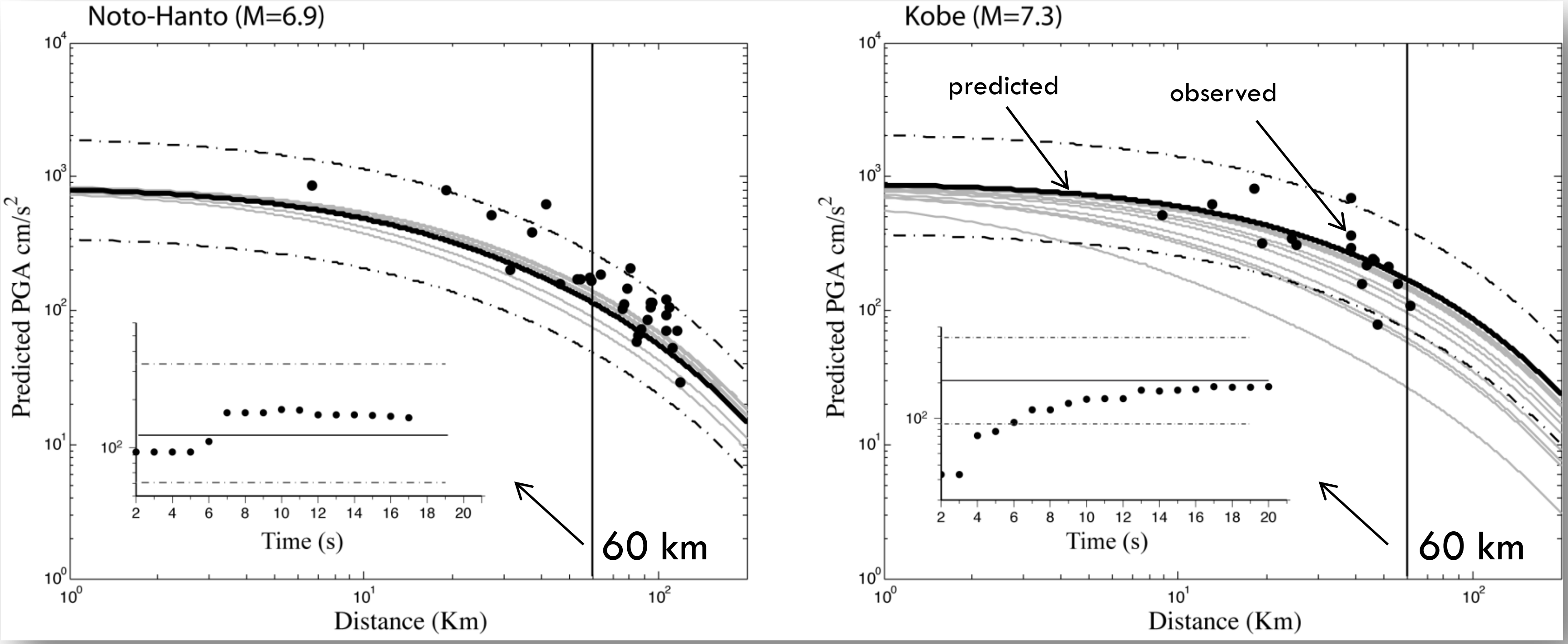


Magnitude vs Time

Probability to exceed M 6.5 and M 7.0 thresholds as a function of time

Lancieri & Zollo, JGR, 2008

Prediction of Peak Ground motion at the target site

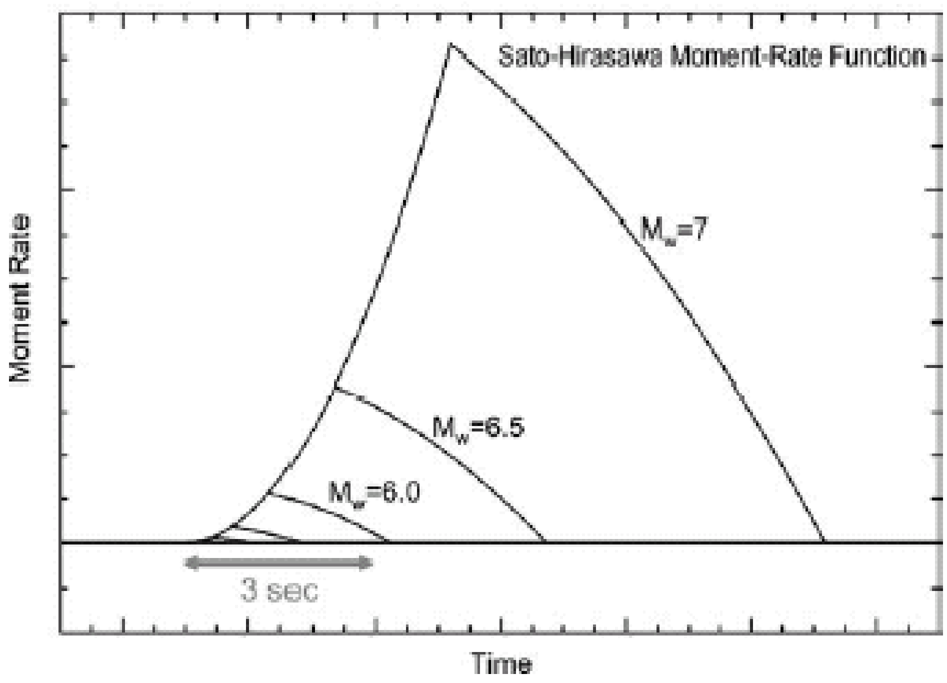


❑ Attenuation relationships are used to predict the Peak Ground Acceleration at any time step after first-P detection.

❑ Reliable predictions of peak ground motion can be obtained few seconds after the first P arrival at the network, despite of a significant uncertainty in the initial magnitude estimates.

Lancieri & Zollo , JGR,2008

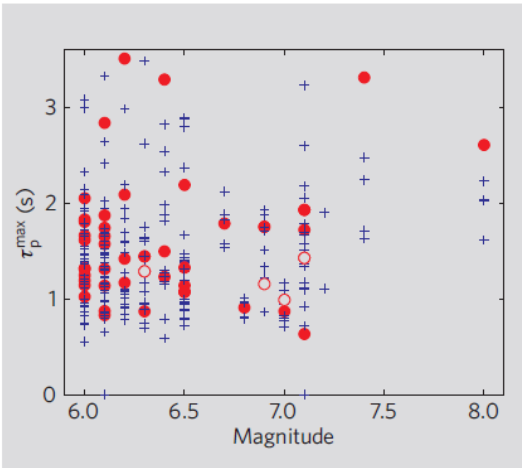
Paradox of the real-time estimate of magnitude



How is it possible to have in 3 seconds of signal information about the size of an earthquake for which the rupture lasts ten seconds or more?

From Kanamori,Ann.Rev.Earth Pla.Sc2005

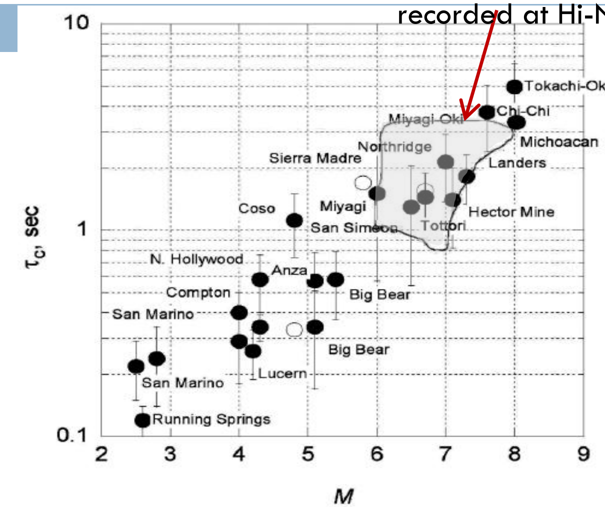
Debates: saturation effect at M~6-6.5



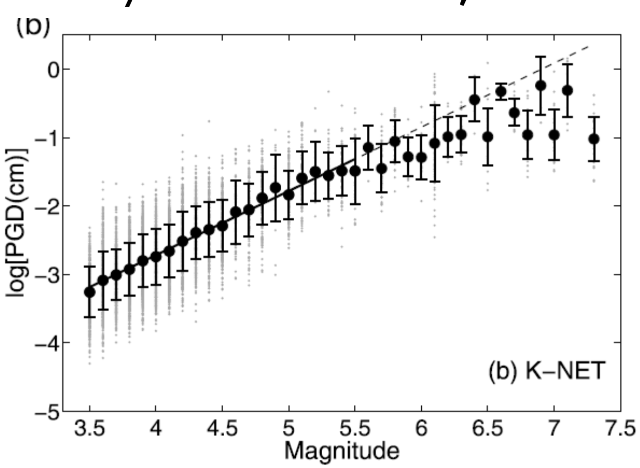
Rydelek & Horiuchi, 2006

tau

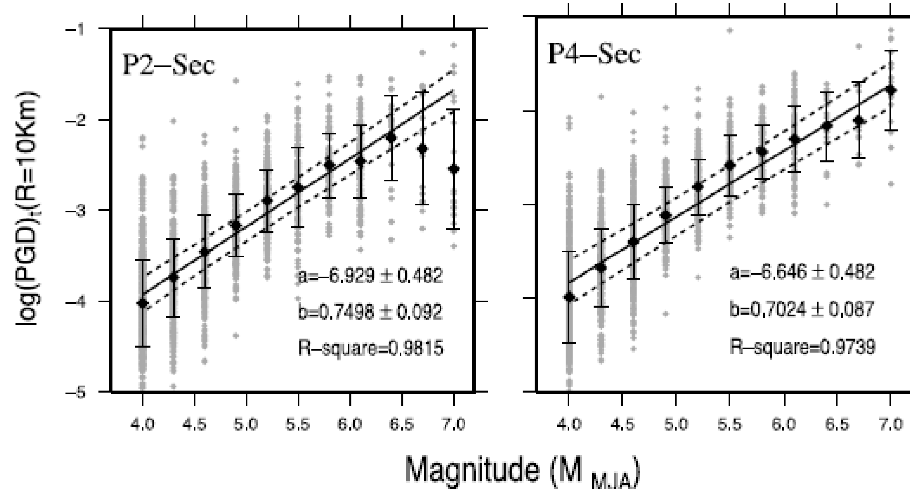
Japanese eqks recorded at Hi-Net



Wu & Kanamori, 2008



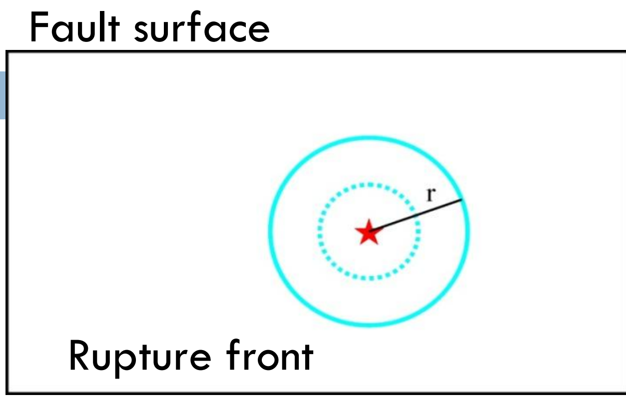
Pd



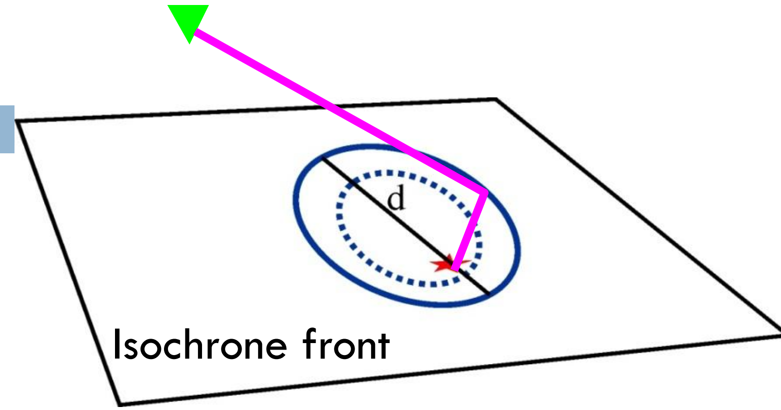
Rydelek et al, 2007

Zollo et al, 2007

The saturation effect

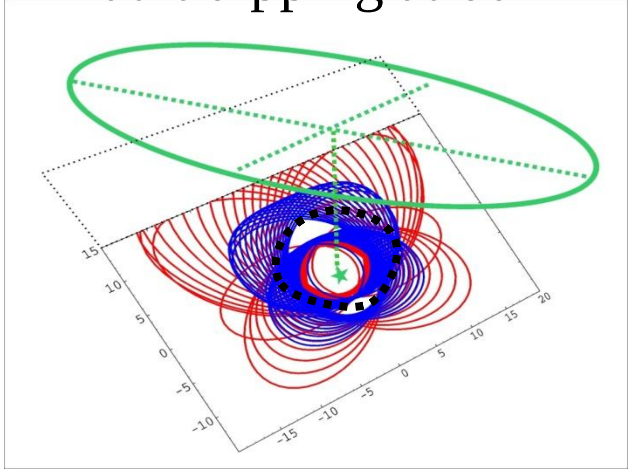


$t_r = r/v_r$



$T_{iso} = t_r + t_p$

Fault dipping at 60°

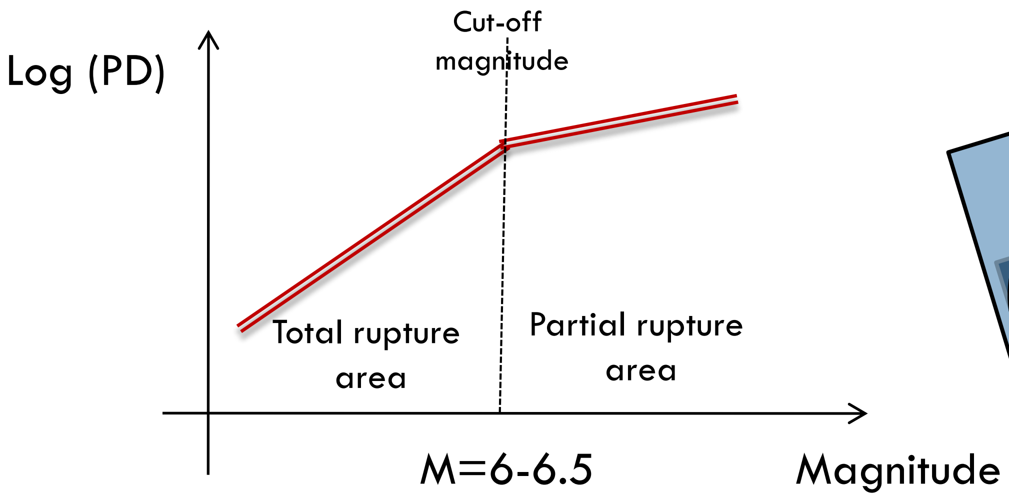


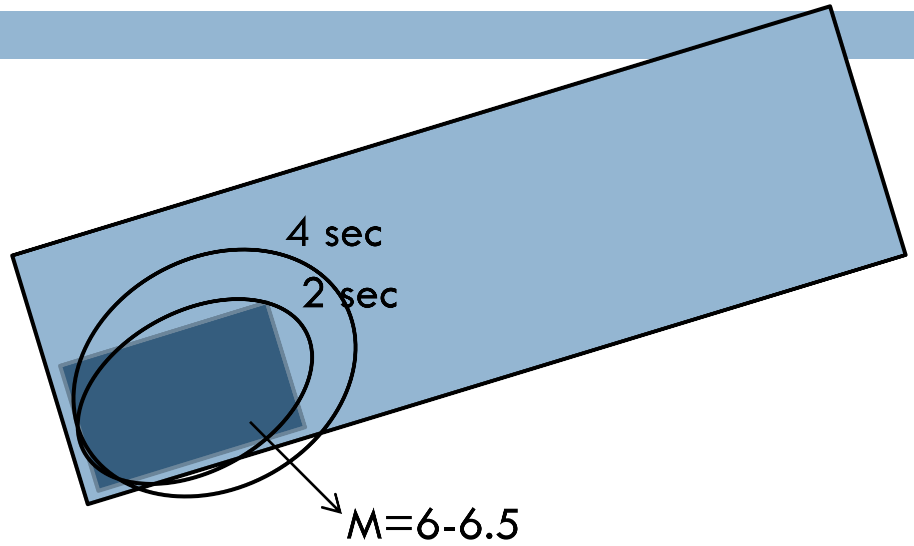
- The fault area spanned by **X seconds of P/S records** (isochrone front) is generally larger than the fractured area in **X seconds** (rupture front).

- The area imaged by X sec of S-waves is larger than for X sec of P-waves

- The saturation is due to an under-sampling of fault surface by 2sec of P-waves. It disappear for an enlarged P-window of 4sec

The scaling of peak displacement with magnitude

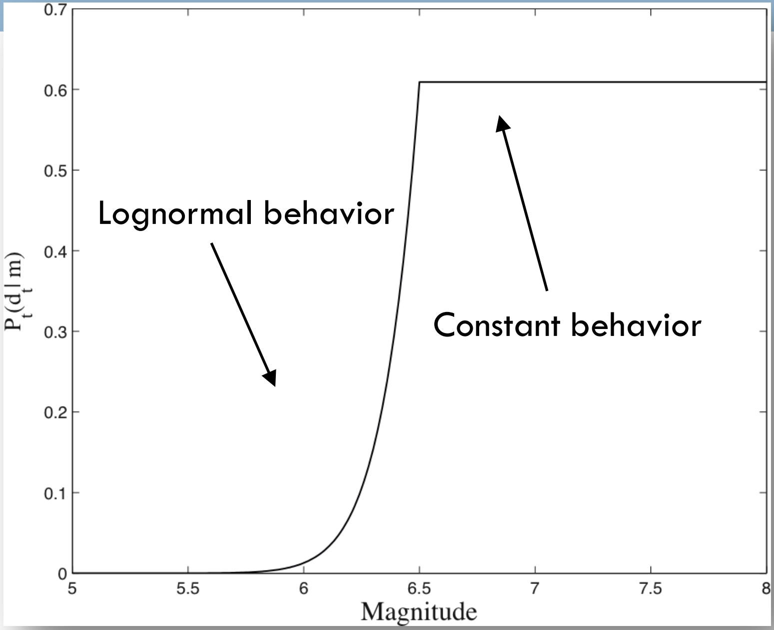


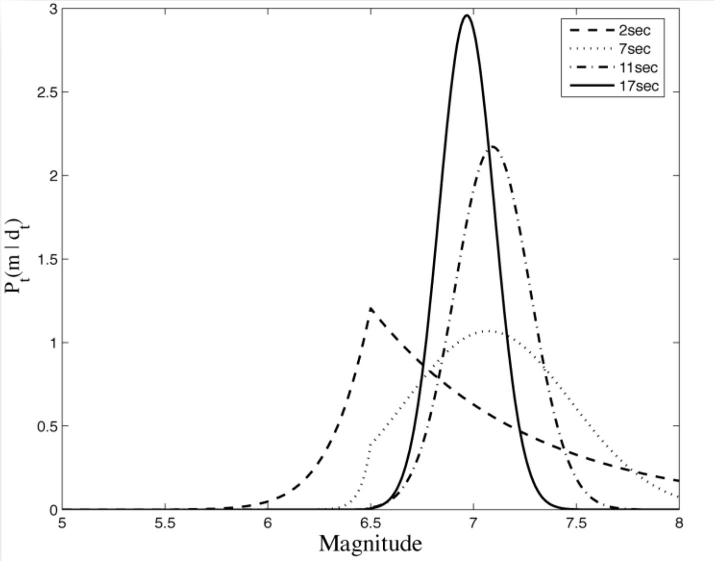


2-sec of P-waves at near-source distances map almost entirely the rupture area for M≤ 6-6.5 events. For larger events only a portion of the rupture area is sampled in the same time window.

A Bayesian Approach to overcome the saturation effect

The **saturation effect on P_2 sec data** is taken into account by defining an 'ad hoc' PDF which assigns an uniform probability to events with M≥6.5. This means that for M≥6.5 the magnitude PDF is controlled by the Gutenberg-Richter relationship.



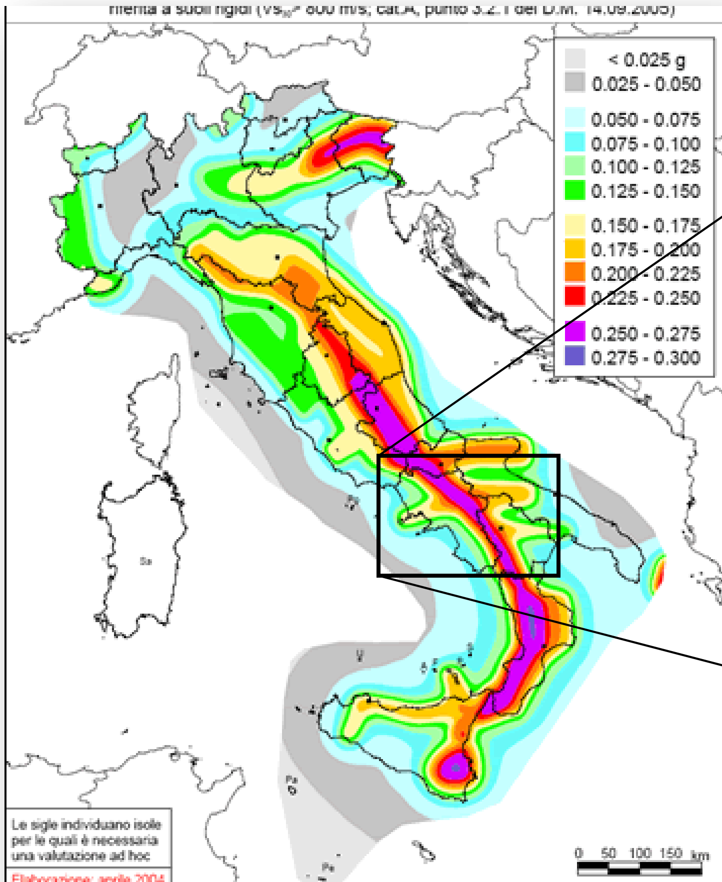


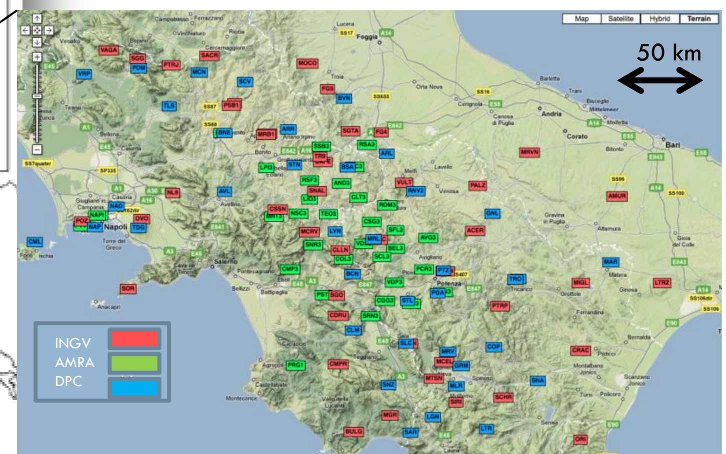
At each time step, after the first P-wave is detected at the network, **the magnitude PDF is estimated using P and S displacement peaks** available at that time window , **including P(2sec), P(4sec) and S(2sec).**

Lancieri & Zollo , JGR,2008

An EEW system in Southern Italy

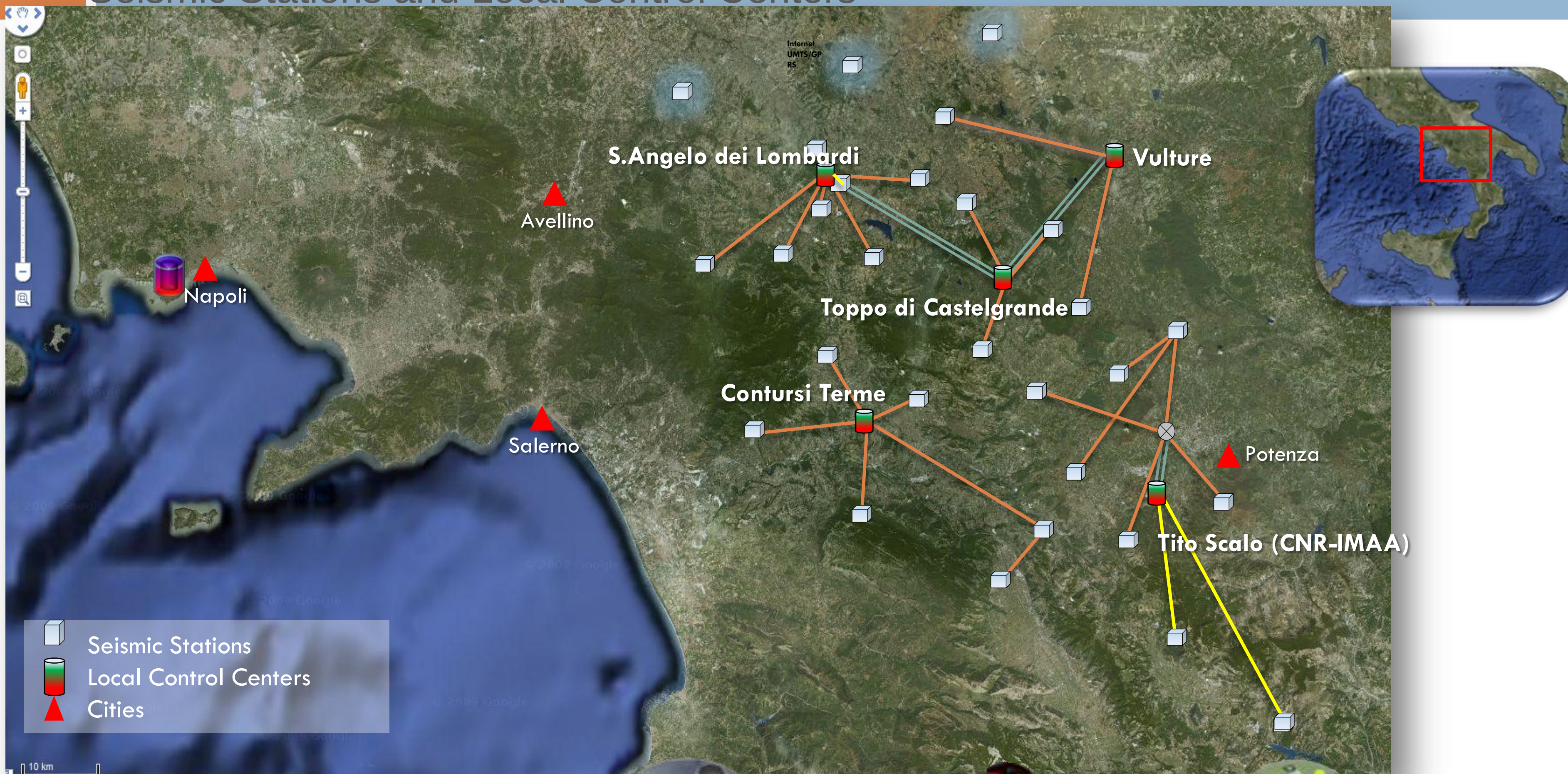
A real-time seismic alert management system is under testing in southern Italy. It is based on a dense, wide dynamics seismic network monitoring one of the highest earthquake hazardous areas in Italy.





The Irpinia Seismic Network (ISNet)

Seismic Stations and Local Control Centers



31 Sites

OSIRIS

CMG-5T and

S13-J or

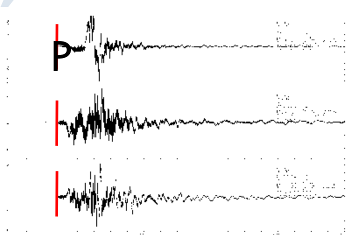
Trillium 40S

PRESTo

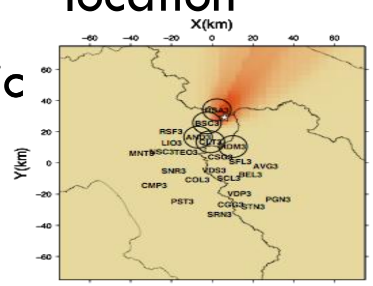
(**P**robabilistic & evolutiona**R**y **E**arly warning **S**ys**T**em)

Automatic procedures for the probabilistic and evolutionary estimation of source parameters and prediction of ground motion shaking.

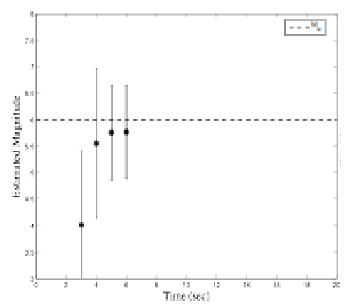
Automatic Picking



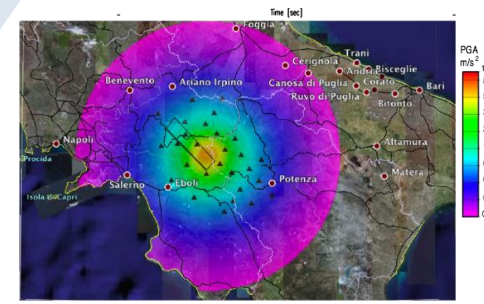
RT Earthquake location



RT Magnitude estimation



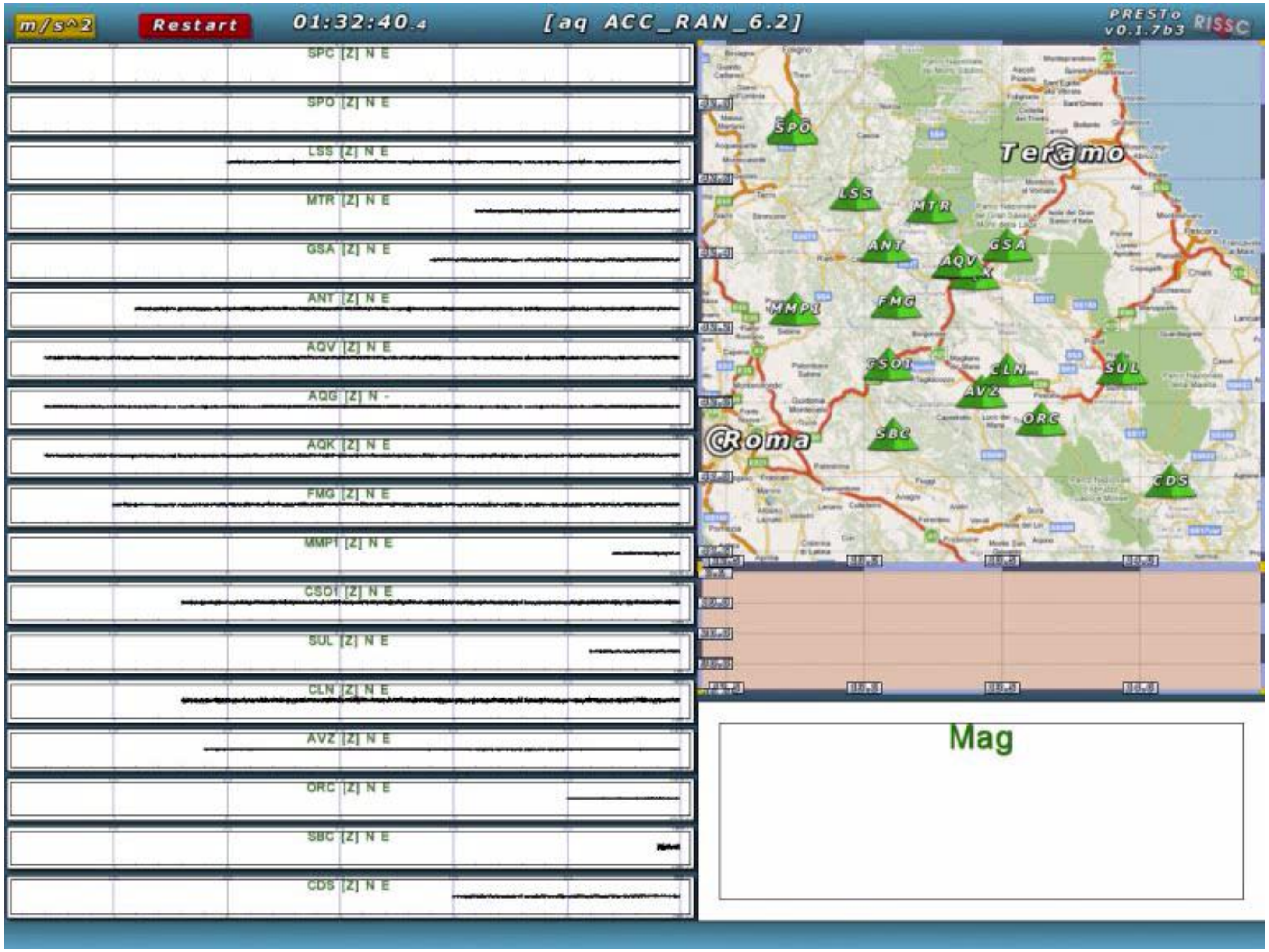
PGX prediction at the target sites



An integrated software platform for the real data processing and seismic alert notification.

Satriano et al., SDEE, 2010

Off-line application of PRESTo: The example of 2009 Mw 6.3, L'Aquila eqk



RAN

Epicenter & P,S wave propagation, PGA prediction at Teramo & Roma

Vertical component records

depth

Magnitude vs time

Issuing an EW alert: Can we by-pass the Magnitude estimation?

Observed correlation between PD and PGV (Wu & Kanamori)

For moderate to strong eqks PGV is related to seismic intensity

Using PD and Tau for setting up an alert decision table

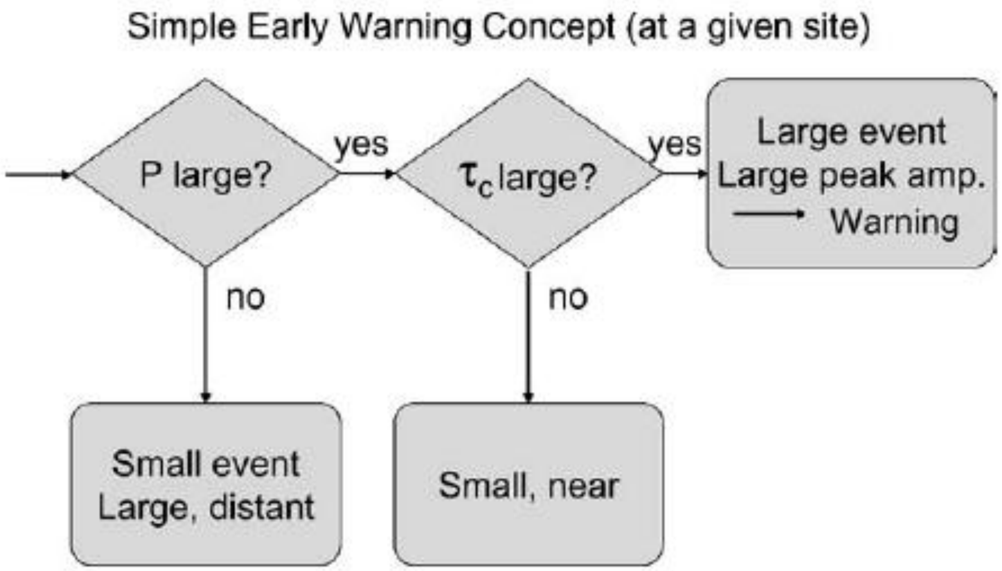


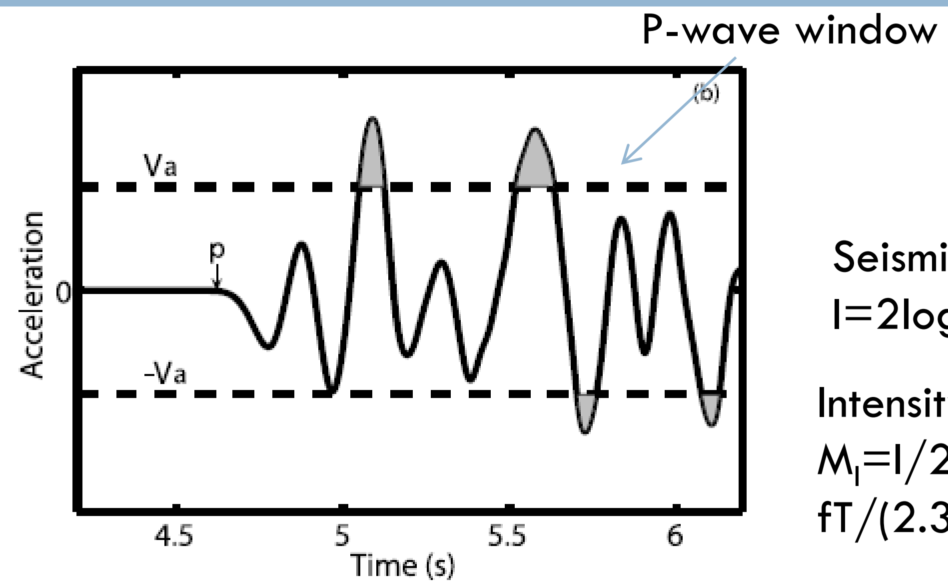
Figure 8 A simple scheme for on-site early warning.

From Kanamori, 2005

An alternative approach: seismic intensity

Yamamoto et al.,GRL, 2008

V_a is the level at which the acceleration stays higher for more than 0.3 seconds

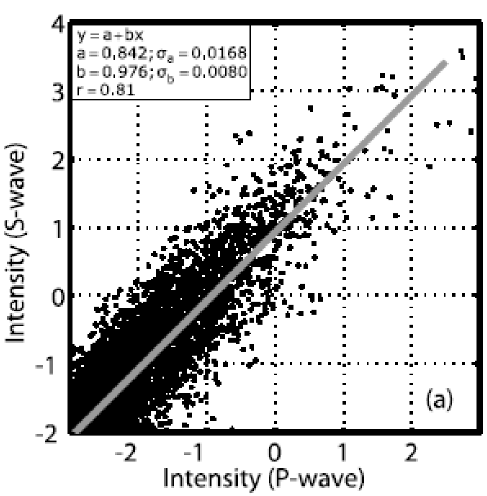


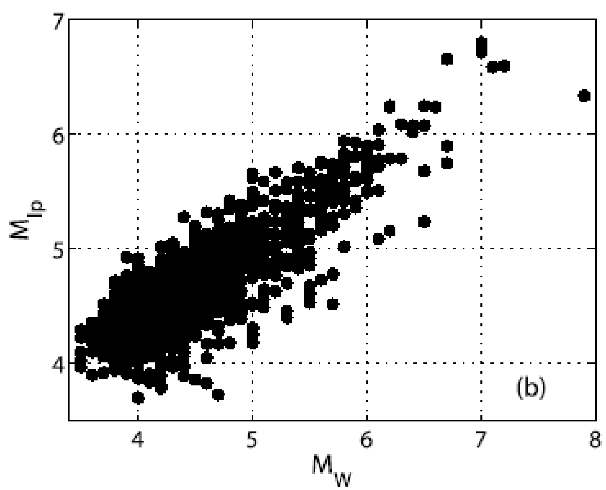
Seismic intensity:

$I = 2\log_{10}(V_a) + 0.94$

Intensity magnitude:

$M_I = I/2 + \log_{10}(r) + \pi fT/(2.3Q) + b + \log_{10}(C_j)$





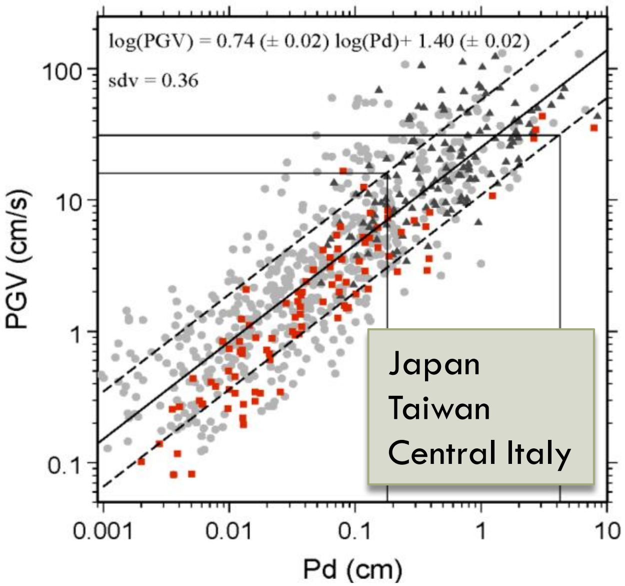
Needs estimates of:

r=hypocentral distance,

Q=attenuation parameter

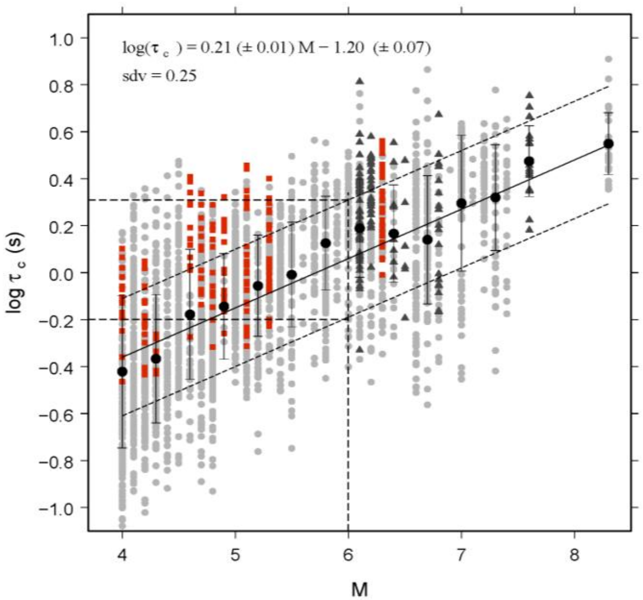
Cj=site amplification effect

A Threshold-Based Early Warning



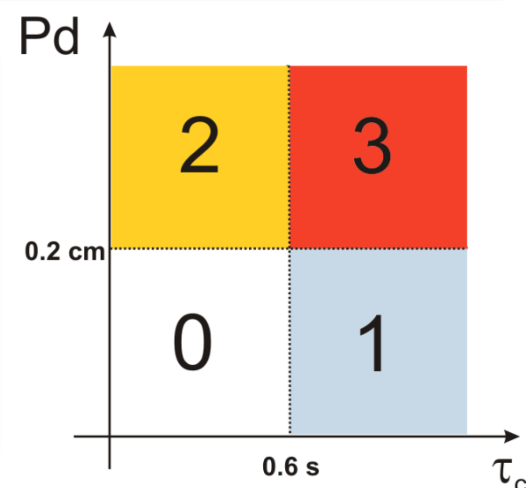
Zollo et al., GJInt,2010

- Initial P-peak displacement (Pd) correlates with whole-record Peak Ground Velocity.
  Pd>0.2 cm → PGV > 16 cm/sec → I_{MM}> VII : DAMAGING EQK!
- Initial P-period parameter (τ_c) correlates with final magnitude. **τ_c > 0.6 sec → M> 6**



Alert levels and threshold values for P_d and τ_c

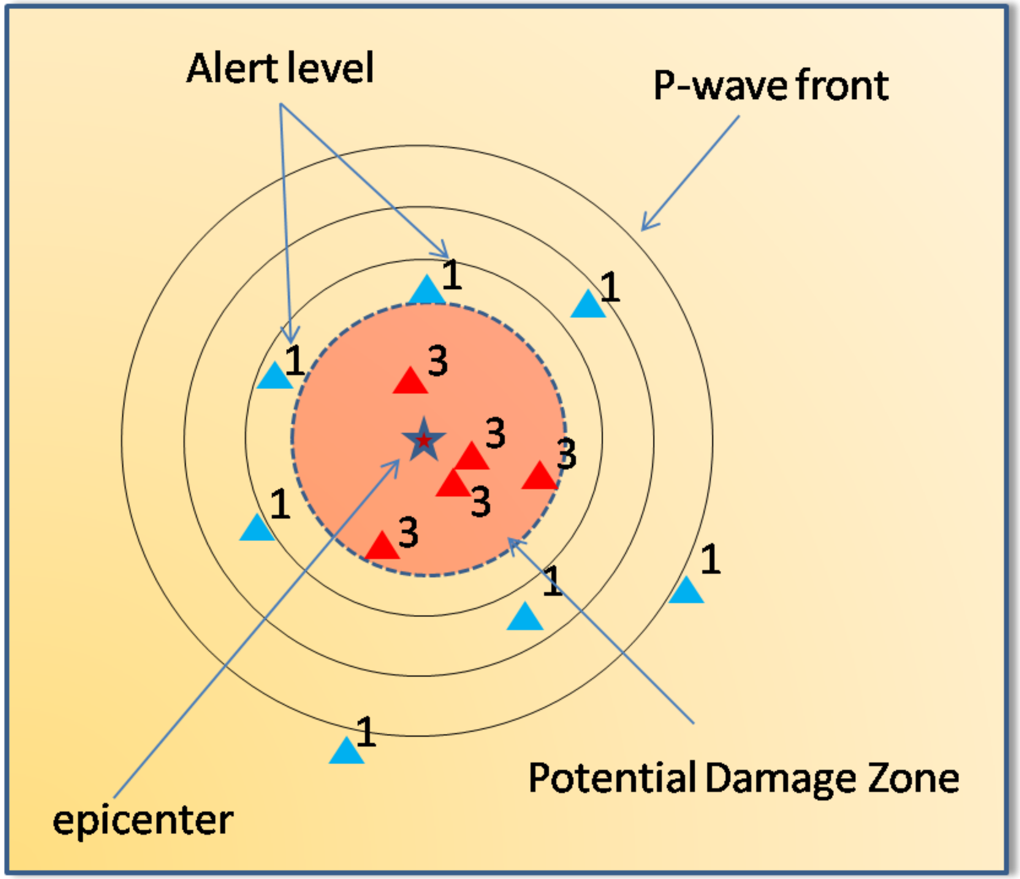
Alert levels			
Damages nearby & far away from the station	Damages only nearby the station	Damages only far away from the station	No damages
3	2	1	0



New Developments: Threshold-based

The local measurement of P_d and τ_c can be used to:

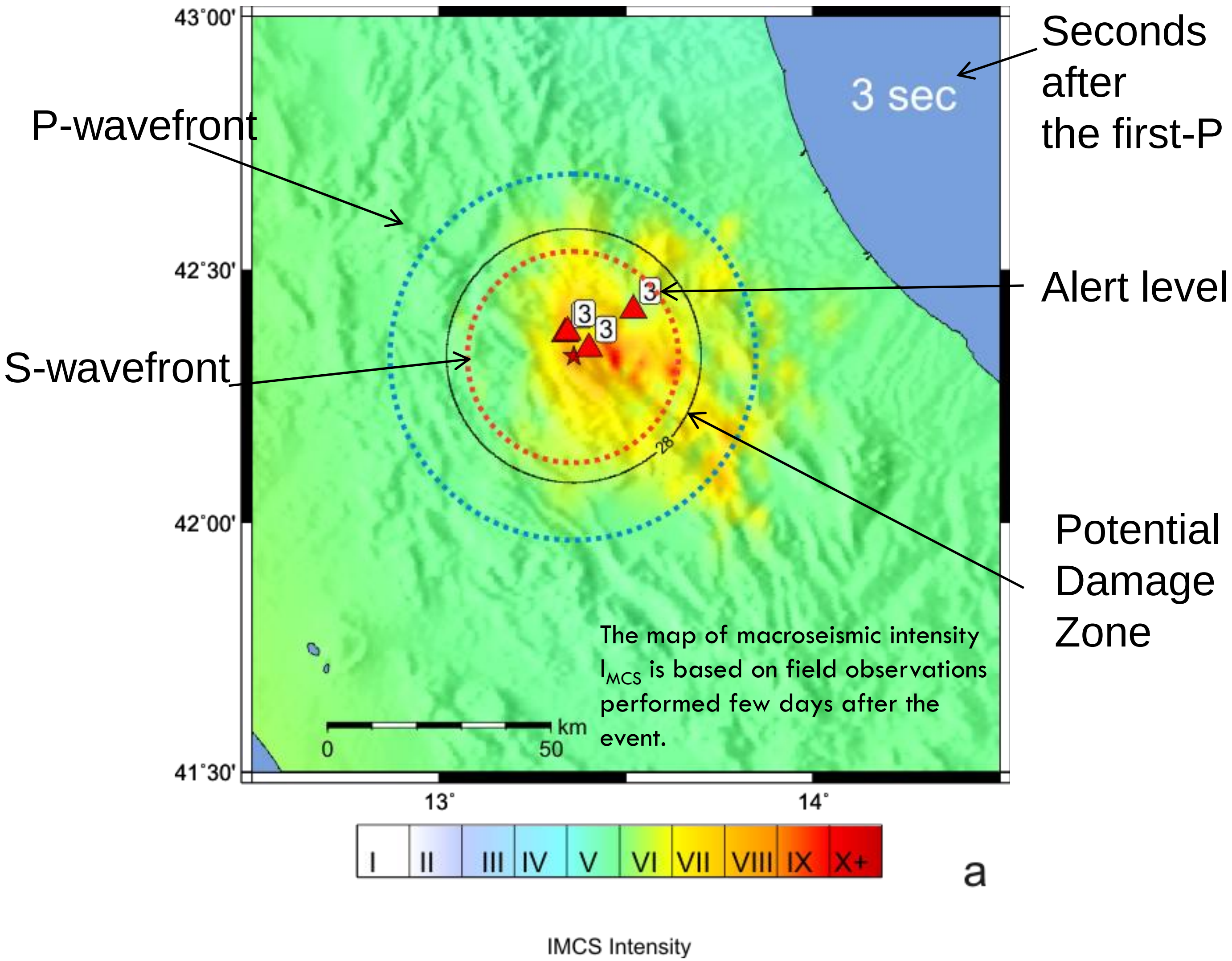
- define the alert level for that site
- define the potential damaged/not damaged areas
- send an alert to distant sites
- make a decision based on the regional information and the local measurement of ground motion



The extent of the potential damage zone (PDZ) is mapped from the geographical distribution of recorded alert levels and updated averages of τ_c as new measurements are available at the network.

Off-line application to the 2009, Mw 6.3 L'Aquila earthquake

Space and time evolution of the recorded alert levels . The figure shows how they can be used to rapidly estimate the extent of the potential damage zone.



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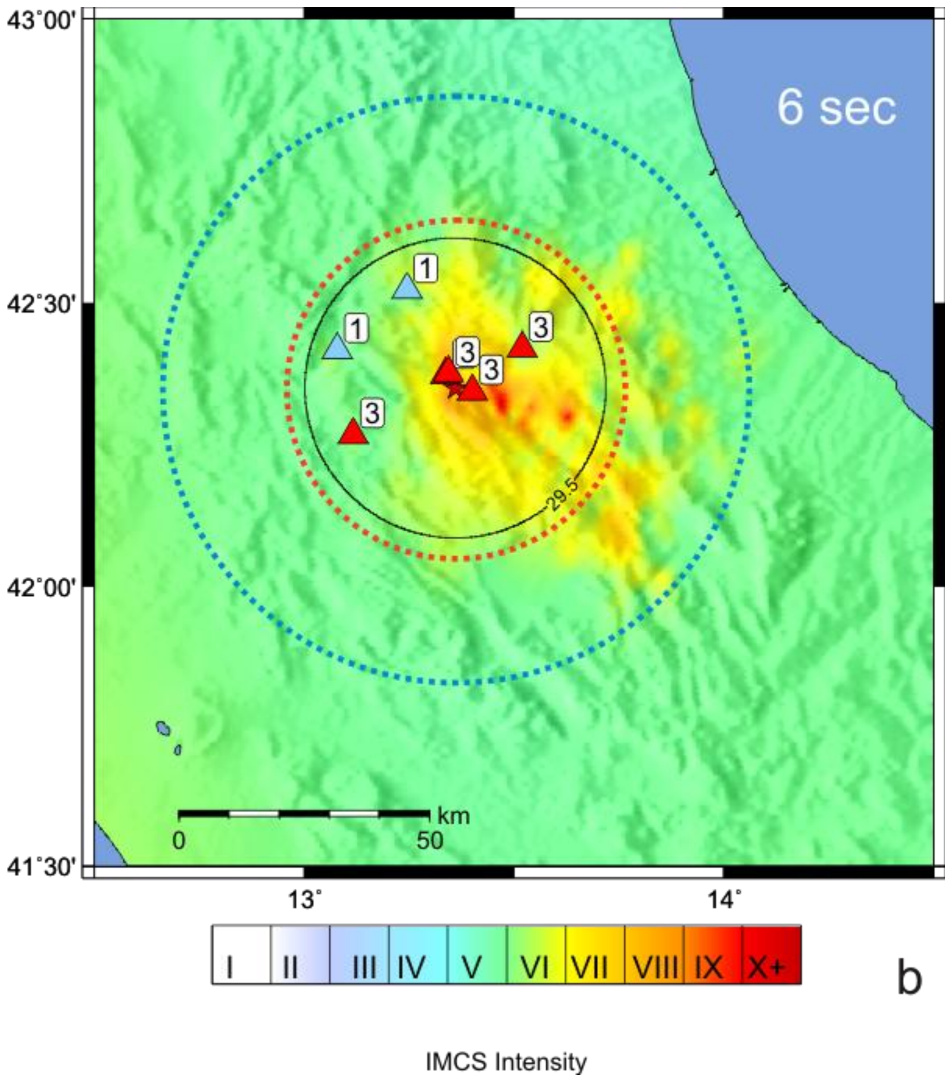

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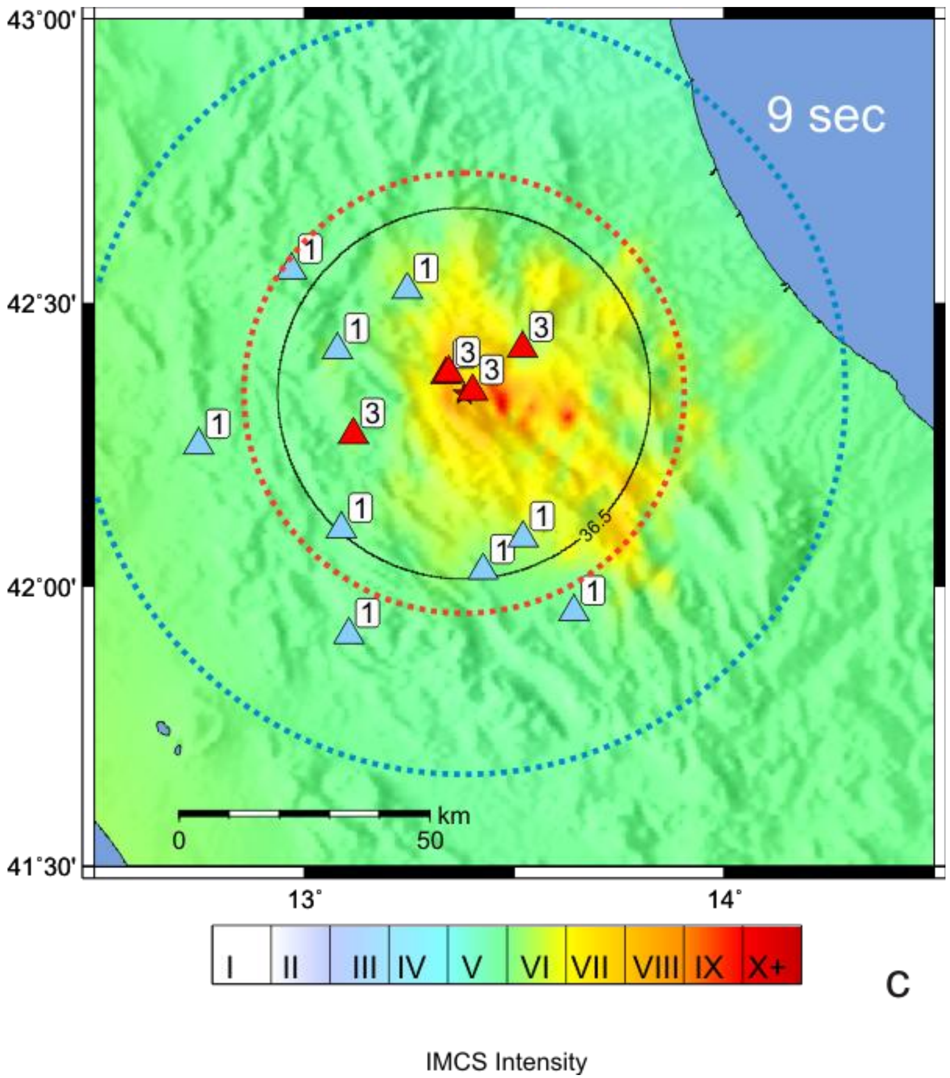

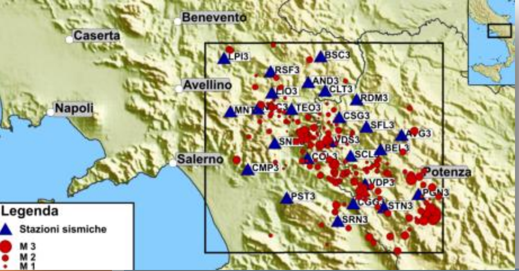

Conclusions & Perspectives

The Earthquake Early Warning is the next decade, scientific and technological challenge of real-time seismology and earthquake engineering

- The Earthquake Early Warning is feasible, despite of the limited alert times (seconds to tens of seconds), and usable for both automatic and individual actions for mitigation of earthquake effects
- Applications and Control systems: Targets and mitigation actions must be defined according to available lead-times. Need to develop control mechanisms able to take automatic decisions and interfaces, end-user oriented (civil protection, industrial plants security, transport networks,…)
- The legal issue of Early Warning: Need for specific laws regulating the experimentation and practice of Early Warning (the Japan example)
- Diffusion of knowledge and information about Early Warning: The system implementation must be accompanied by an adequate education and training of end-users

Thanks for your attention !

Suggested Reading

- Hiroo Kanamori, "Real-Time seismology and earthquake damage mitigation" 2005, *Annu. Rev. Earth Planet. Sci.* 33: 195–214, doi:10.1146/annurev.earth.33.092203.122626.
- Earthquake Early Warning Systems, Gasparini, Paolo; Manfredi, Gaetano; Zschau, Jochen (Eds.) 2007,**Springer**, XXIV, 350 p. 153
- R. Allen, P. Gasparini, O. Kamigaichi, and M. Bose, ***The Status of Earthquake Early Warning around the World: An Introductory Overview,*** Seismological Research Letters Volume 80, 2009
- C. Satriano, Y.-M.Wu, A. Zollo and H. Kanamori, **Earthquake early warning: Concepts, methods and physical grounds**, Soil Dyn. Earthq. Eng., 2010, in press