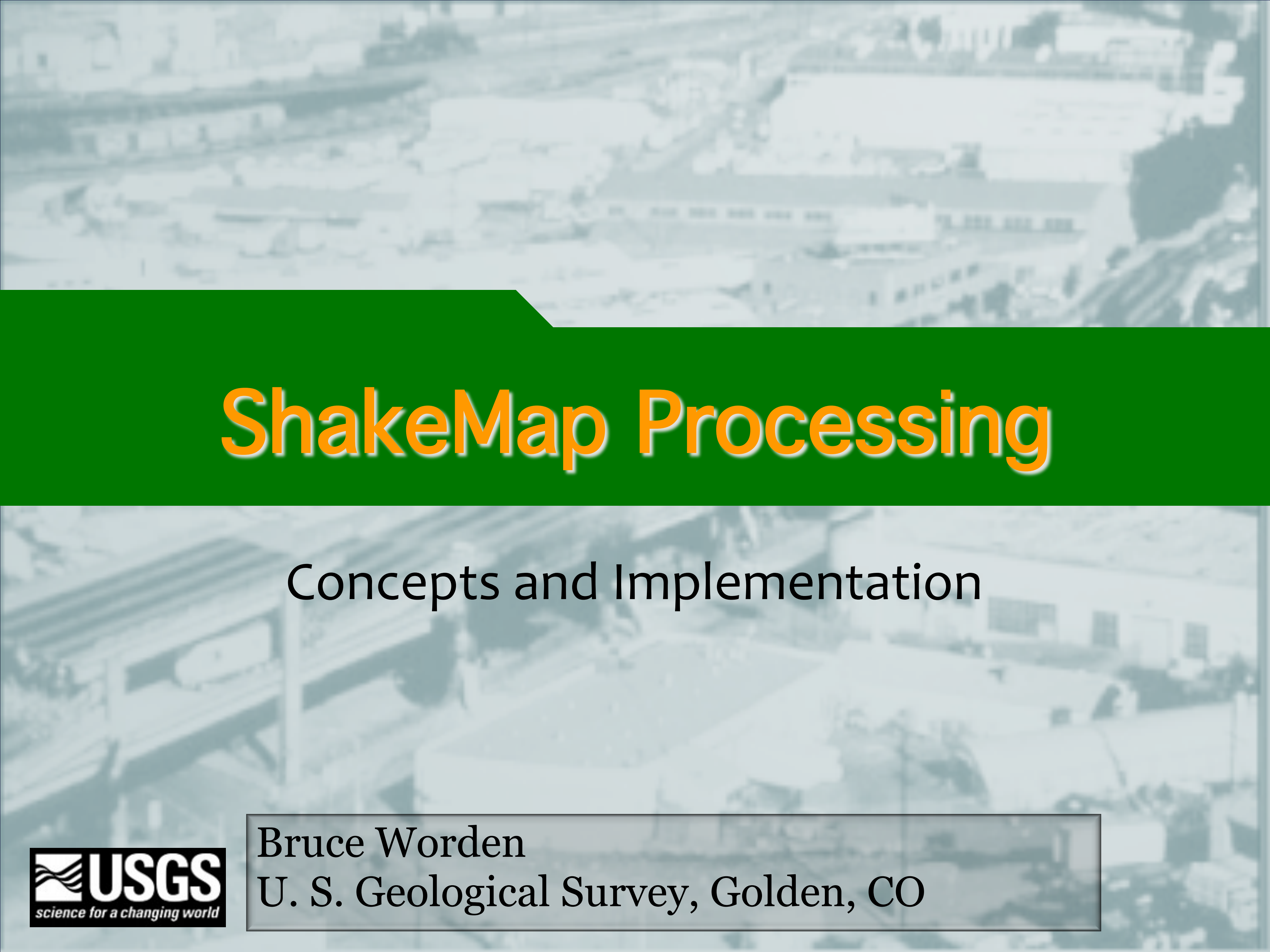


ShakeMap Processing

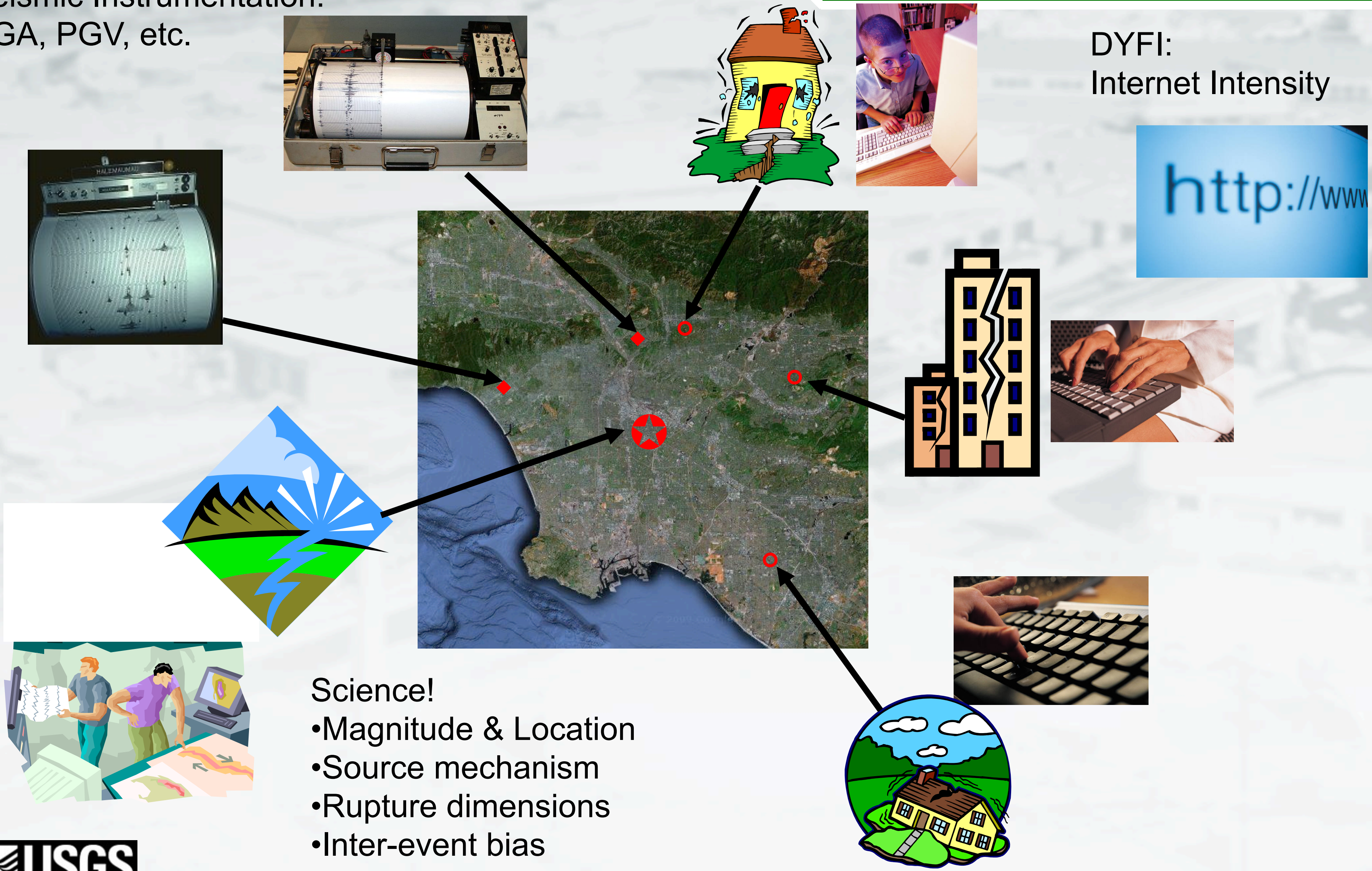
Concepts and Implementation

Bruce Worden
U. S. Geological Survey, Golden, CO

Data Sources

Seismic Instrumentation:
PGA, PGV, etc.

DYFI:
Internet Intensity



Science!
- Magnitude & Location
- Source mechanism
- Rupture dimensions
- Inter-event bias
- Directivity

Processing Overview

- Data Preparation
  - Remove flagged stations
  - Convert MMI to PGM and PGM to MMI (GMICE)
  - Correct data to “rock” (reverse Vs30 site amp.)
  - Remove basin amplification
- Compute event bias
  - Compute preliminary bias
  - Remove outliers
  - Repeat until no outliers

Processing Overview (cont.)

- Interpolate ground motions to a uniform grid
  - Compute biased GMPE estimates at each station and for each point in the output grid
  - Interpolate (Worden et al., 2010)
- Amplify ground motions
  - Basin amplification
  - Vs30 site amplification

Processing Overview

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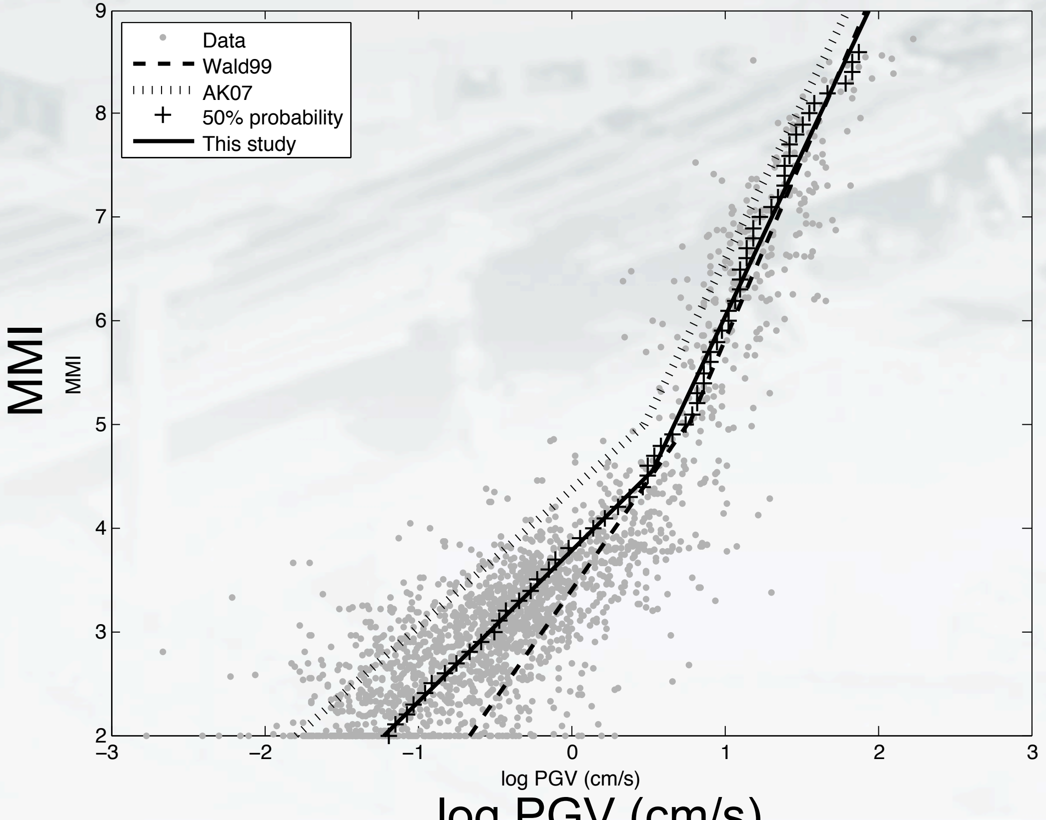
GMICE

GMICE: Ground Motion/Intensity Conversion Equation

- Relates macroseismic intensity to specific ground motion parameters (Wald et al., 1999; Worden et al., 2012; etc.)



Processing Overview

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  - Remove flagged stations
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Reverse Site Amplification

Reverse the effect of site (de)amplification to correct ground motion amplitudes to arbitrarily defined “rock” site.

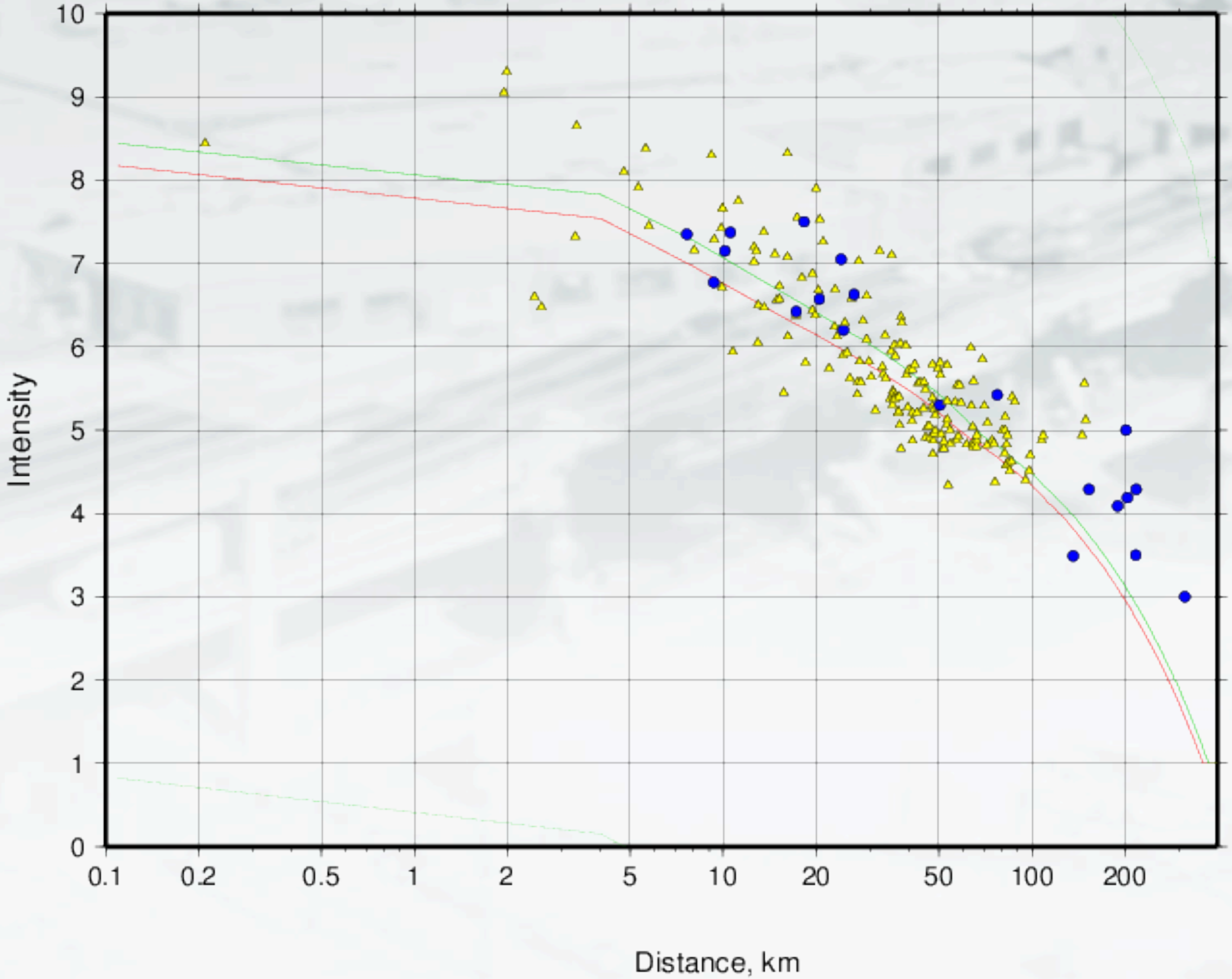
- Reverse amplification should be reversible (i.e., a “round trip” should reproduce the original amplitude.)
- Many GMPEs define site terms, otherwise use Borcherdt-style amplification terms.
- GMPE amplification terms can be complicated and may require iterative solution.

Processing Overview

- Data Preparation
  - Remove flagged stations
  - Convert MMI to PGM and PGM to MMI (GMICE)
  - Correct data to “rock” (reverse Vs30 site amp.)
  - Remove basin amplification
- Compute event bias
  - Compute preliminary bias
  - Remove outliers
  - Repeat until no outliers

Event Bias

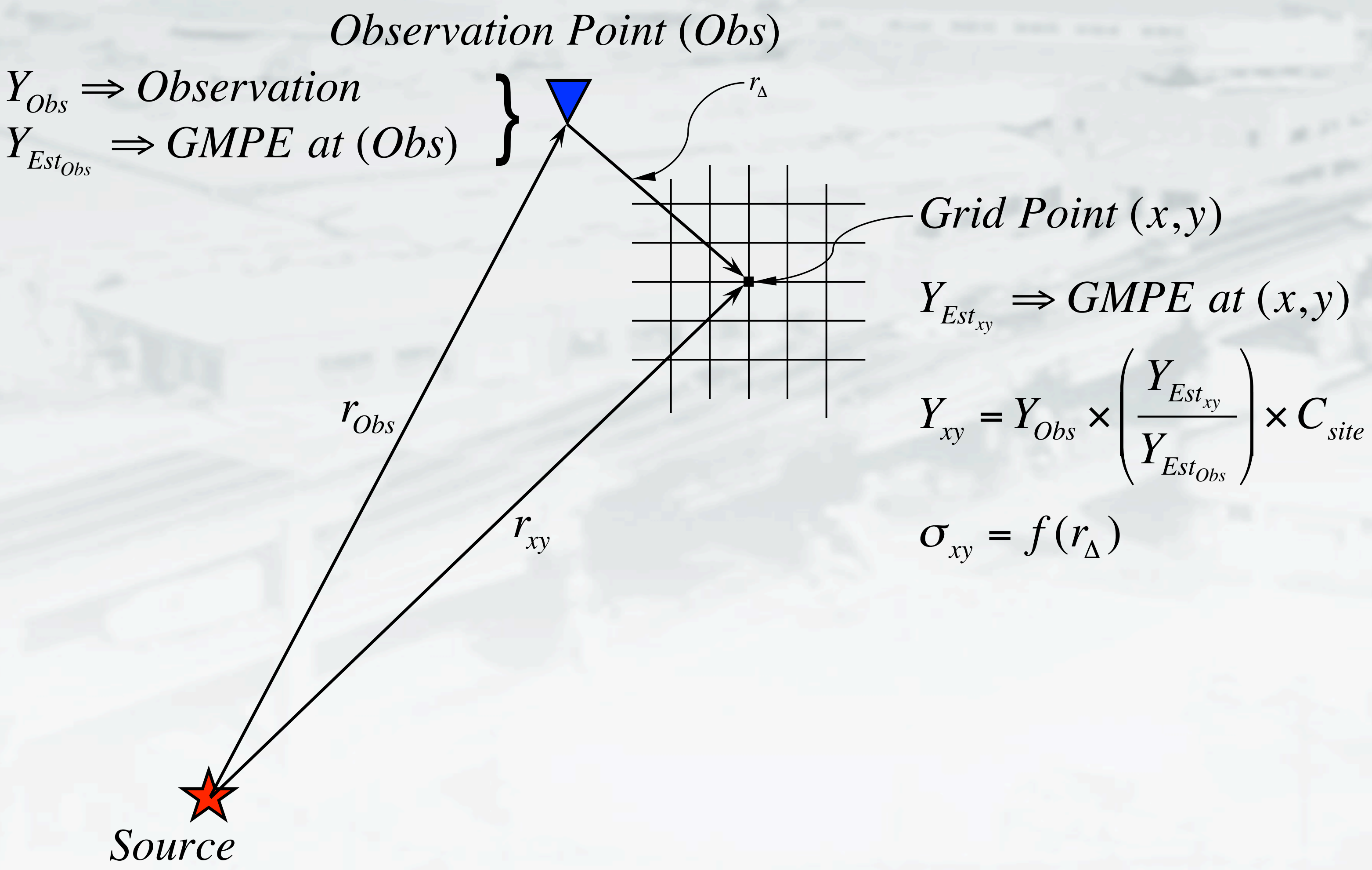
Adjust the event magnitude to best fit the available data.



Processing Overview (cont.)

- Interpolate ground motions to a uniform grid
  - Compute biased GMPE estimates at each station and for each point in the output grid
  - Interpolate (Worden et al., 2010)
- Amplify ground motions
  - Basin amplification
  - Vs30 site amplification

Amplitude Near an Observation



$Y_{Obs} \Rightarrow$ *Observation*

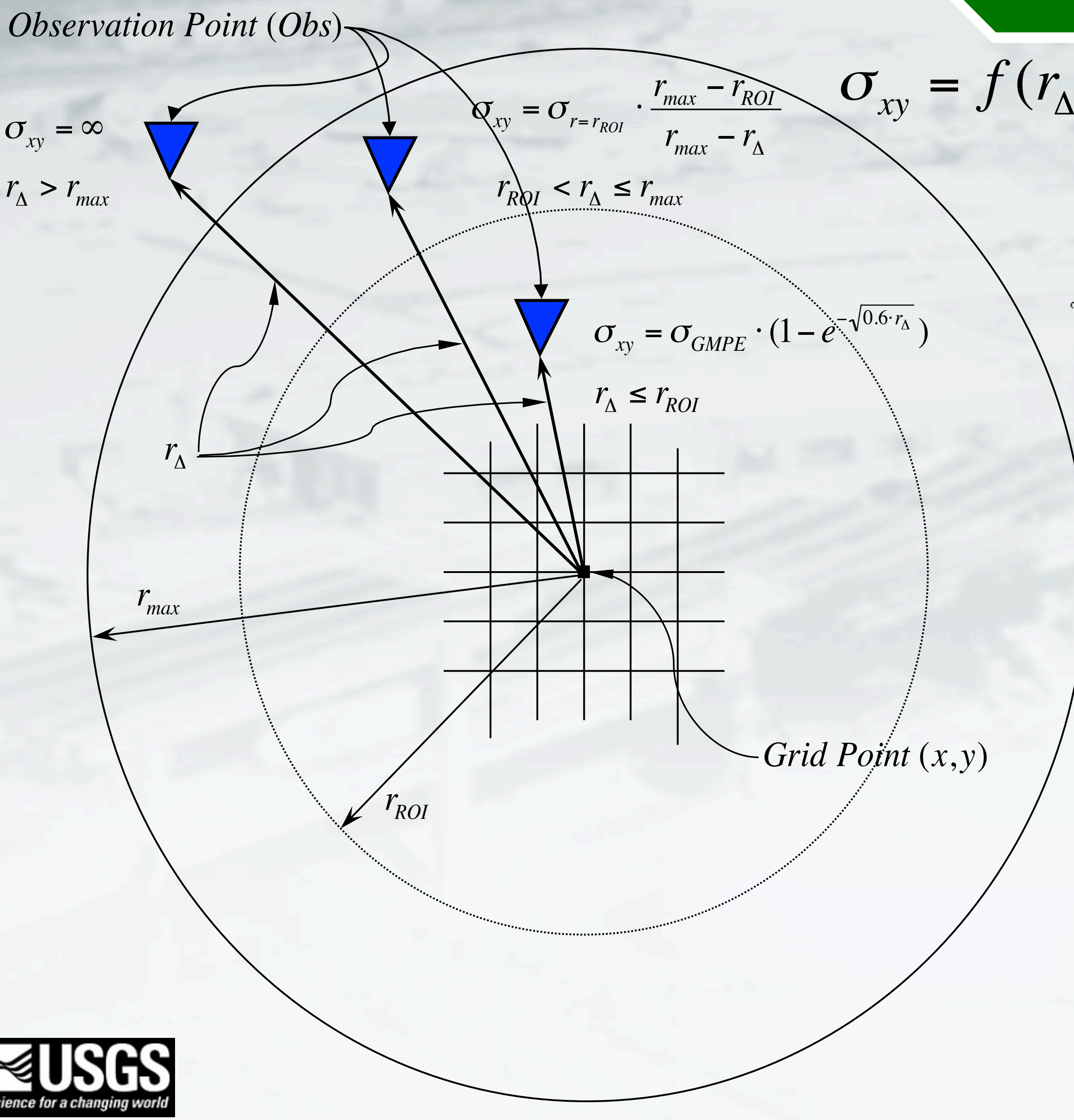
$Y_{Est_{Obs}} \Rightarrow$ *GMPE at (Obs)*

$Y_{Est_{xy}} \Rightarrow$ *GMPE at* (x,y)

$$Y_{xy} = Y_{Obs} \times \left(\frac{Y_{Est_{xy}}}{Y_{Est_{Obs}}} \right) \times C_{site}$$

$$\sigma_{xy} = f(r_\Delta)$$

Uncertainty Near an Observation



Observation Point (Obs)

$\sigma_{xy} = \infty$

$r_\Delta > r_{max}$

$\sigma_{xy} = \sigma_{r=r_{ROI}} \cdot \frac{r_{max} - r_{ROI}}{r_{max} - r_\Delta}$

$r_{ROI} < r_\Delta \le r_{max}$

$\sigma_{xy} = \sigma_{GMPE} \cdot (1 - e^{-\sqrt{0.6 \cdot r_\Delta}})$

$r_\Delta \le r_{ROI}$

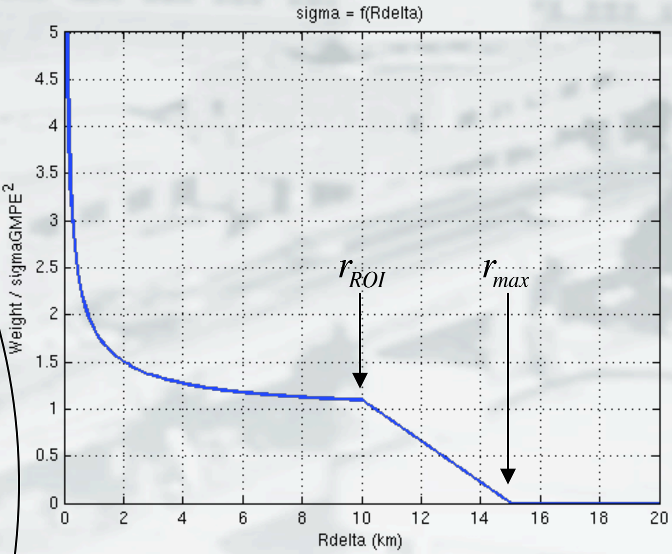
r_Δ

r_{max}

r_{ROI}

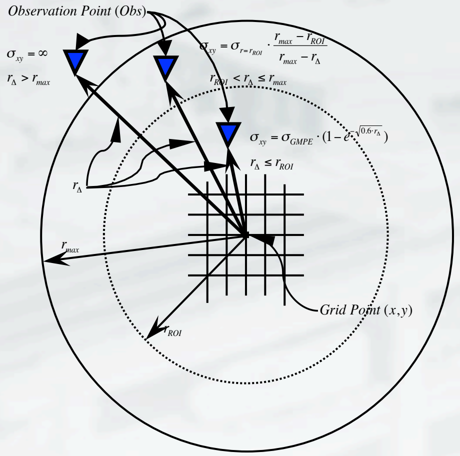
Grid Point (x,y)

$$\sigma_{xy} = f(r_\Delta)$$



Total Uncertainty

$$\sigma_{xy} = f(r_\Delta)$$



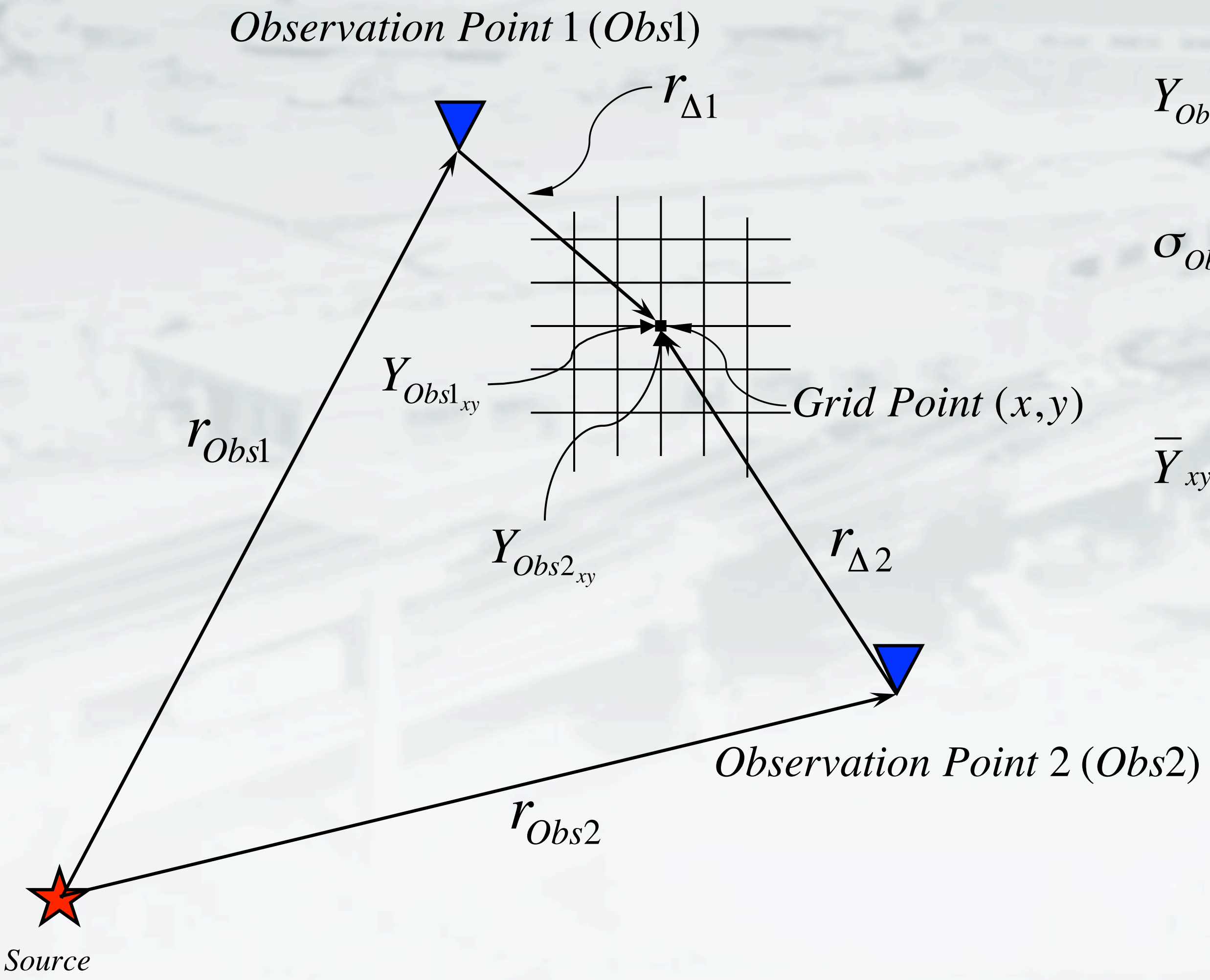
$$\sigma_{Conv} \begin{cases} = 0 & \text{native observations} \\ \neq 0 & \text{converted observations} \end{cases}$$

$$\sigma_{Obs} \begin{cases} = 0 & \text{PGM *} \\ \neq 0 & \text{Intensity} \end{cases}$$

$$\sigma_{T_{xy}} = \sqrt{\sigma_{xy}^2 + \sigma_{Conv}^2 + \sigma_{Obs}^2}$$

*If network-assigned uncertainties were available for PGM, non-zero uncertainties could be applied here.

Combining Multiple Observations



$$Y_{Obs_{xy}} = Y_{Obs} \times \left(\frac{Y_{Est_{xy}}}{Y_{Est_{Obs}}} \right) \times C_{site}$$

$$\sigma_{Obs_{xy}} = f(r_{\Delta Obs})$$

$$\bar{Y}_{xy} = \frac{\dfrac{Y_{Obs1_{xy}}}{\sigma^2_{Obs1_{xy}}} + \dfrac{Y_{Obs2_{xy}}}{\sigma^2_{Obs2_{xy}}}}{\dfrac{1}{\sigma^2_{Obs1_{xy}}} + \dfrac{1}{\sigma^2_{Obs2_{xy}}}}$$

Generalizing…

$$\bar{Y}_{xy} = \frac{\sum_{i=1}^{n} \dfrac{Y_{O,i}}{\sigma^2_{O,i}}}{\sum_{i=1}^{n} \dfrac{1}{\sigma^2_{O,i}}}$$

Putting it all together…

$$\bar{Y}_{xy} = \frac{\dfrac{Y_E}{\sigma_E^2} + \displaystyle\sum_{i=1}^{n} \frac{Y_{O,i}}{\sigma_{O,i}^2} + \sum_{j=1}^{n} \frac{Y_{C,j}}{\sigma_{C,j}^2}}{\dfrac{1}{\sigma_E^2} + \displaystyle\sum_{i=1}^{n} \frac{1}{\sigma_{O,i}^2} + \sum_{j=1}^{n} \frac{1}{\sigma_{C,j}^2}}$$

$$\bar{\sigma}_{xy}{}^2 = \frac{1}{\dfrac{1}{\sigma_E^2} + \displaystyle\sum_{i=1}^{n} \frac{1}{\sigma_{O,i}^2} + \sum_{j=1}^{n} \frac{1}{\sigma_{C,j}^2}}$$

Note that Y_E and σ_E include adjustments for additional aleatory uncertainty if a finite fault is not specified.

Grid Based Processing

Now using GMT’ s *grdmath* for most number crunching:

- Extremely efficient
- Large user base, well maintained, open source
- Only one GMT program was modified: *nearneighbor* became *sm_nearneighbor*
- Can be a bit awkward to program: requires array-think (*a la* Matlab) and RPN

```
`grdmath $ingrd $velgrd $Vs DIV LOG $c->{Bv} MUL EXP = $outgrd`;
```

Grid Based Processing

```
grdmath: /Users/bruce/Unix/ShakeMap/shake/dawn/bin/../data/Northridge/richter/
pga_rock.grd DUP 15.2905 GT EXCH DUP 25.4842 GT EXCH DUP 35.6779 GT EXCH
POP ADD ADD /Users/bruce/Unix/ShakeMap/shake/dawn/bin/../data/Northridge/output/
EohrLl5OwL.grd DUP 163 GT EXCH DUP 298 GT EXCH DUP 301 GT EXCH DUP 382
GT EXCH DUP 464 GT EXCH DUP 686 GT EXCH POP ADD ADD ADD ADD ADD 4 MUL
ADD DUP = /Users/bruce/Unix/ShakeMap/shake/dawn/bin/../data/Northridge/output/
FkKLZu2hhi.grd DUP 0 EQ 1.65 MUL EXCH DUP 1 EQ 1.43 MUL EXCH DUP 2 EQ 1.15
MUL EXCH DUP 3 EQ 0.93 MUL EXCH DUP 4 EQ 1.34 MUL EXCH DUP 5 EQ 1.23
MUL EXCH DUP 6 EQ 1.09 MUL EXCH DUP 7 EQ 0.96 MUL EXCH DUP 8 EQ 1.33
MUL EXCH DUP 9 EQ 1.23 MUL EXCH DUP 10 EQ 1.09 MUL EXCH DUP 11 EQ 0.96
MUL EXCH DUP 12 EQ 1.24 MUL EXCH DUP 13 EQ 1.17 MUL EXCH DUP 14 EQ 1.06
MUL EXCH DUP 15 EQ 0.97 MUL EXCH DUP 16 EQ 1.15 MUL EXCH DUP 17 EQ 1.1
MUL EXCH DUP 18 EQ 1.04 MUL EXCH DUP 19 EQ 0.98 MUL EXCH DUP 20 EQ 1
MUL EXCH DUP 21 EQ 1 MUL EXCH DUP 22 EQ 1 MUL EXCH DUP 23 EQ 1 MUL
EXCH DUP 24 EQ 0.98 MUL EXCH DUP 25 EQ 0.99 MUL EXCH DUP 26 EQ 0.99 MUL
EXCH DUP 27 EQ 1 MUL EXCH POP ADD ADD ADD ADD ADD ADD ADD ADD ADD
ADD ADD ADD ADD ADD ADD ADD ADD ADD ADD ADD ADD ADD ADD ADD ADD ADD
ADD 1 AND = /Users/bruce/Unix/ShakeMap/shake/dawn/bin/../data/Northridge/output/
mrT4GAU2Vy.grd
```

GMPEs

- **A10Hawaii:** Atkinson (2010), Hawaii
- **AB06_ENA_BC**: Atkinson & Boore (2006), eastern North America
- **ASB13:** Akkar, Sandikkaya, and Bommer (2013), Europe and Middle East
- **BA08**: Boore & Atkinson (2008, with 2010 updates), NGA
- **CY08**: Chiou & Youngs (2008, with 2009 updates for s. CA), NGA
- **Campbell2003**: Campbell (2003), eastern North America
- **Garcia05:** Garcia et al. (2005), Mexico
- **Kanno06:** Kanno et al. (2006), Japan
- **MA2005:** Motazedian & Atkinson (2005), Puerto Rico
- **PP04**: Pankow & Pechmann (2004), normal faulting (western US)
- **Youngs97**: Youngs, et al. (1997) subduction zone
- **Zhou06:** Zhou et al. (2006), Japan (crustal, interface, intra-slab)

NGA2 relations are under review

Intensity Prediction Equations

Macroseismic Intensity is a fully-vested ground motion parameter:

- Separate function/module from GMPE
- Care must be taken to use compatible GMPE & IPE
- Facilitates the use of non-MMI intensity measures
- Allows the selection of the appropriate relationship for each region
- Need additional relationships

IPEs

- **AWW14:** Atkinson, Wald, Worden (2014), California and CEUS
- **TA12**: Trevor Allen et al. (2012), active crustal
- **DefaultIPE**: GMPE/GMICE-based virtual IPE

DefaultIPE

Used where GMPE is available, but no IPE is applicable:

- Uses the configured GMPE and GMICE functions to generate a virtual IPE
- Combined uncertainty is produced
- Higher total uncertainty ensures that native observations will dominate, when available
- Bias is computed via the intensity observations and is a single value for the GMPE (regardless of the GM parameters used in the PGM<=>MI functions)

GMICE

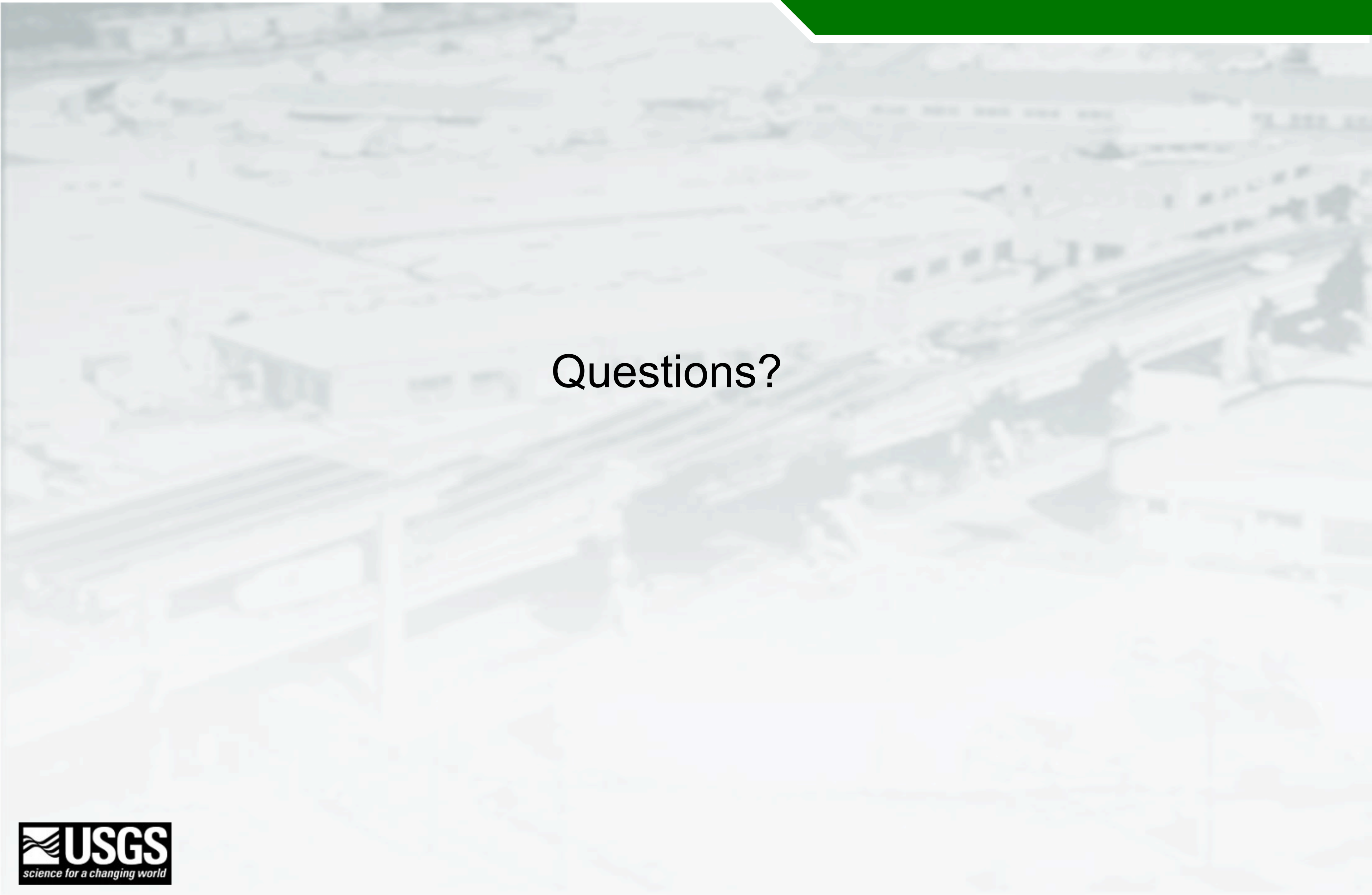
GMICE are modular functions:

- Allows easy testing and adoption of new functions
- Facilitates the use of non-MMI intensity measures
- Allows the selection of the appropriate relationship for each region
- Requires revising the intensity legend on the intensity map

GMICE

- **AK07**: Atkinson & Kaka (2007), California, CEUS
- **BilalAskan14:** Bilal & Askan (2014), Europe
- **DC11:** Dangkua & Cramer (2011), CEUS
- **FM10:** Faenza and Michelini (2010), Italy
- **Wald99**: Wald, et al. (1999), southern California
- **WGRW11**: Worden, et al. (2012), California

The End



Questions?