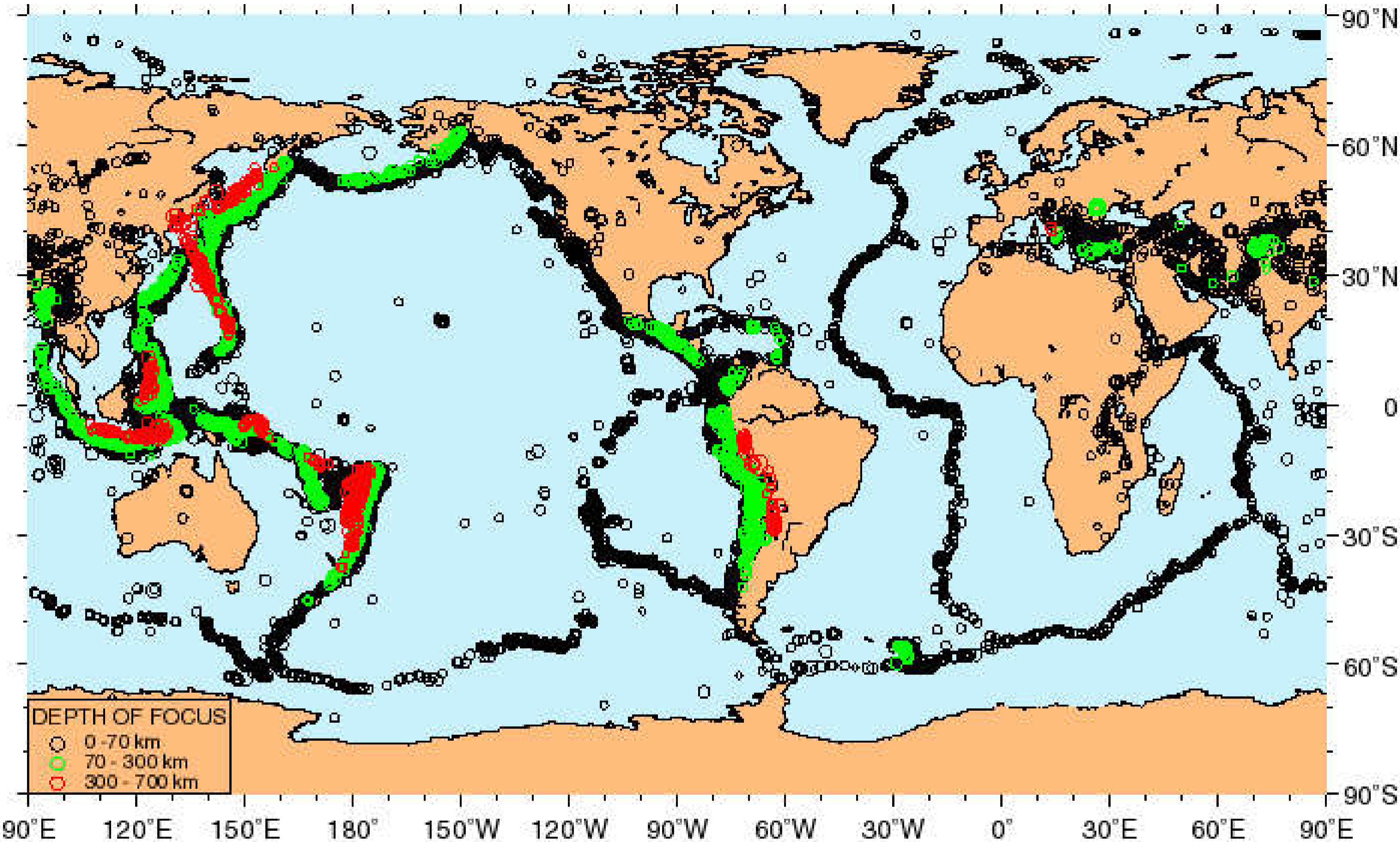
Earthquake location

location

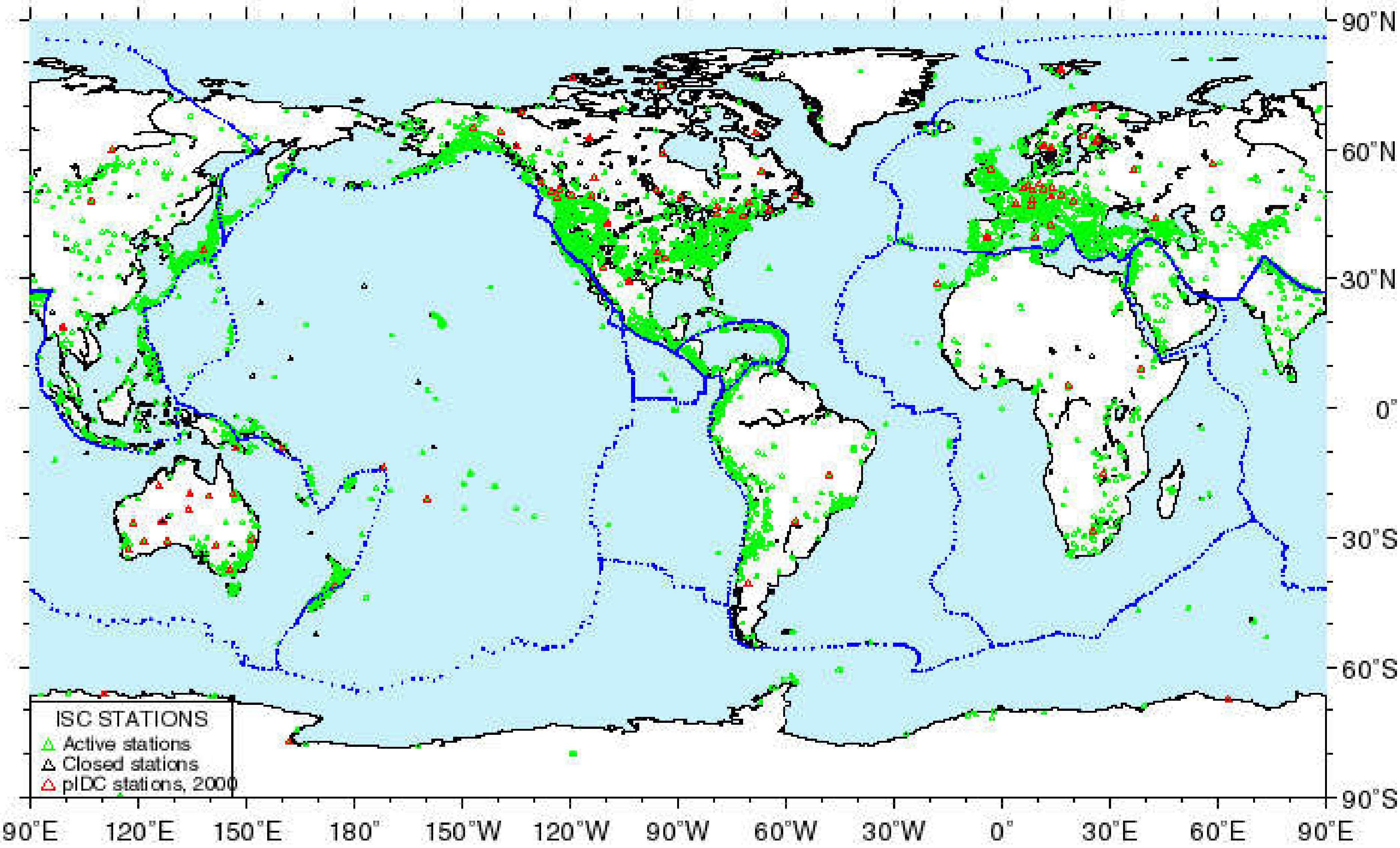
location …

Lamont colloquium, 2002 Sept 27

World Seismicity 1977-2002



Stations Reported to the International Seismological Centre



Three agencies that report on global seismicity:

International Seismological Centre (UK)
"ISC bulletin" (two years in arrears)

U.S. Geological Survey
"PDE" (~ six months in arrears)

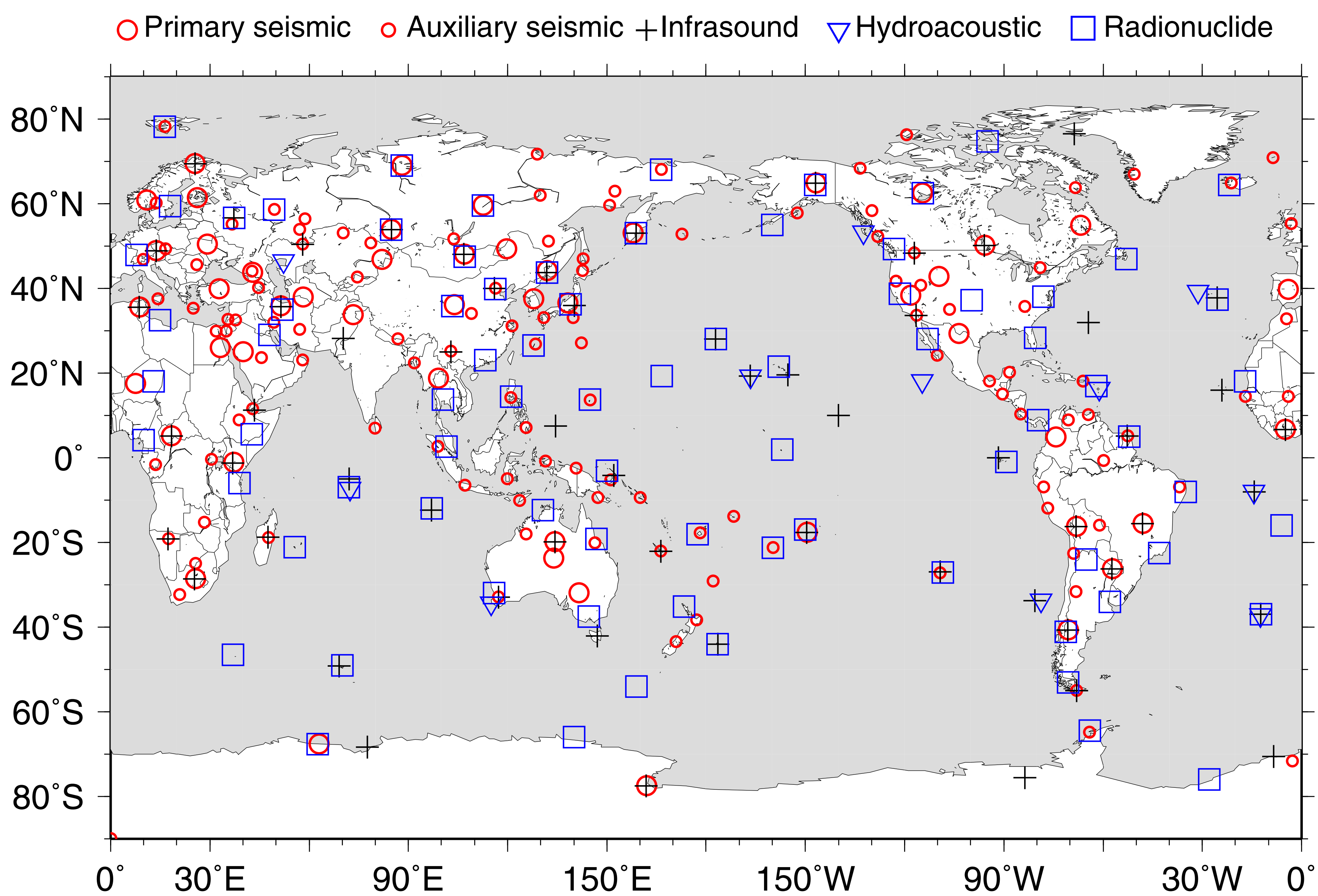
International Data Centre of the Comprehensive Test Ban Treaty Organization
"REB" (~ three days in arrears)

Typically, the seismological community has been more-or-less satisfied to rely upon global or wide-area bulletins that

- locate events one at a time,
- with voluntarily contributed data (USGS, ISC),
- in the Jeffreys-Bullen Earth model (USGS, ISC) or some other.

Note that whenever we have achieved orders-of-magnitude improvement in the accuracy of event locations over a wide-area, we have gained new insight into earthquake physics, and/or new insight into Earth structure and processes.

International Monitoring System for the CTBT



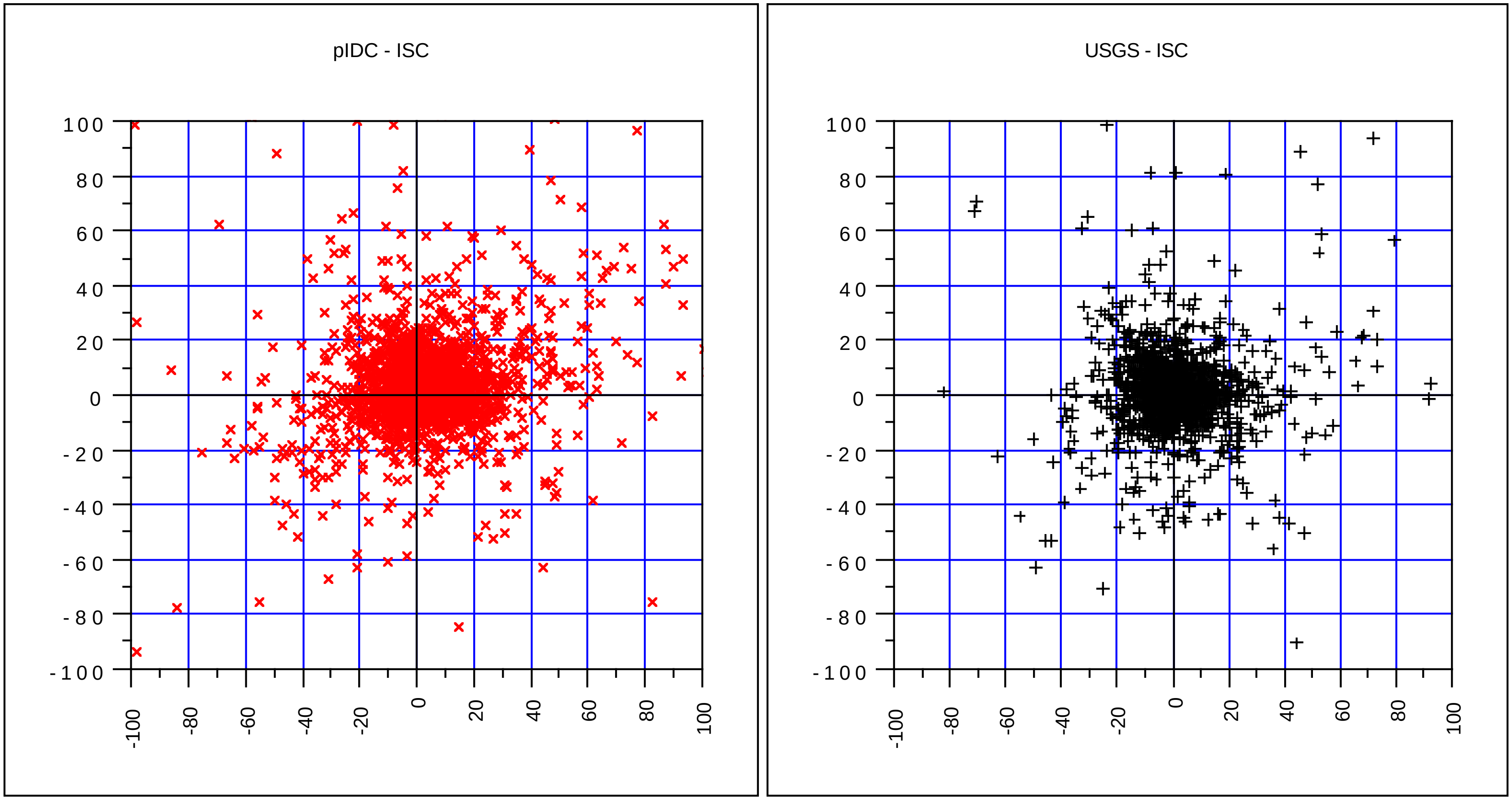
The REB (published by the CTBTO/IDC) is different:

- it comes out more promptly (but few people can now see it)
- it has the potential to supply more accurate locations than at present, because of

    uniform instrumentation,
    sensitive stations (arrays),
    trained analysts making picks at a single facility (IDC)

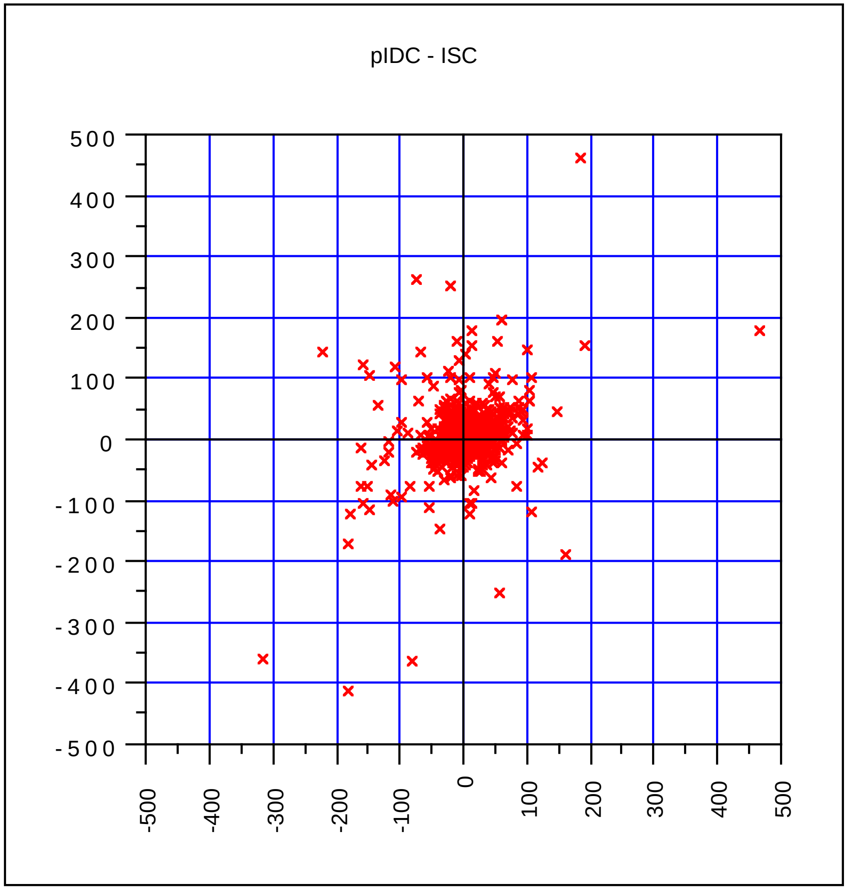
But at present, the REB is **worse** (for locations) than NEIC and ISC:

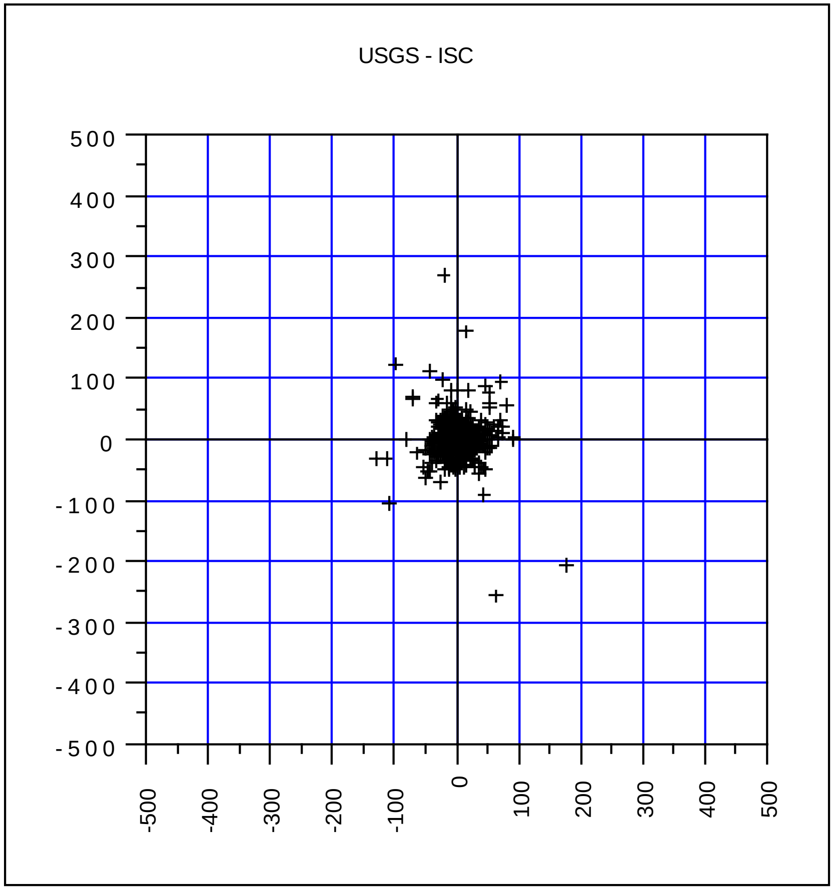
Comparison of locations for 2037 seismic events (fourth quarter of 1999), all assigned magnitudes (mb) and located by ISC, USGS, and pIDC. Distances in km.



Comparison between pIDC and ISC (left), and between USGS and ISC (right).

Same comparisons, but now with a change in scale to ± 500 km



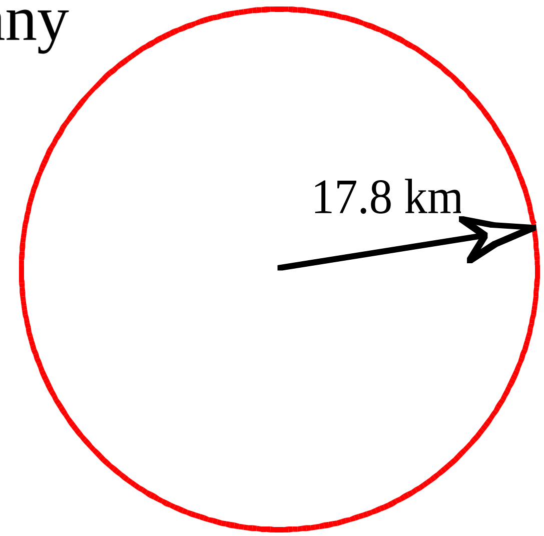


CTBT Protocol, Part II, ¶ 3:

"The area of an on-site inspection shall be continuous and its size shall not exceed 1000 square kilometers. There shall be no linear dimension greater than 50 kilometers in any direction."

If $\pi r^2 = 1000$ sq. km.,

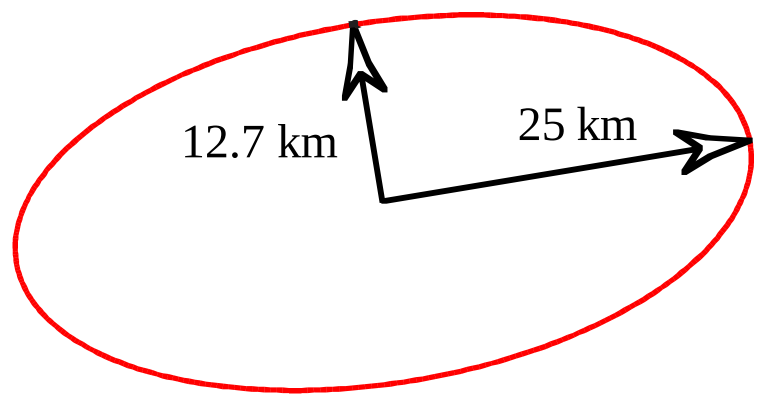
then $r = 17.8$ km.



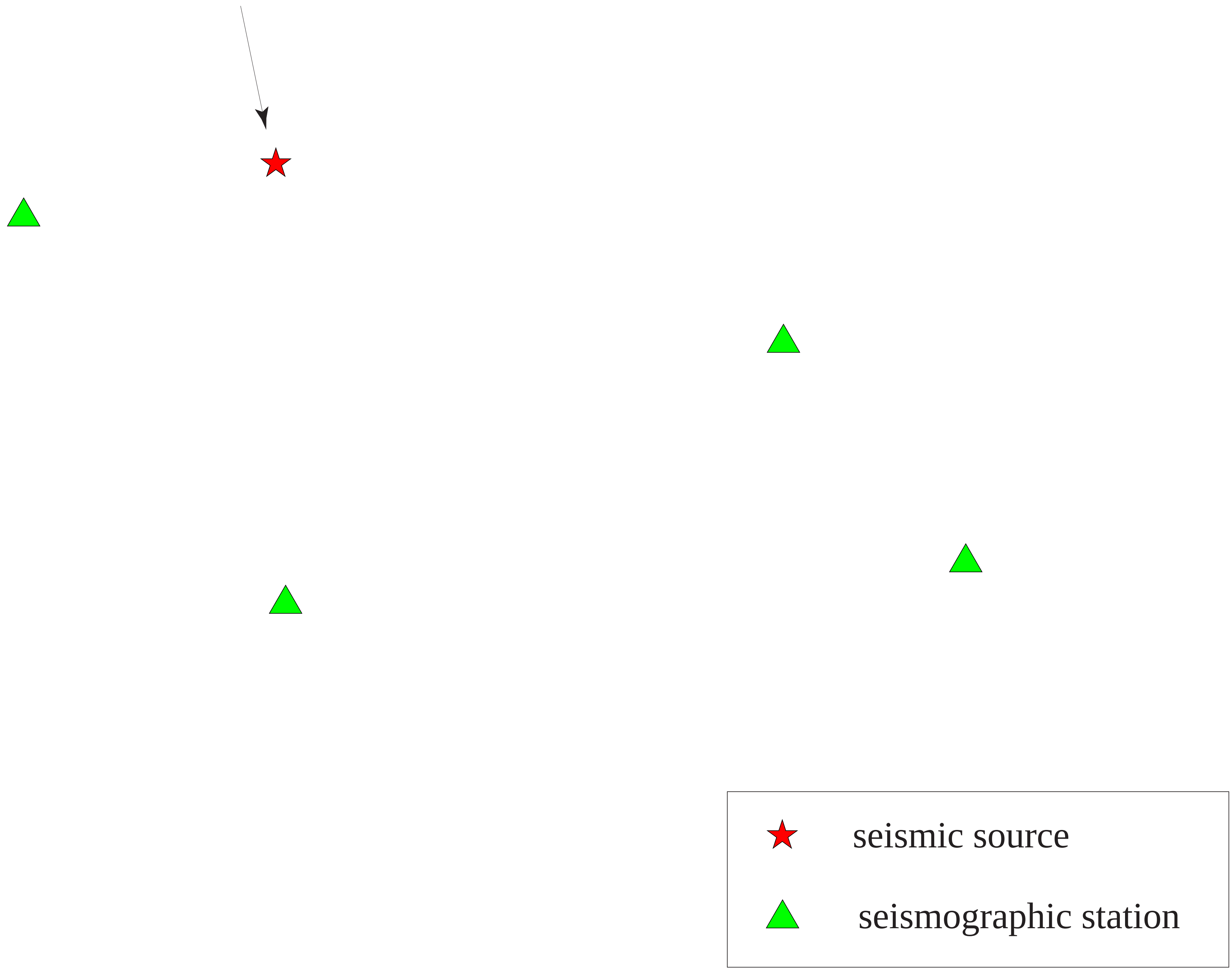
If $\pi a b = 1000$ sq. km.

and $a = 25$ km,

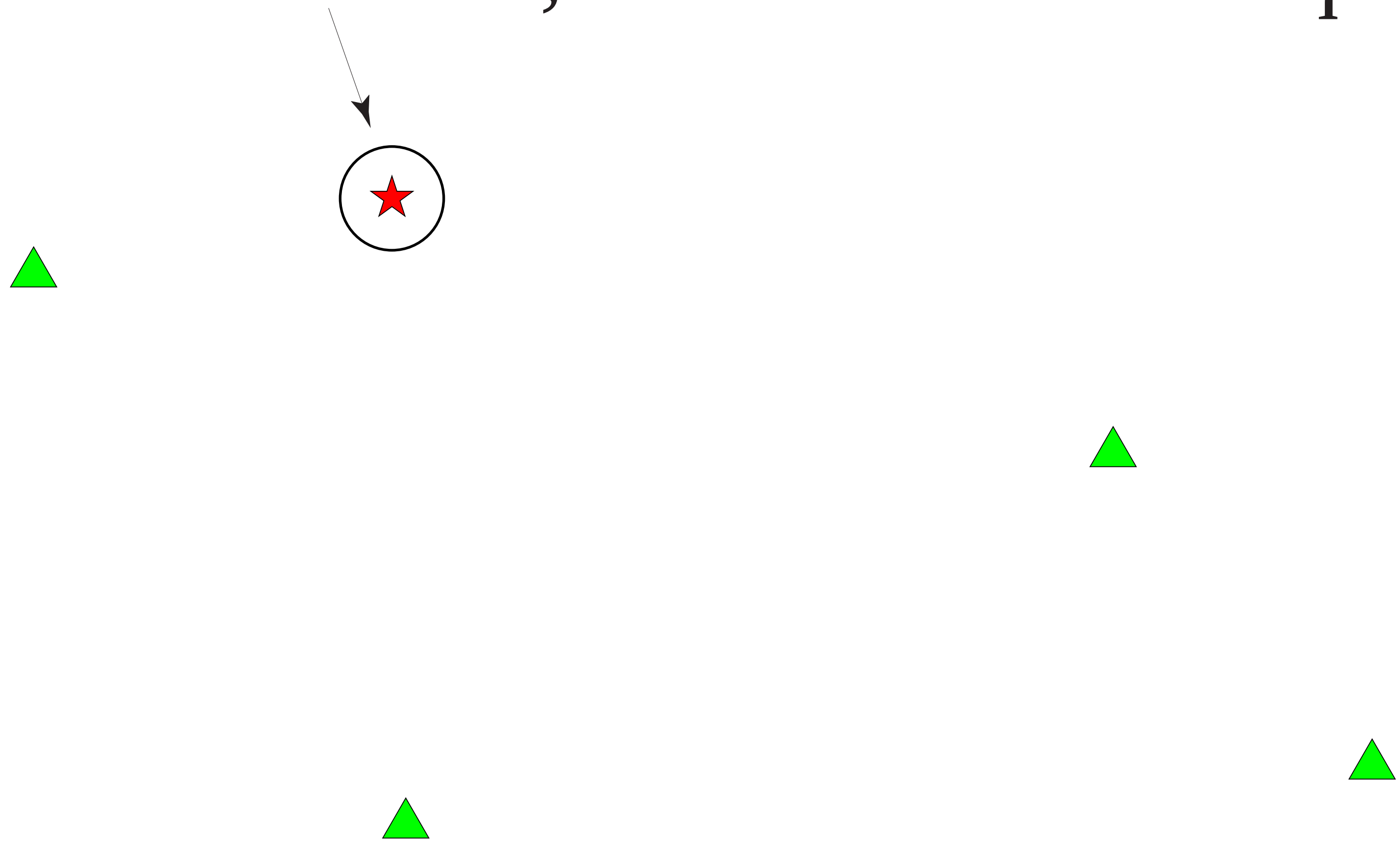
then $b = 12.7$ km.



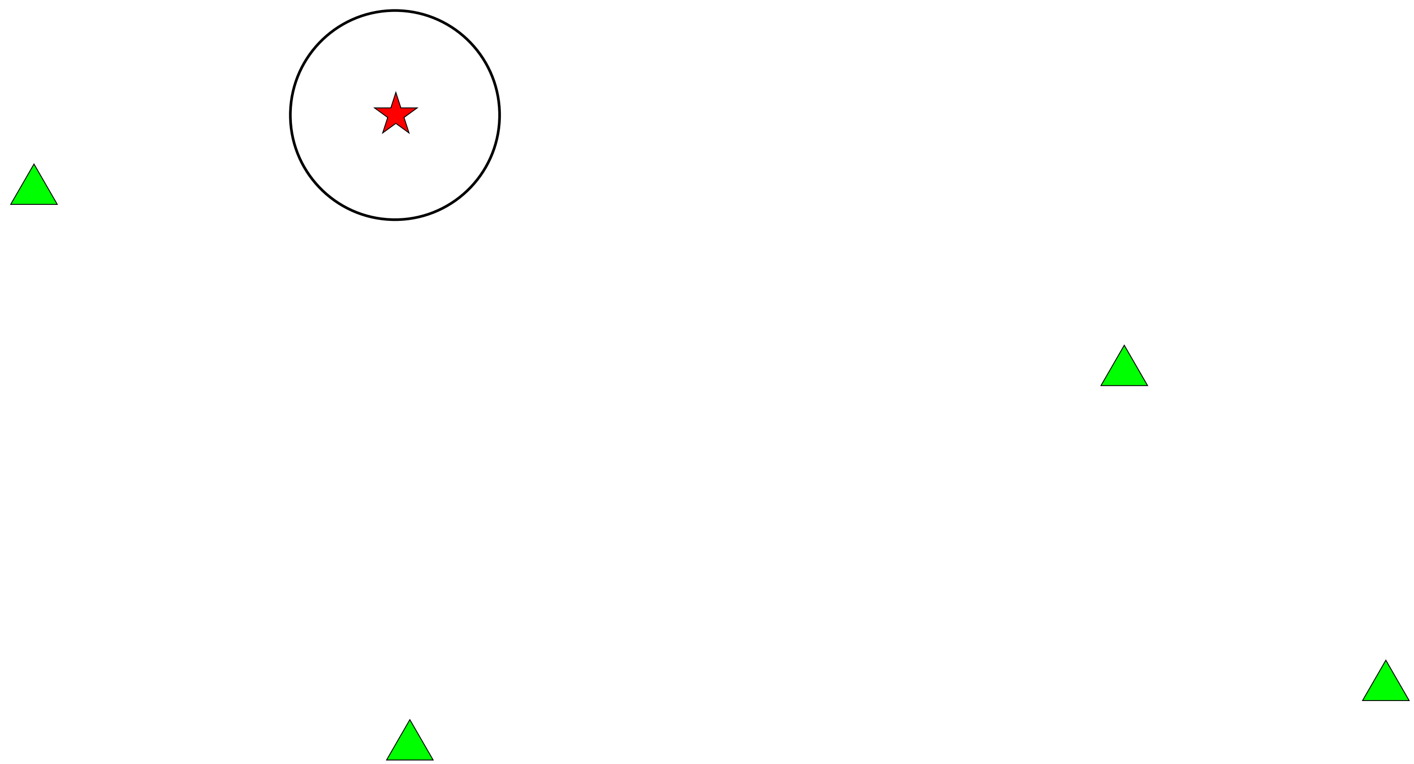
Where is it? (Using data from these 4 stations.)

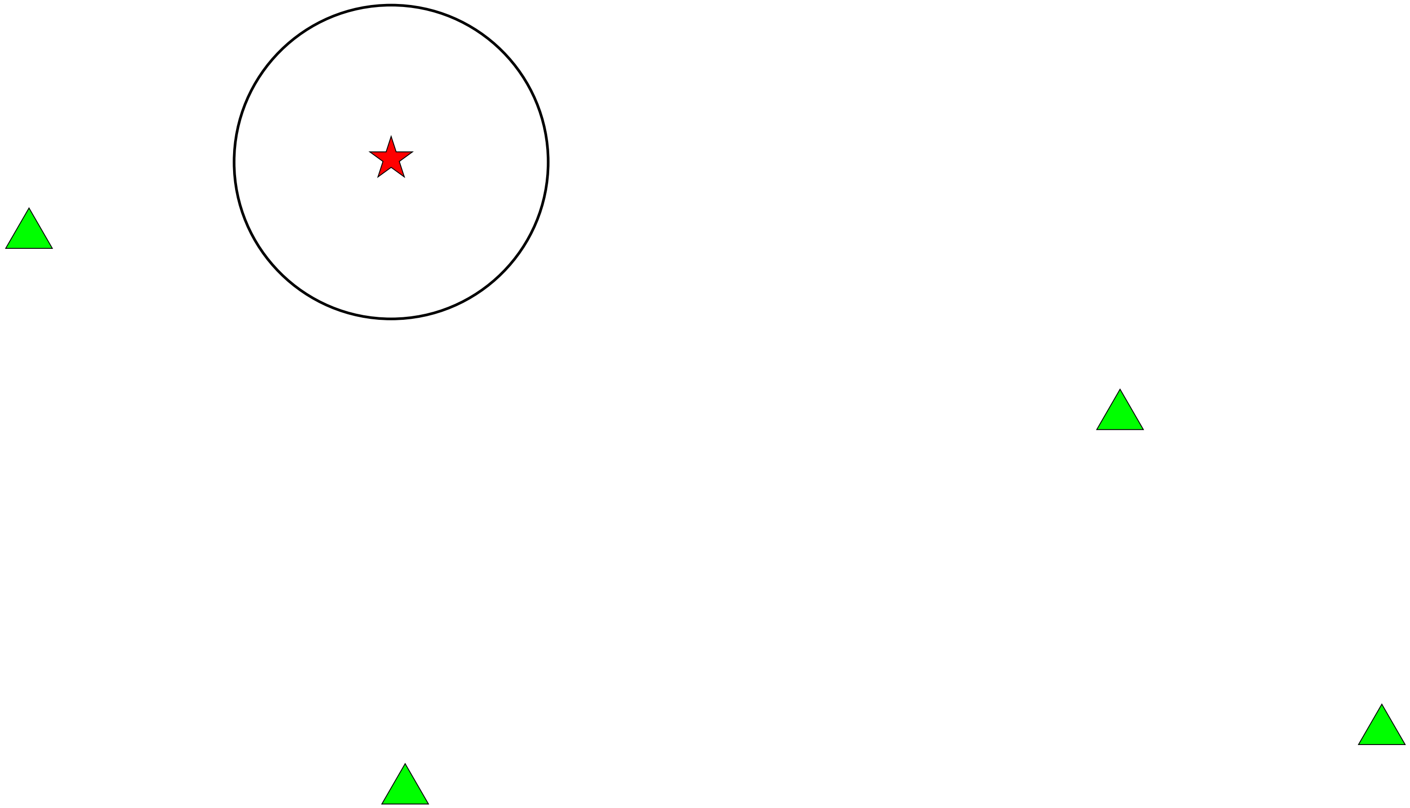


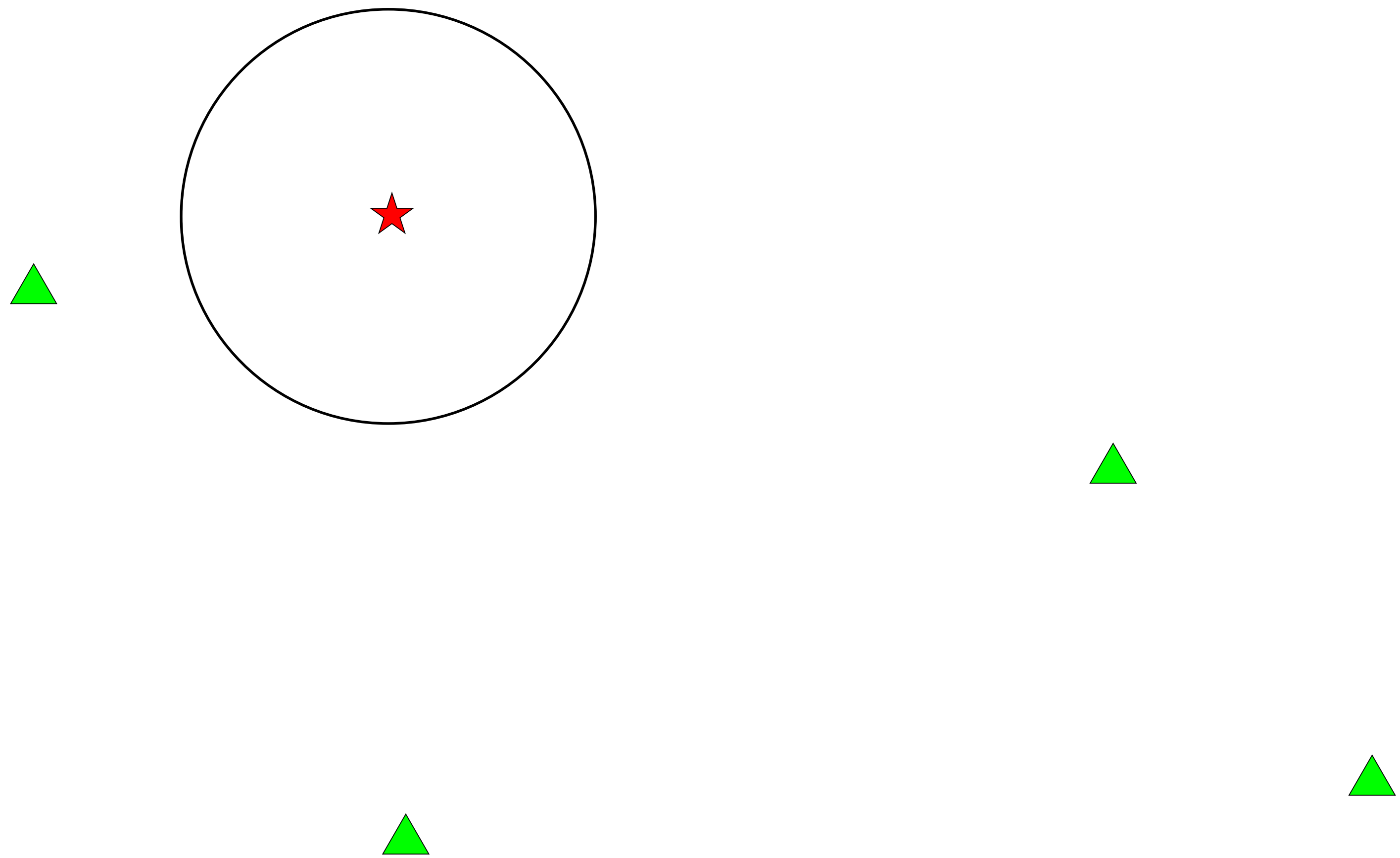
Seismic wavefront, soon after an earthquake starts

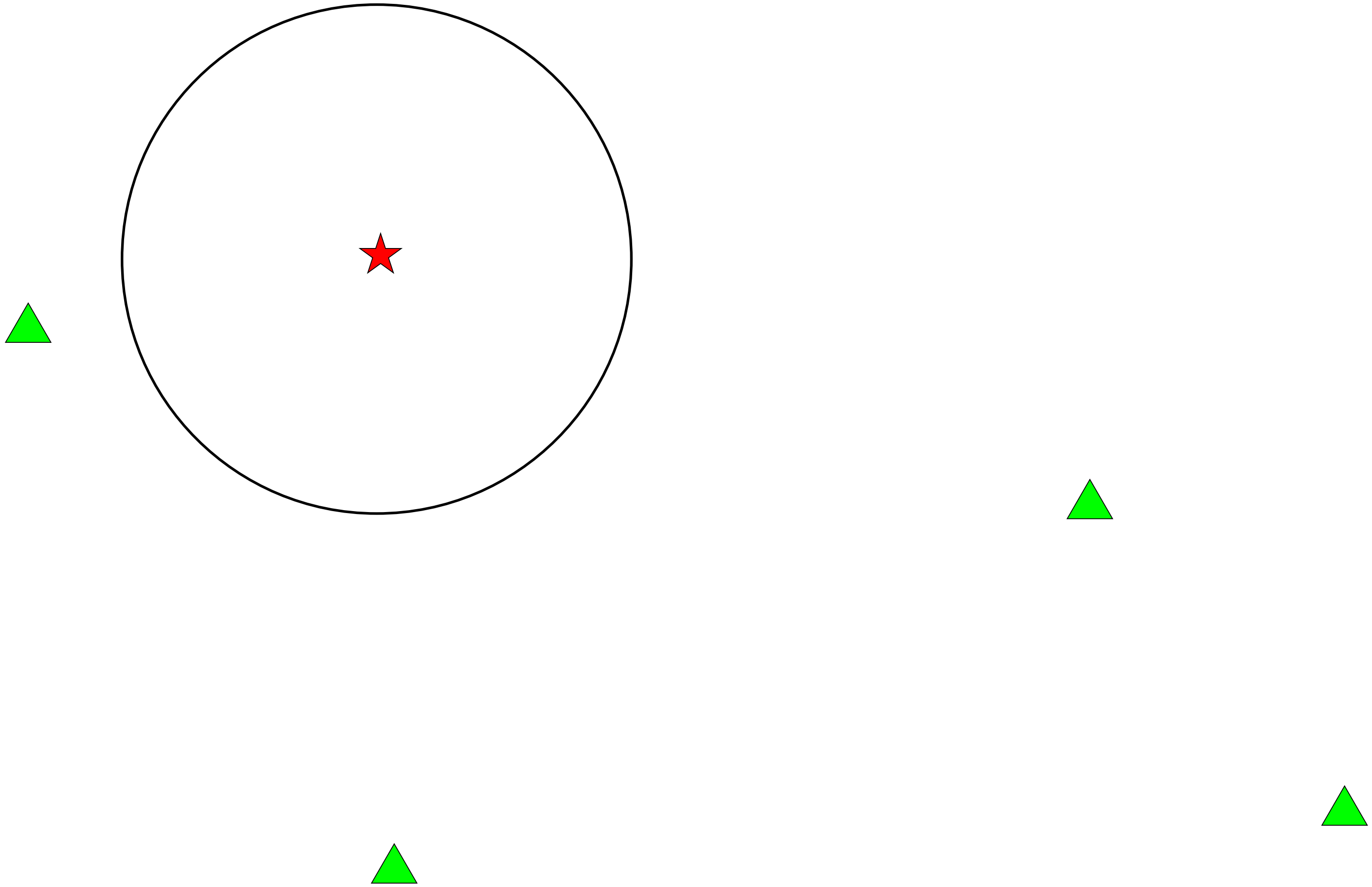


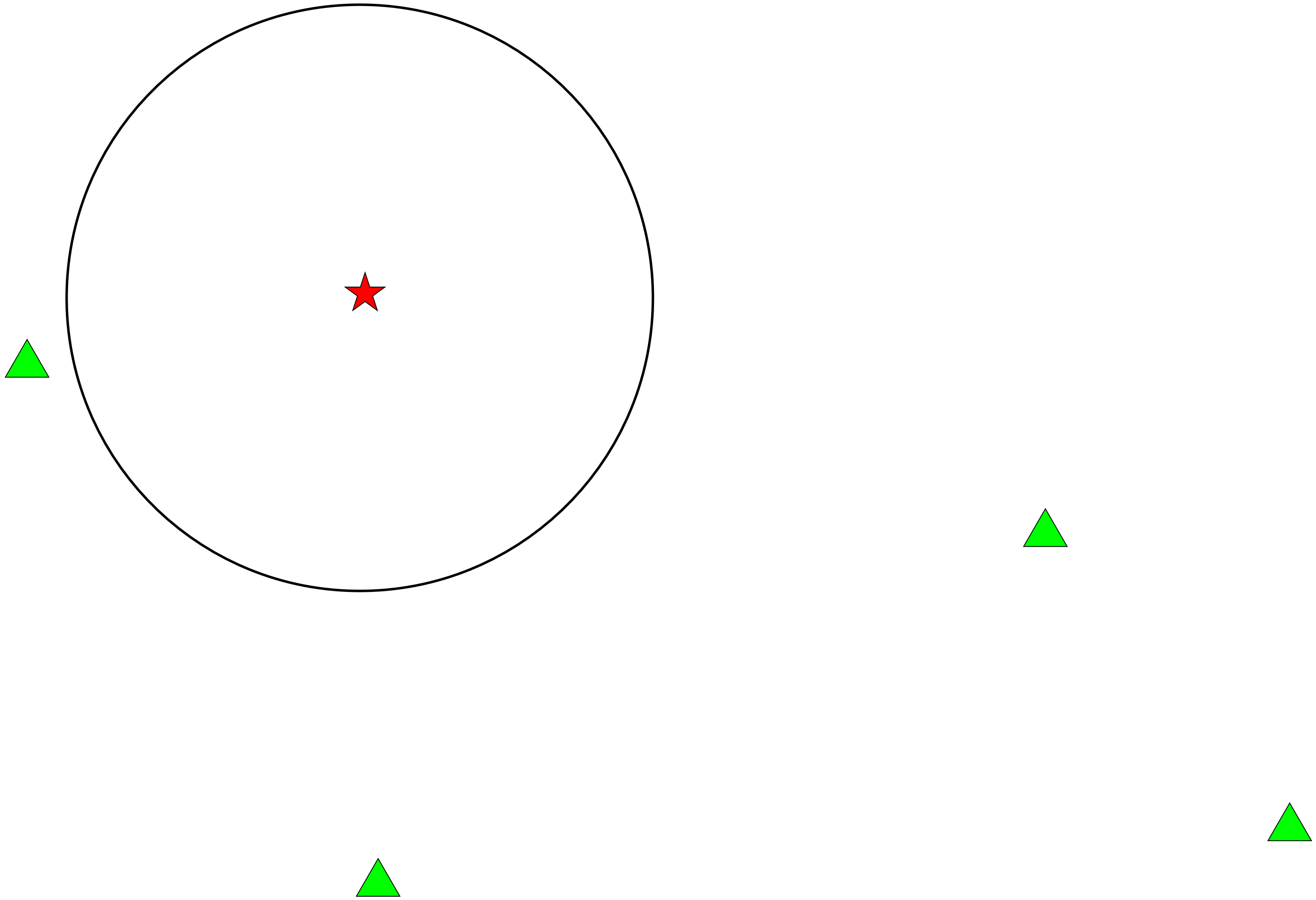
A bit later, the wavefront has expanded

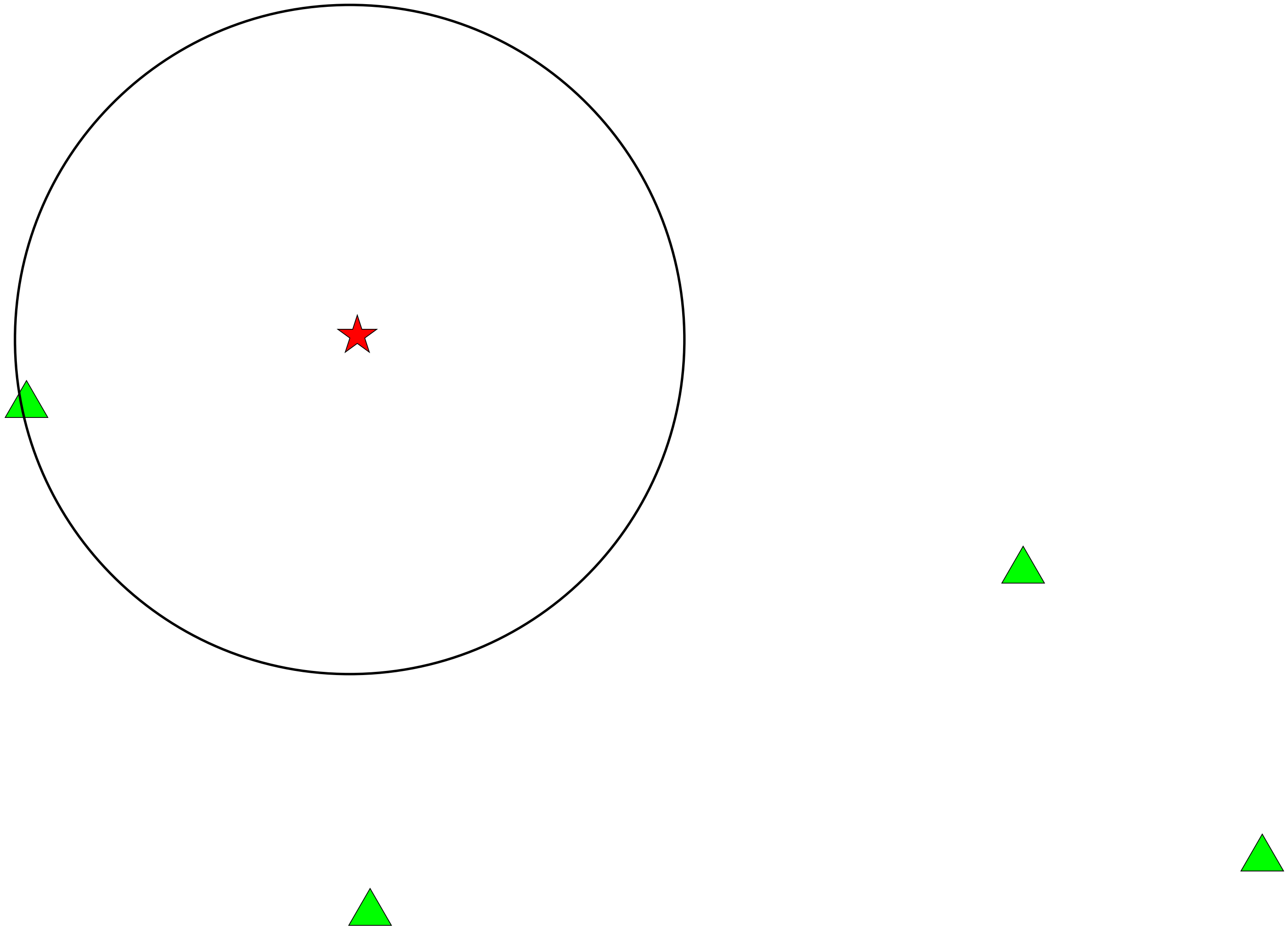




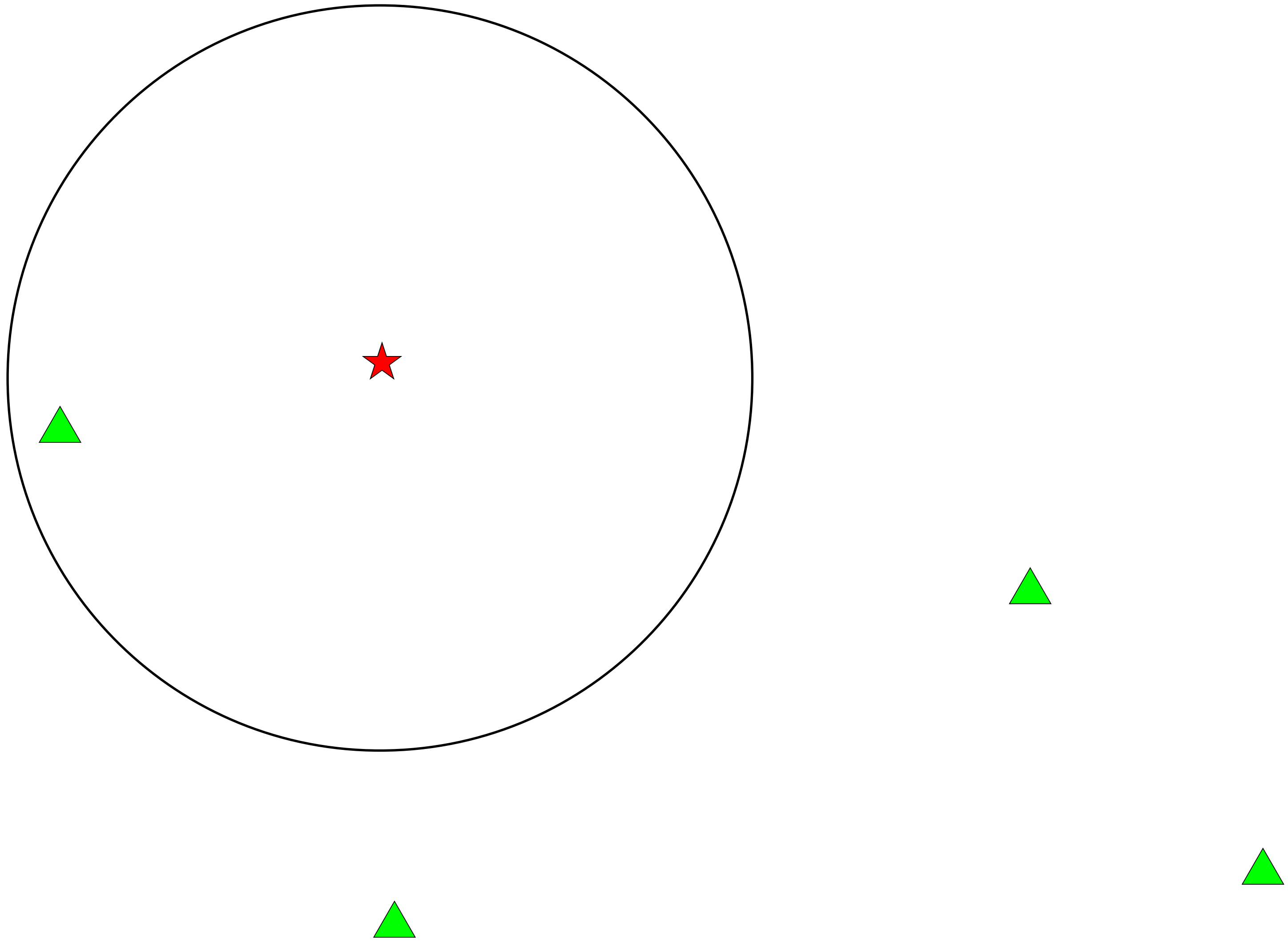


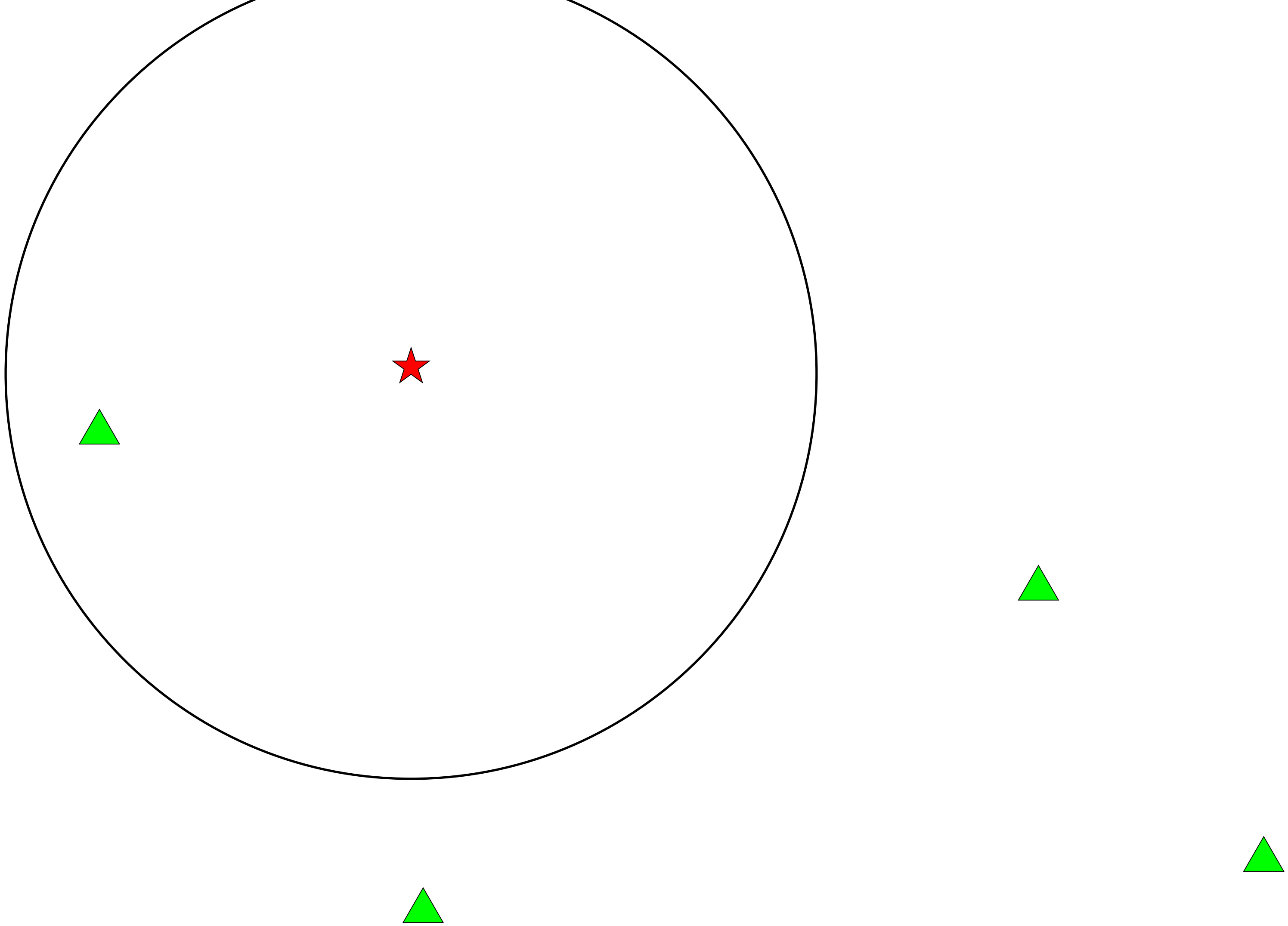


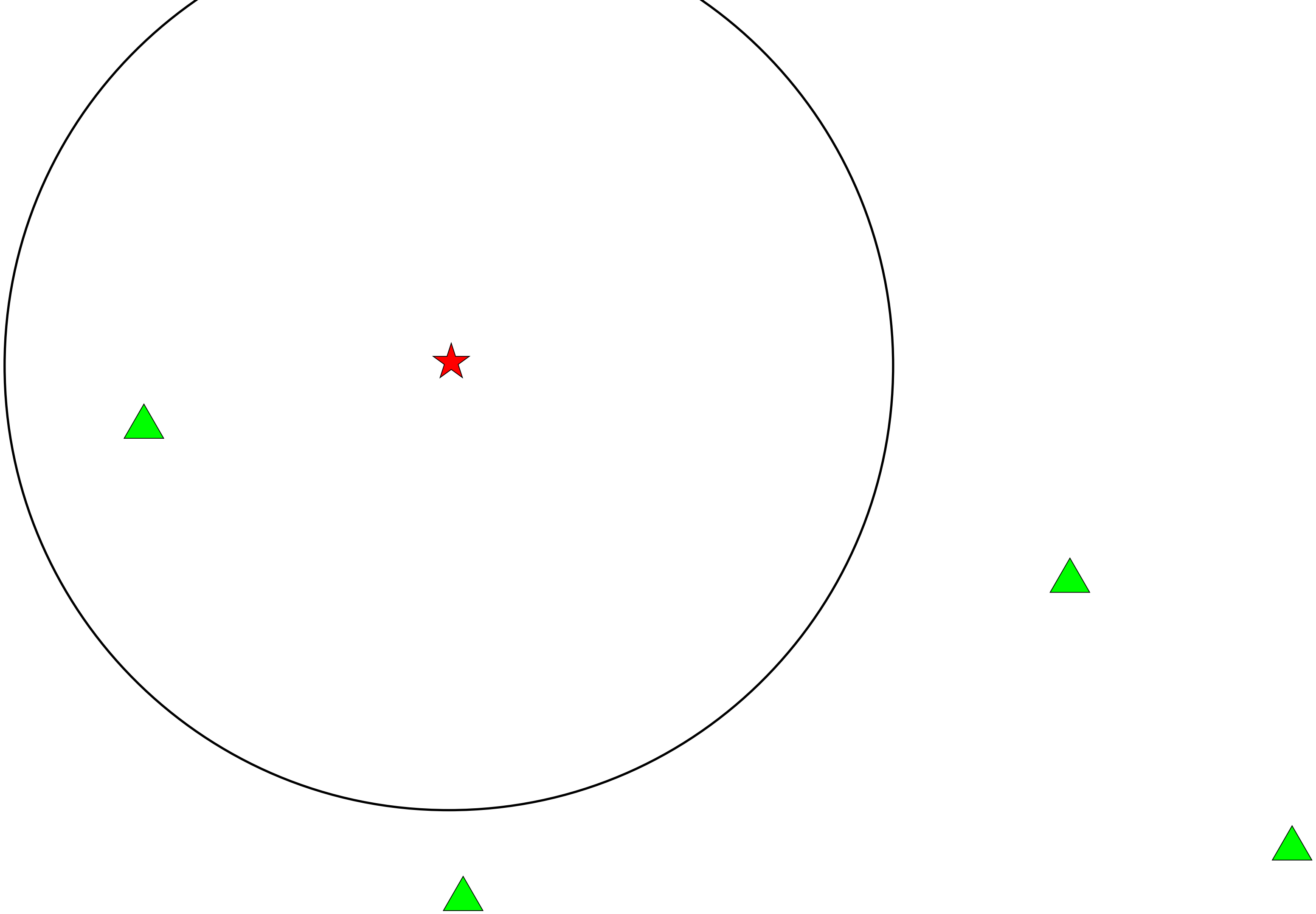


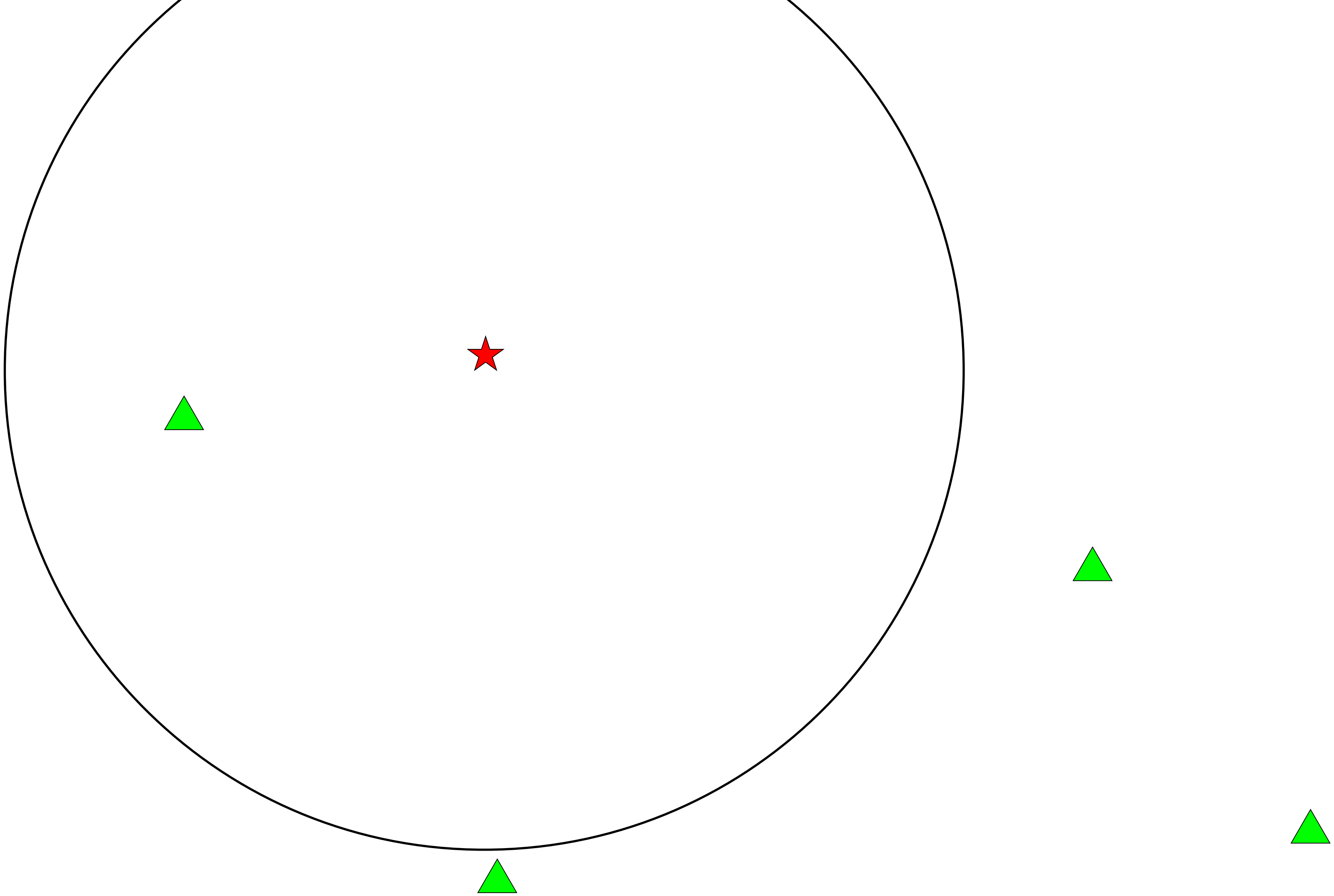


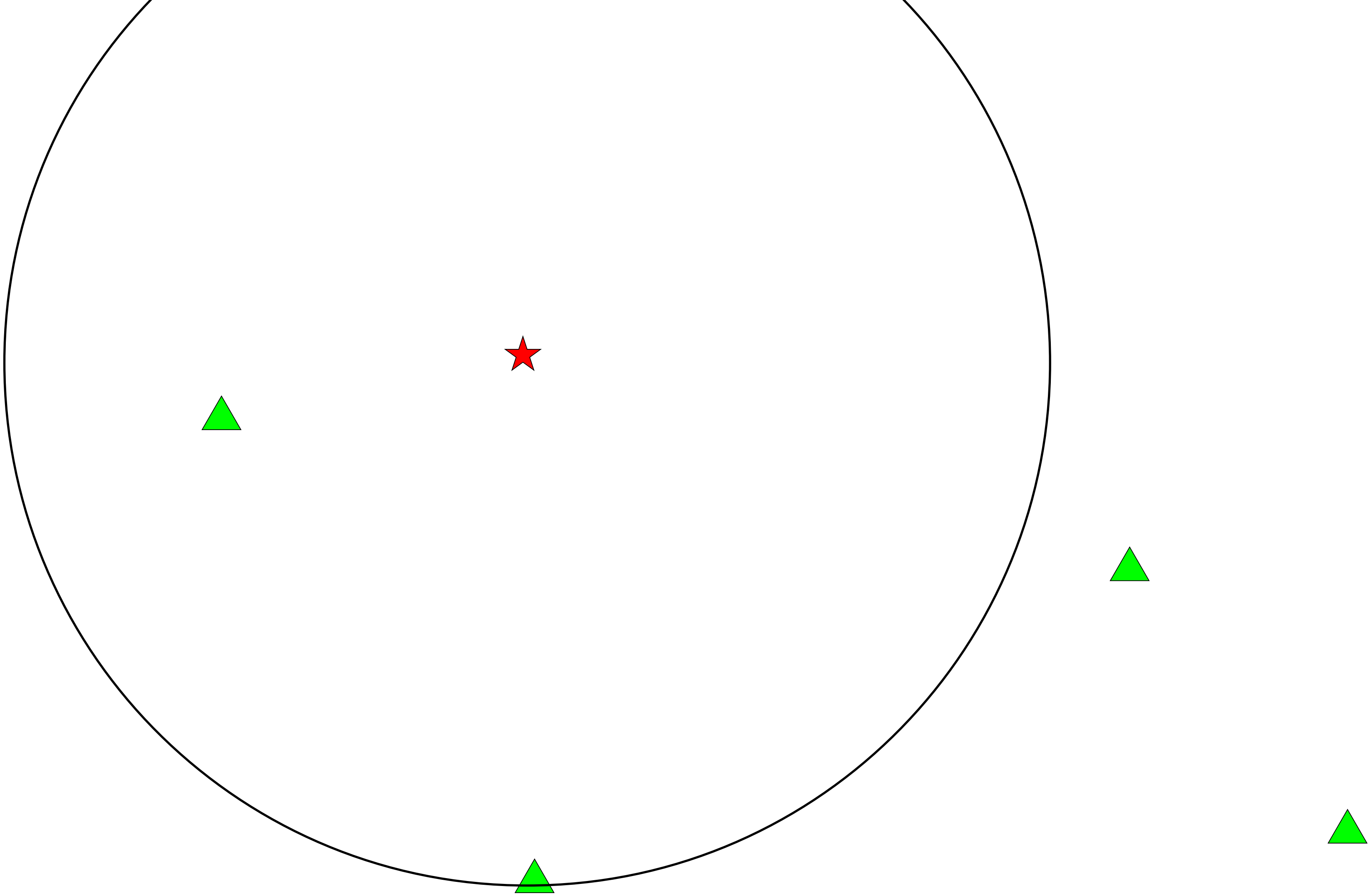
The nearest station gets a signal, at time $t = t_1$



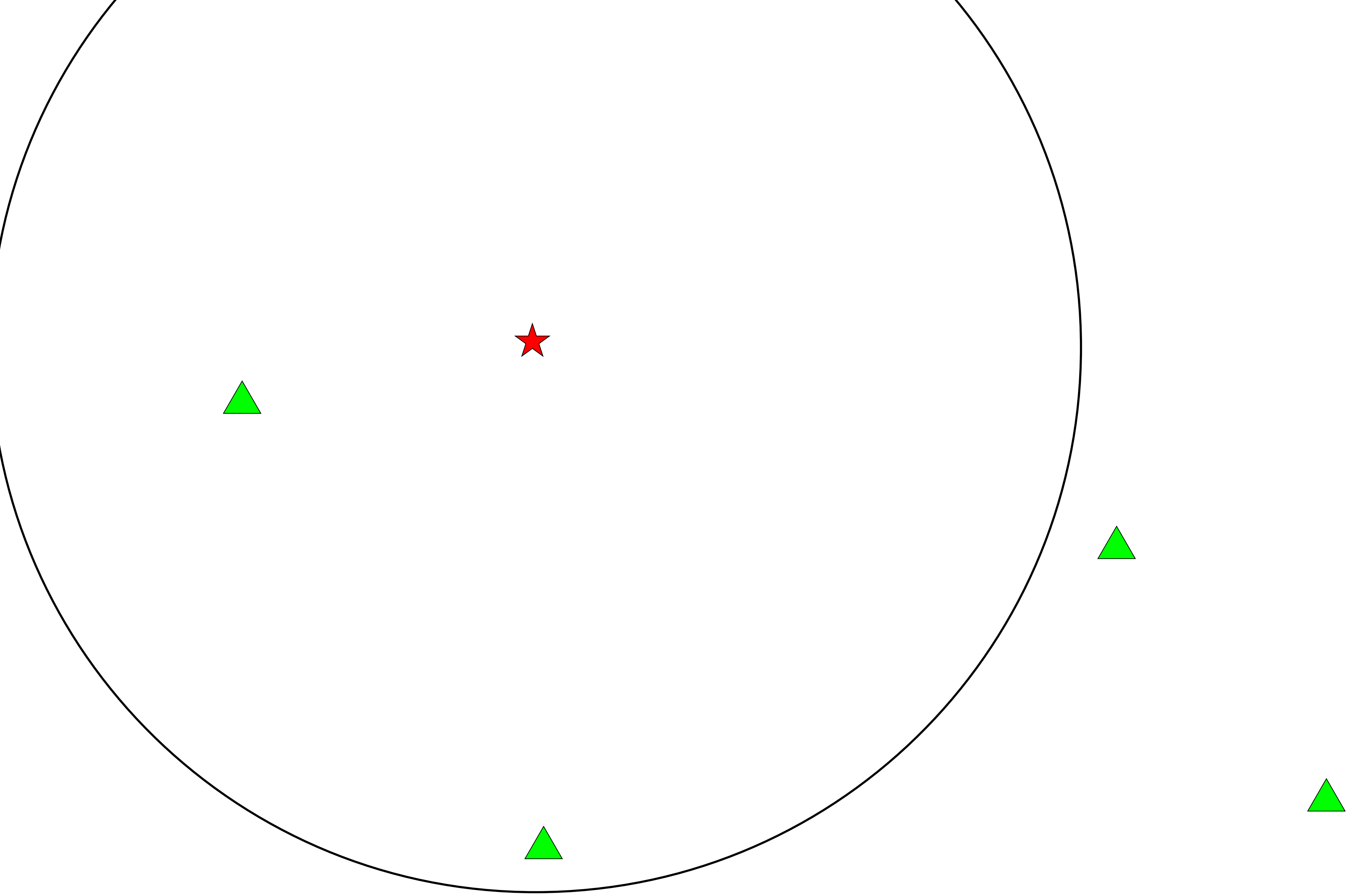


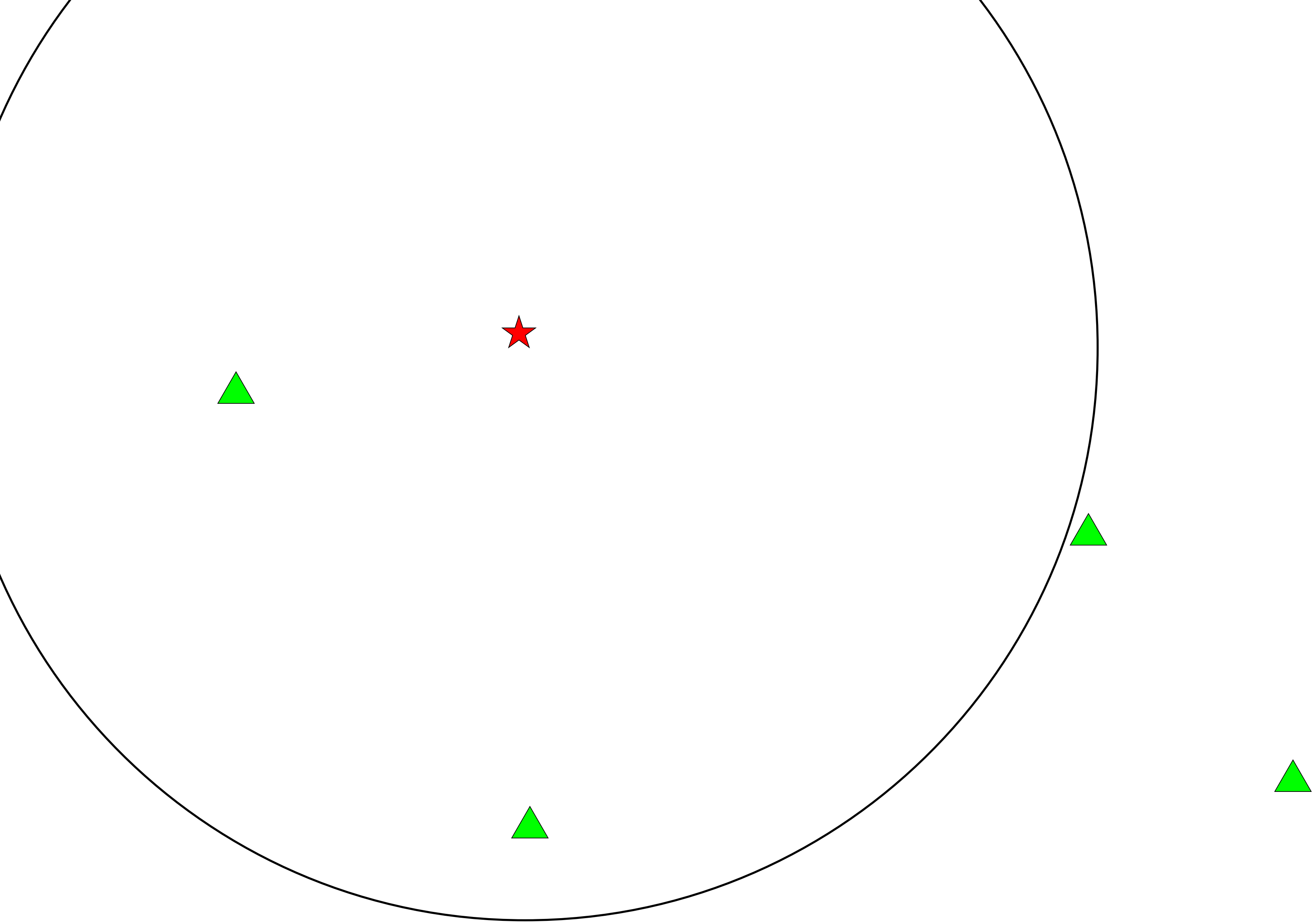


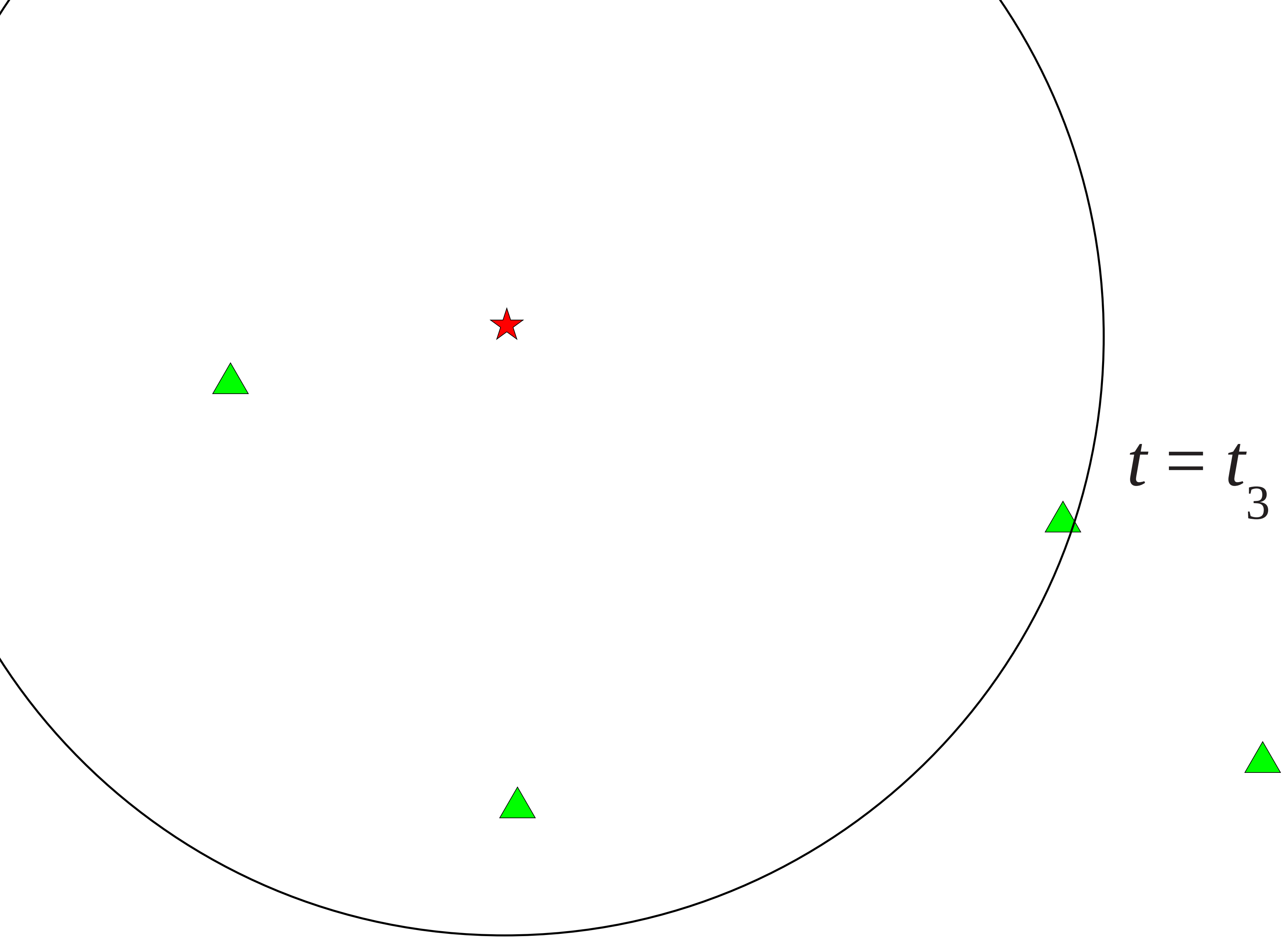


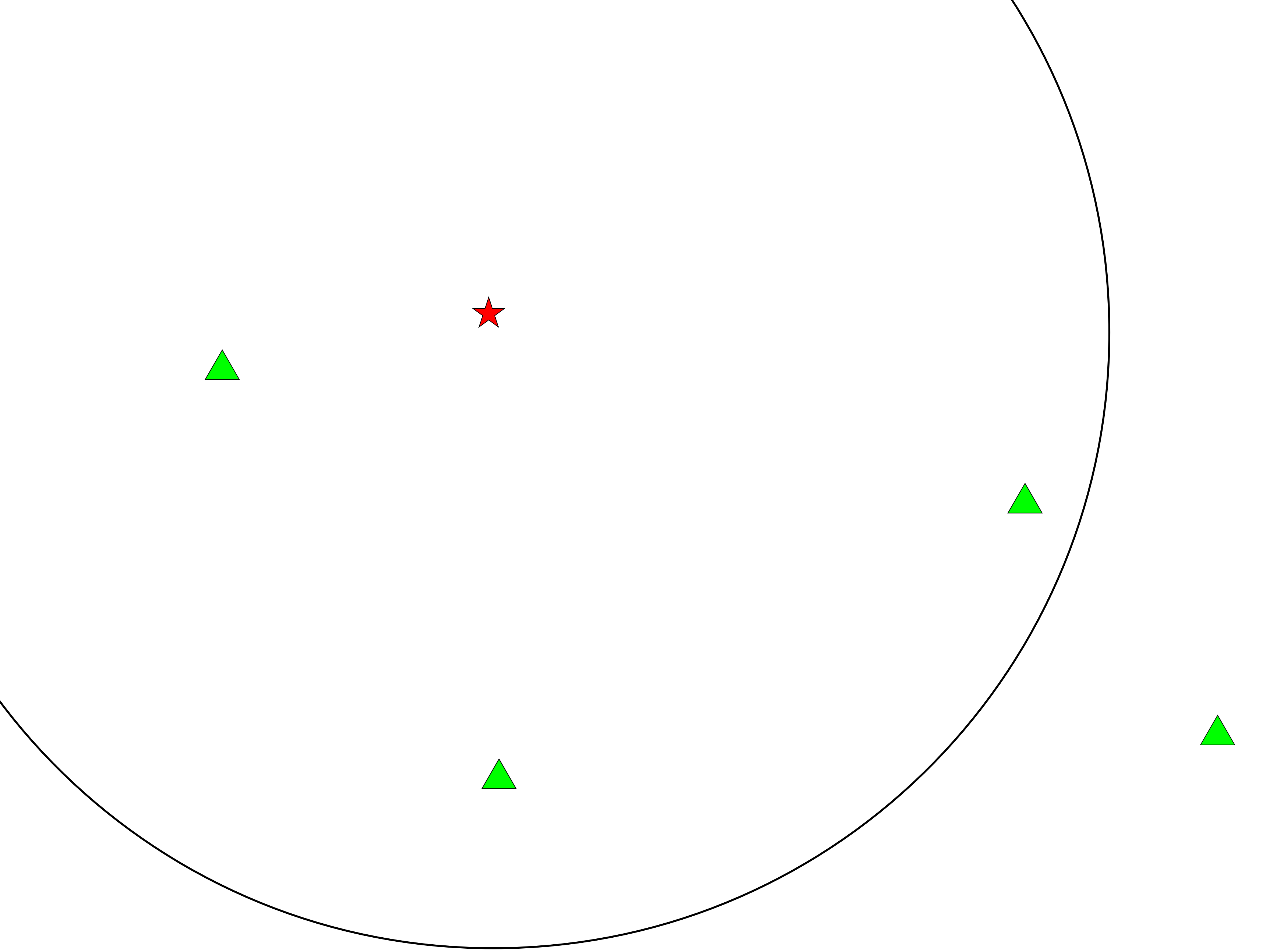


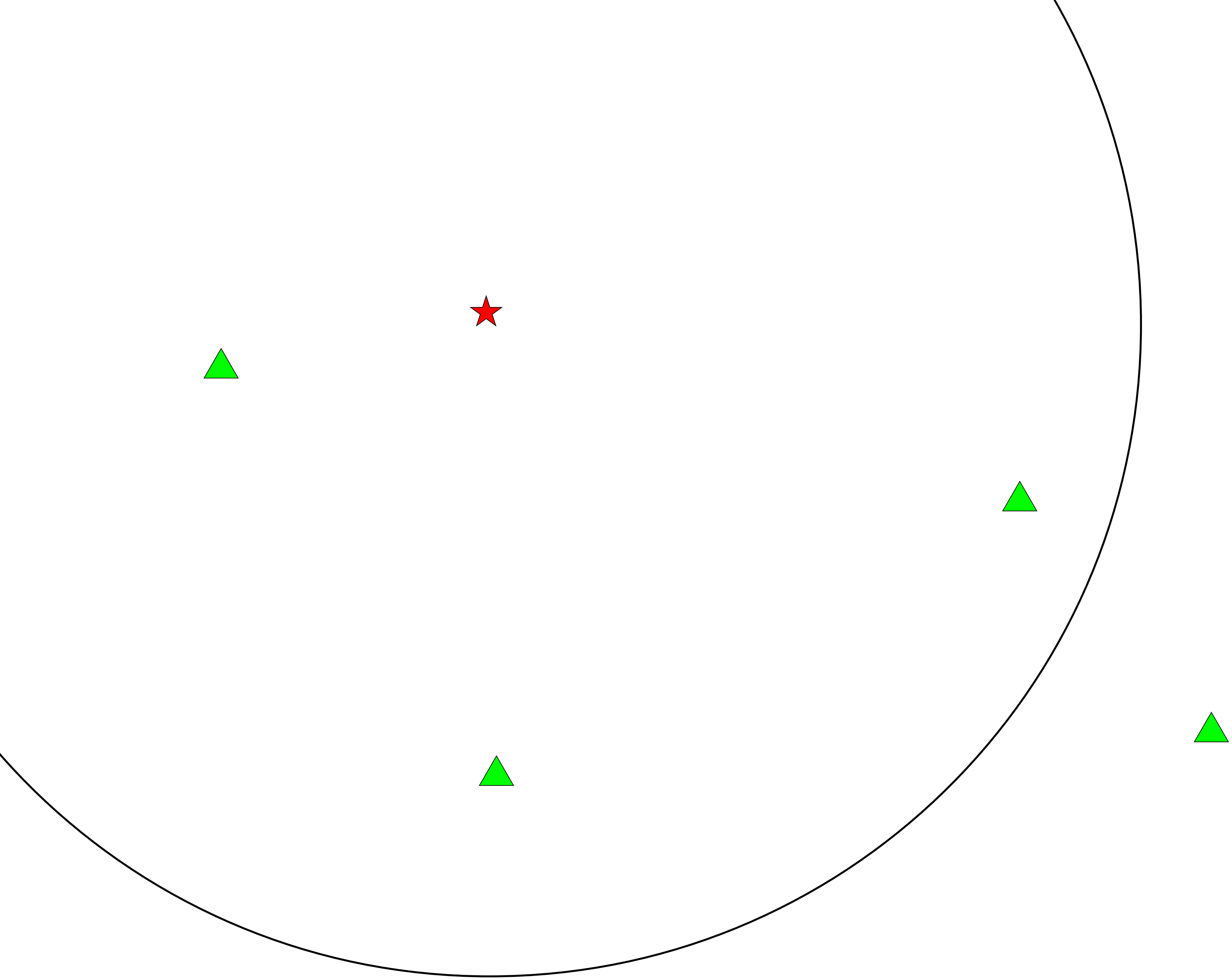
Signal reaches the second station giving an arrival time at $t = t_2$

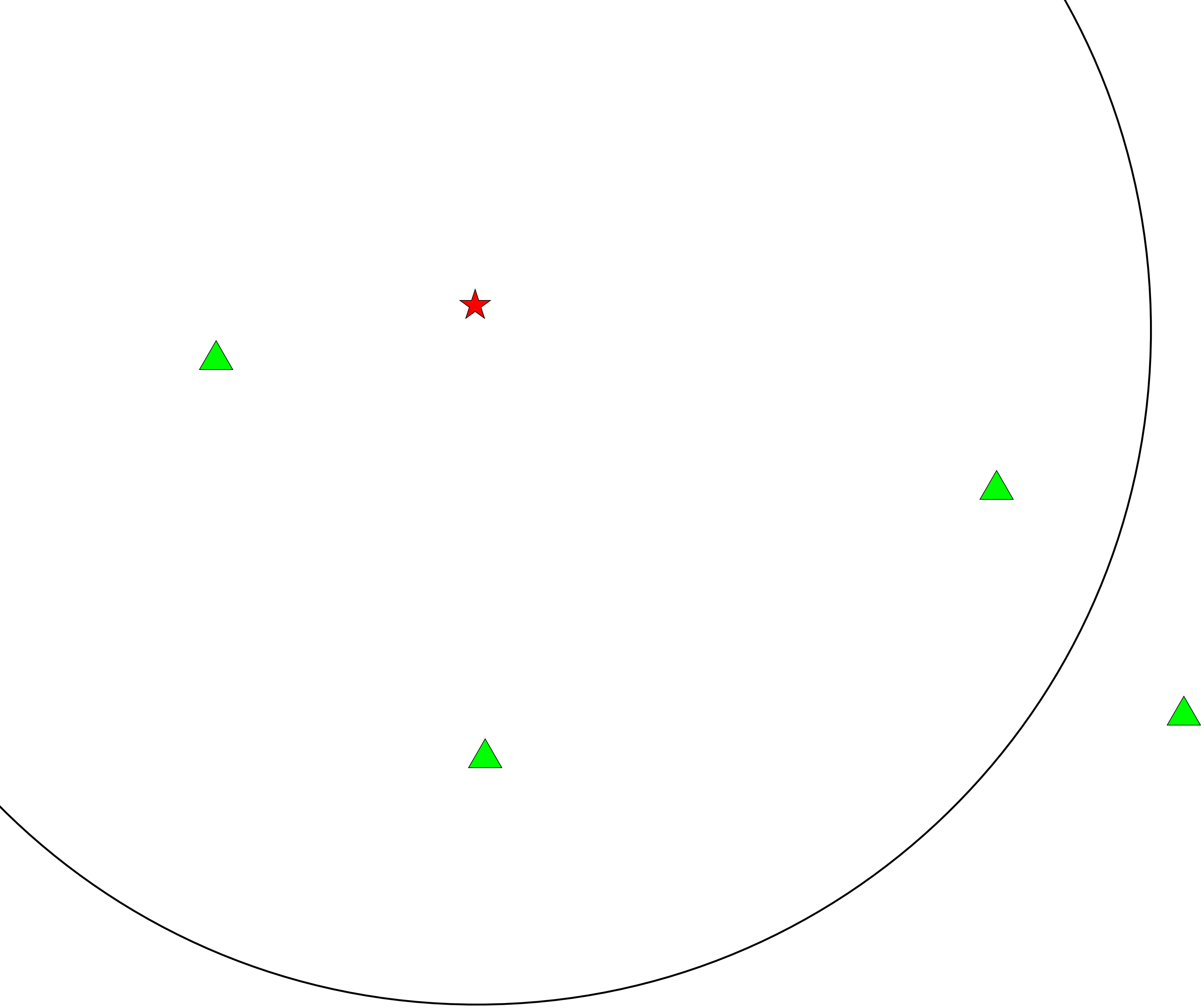


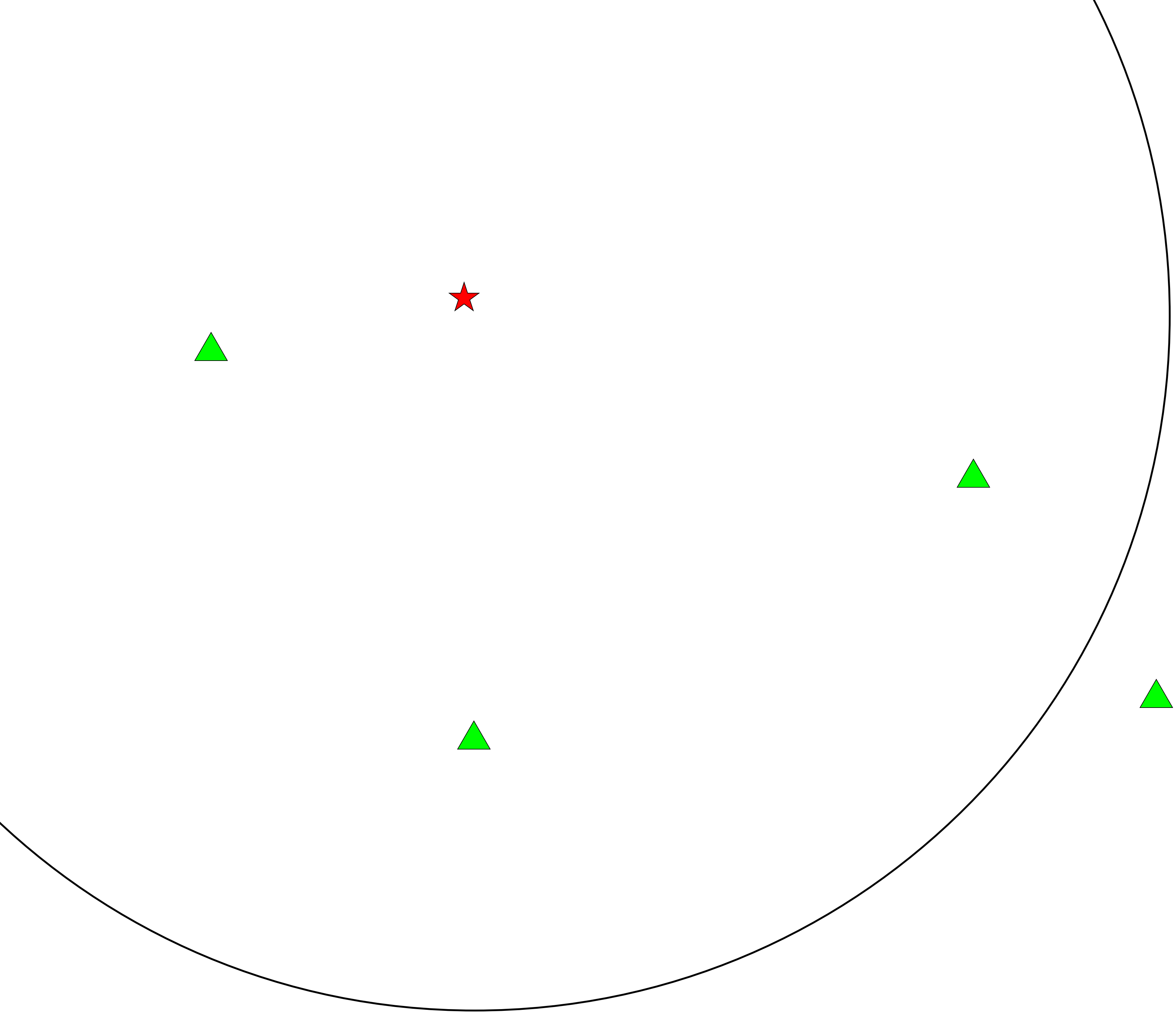


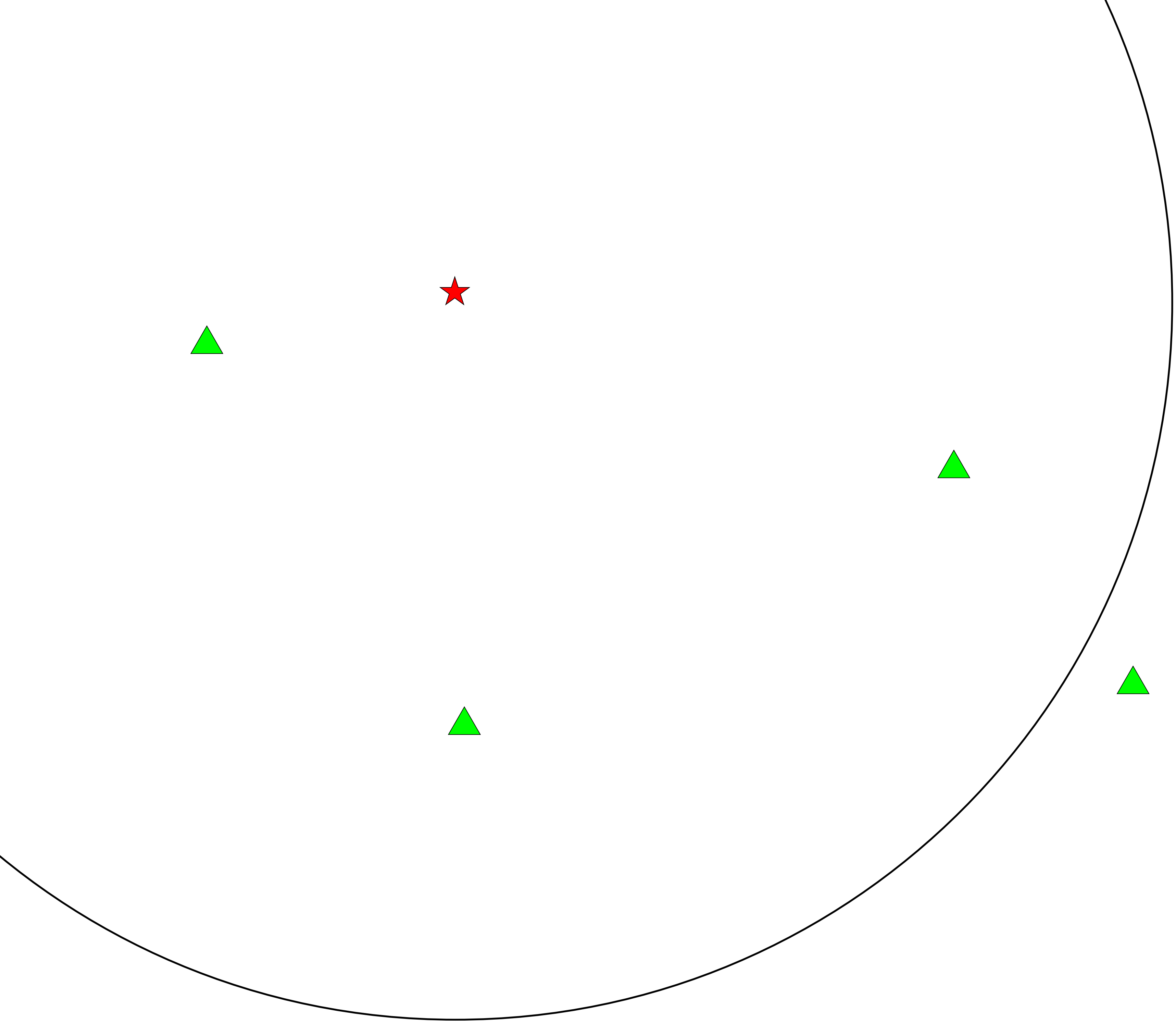

$t = t_3$

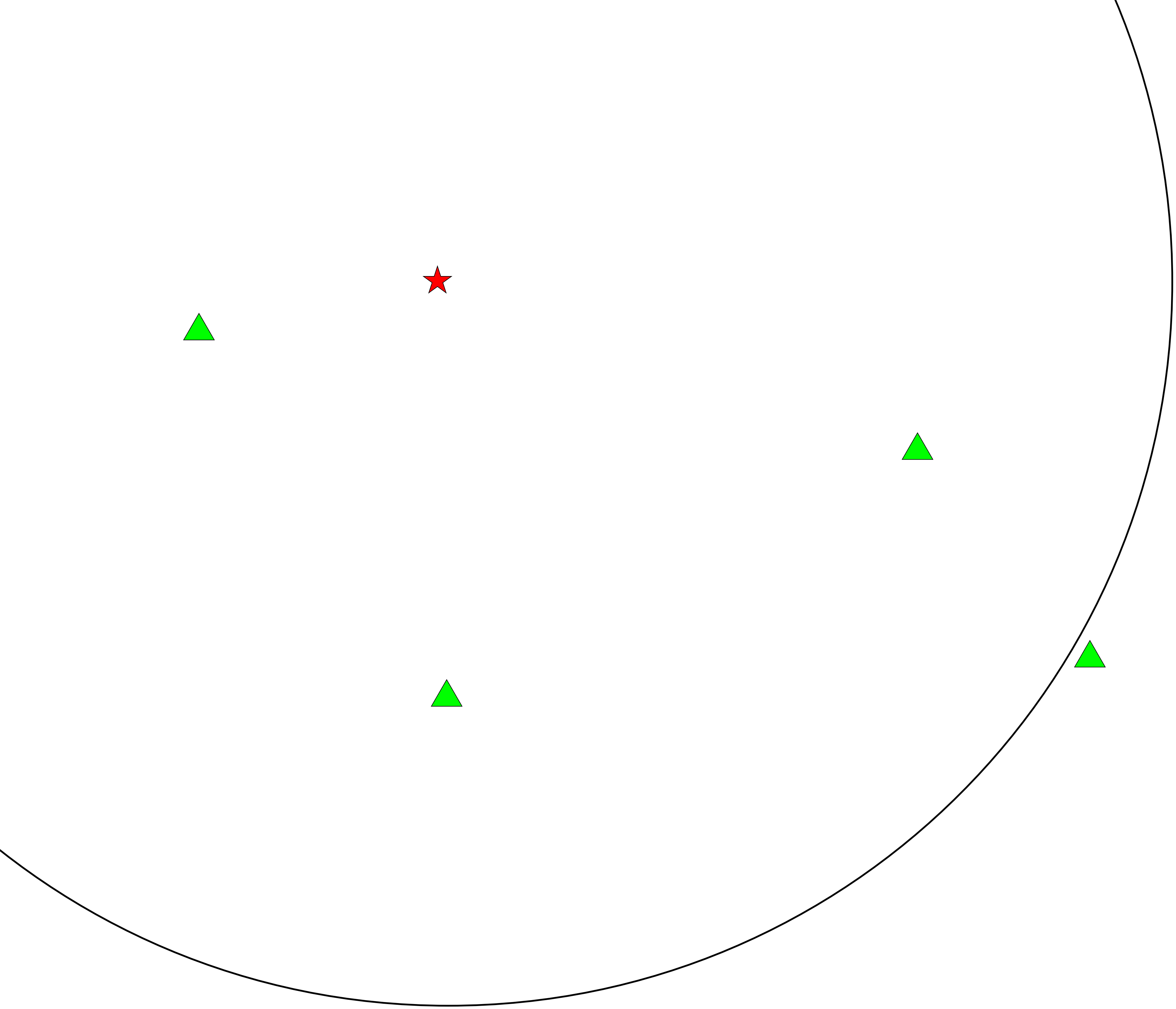


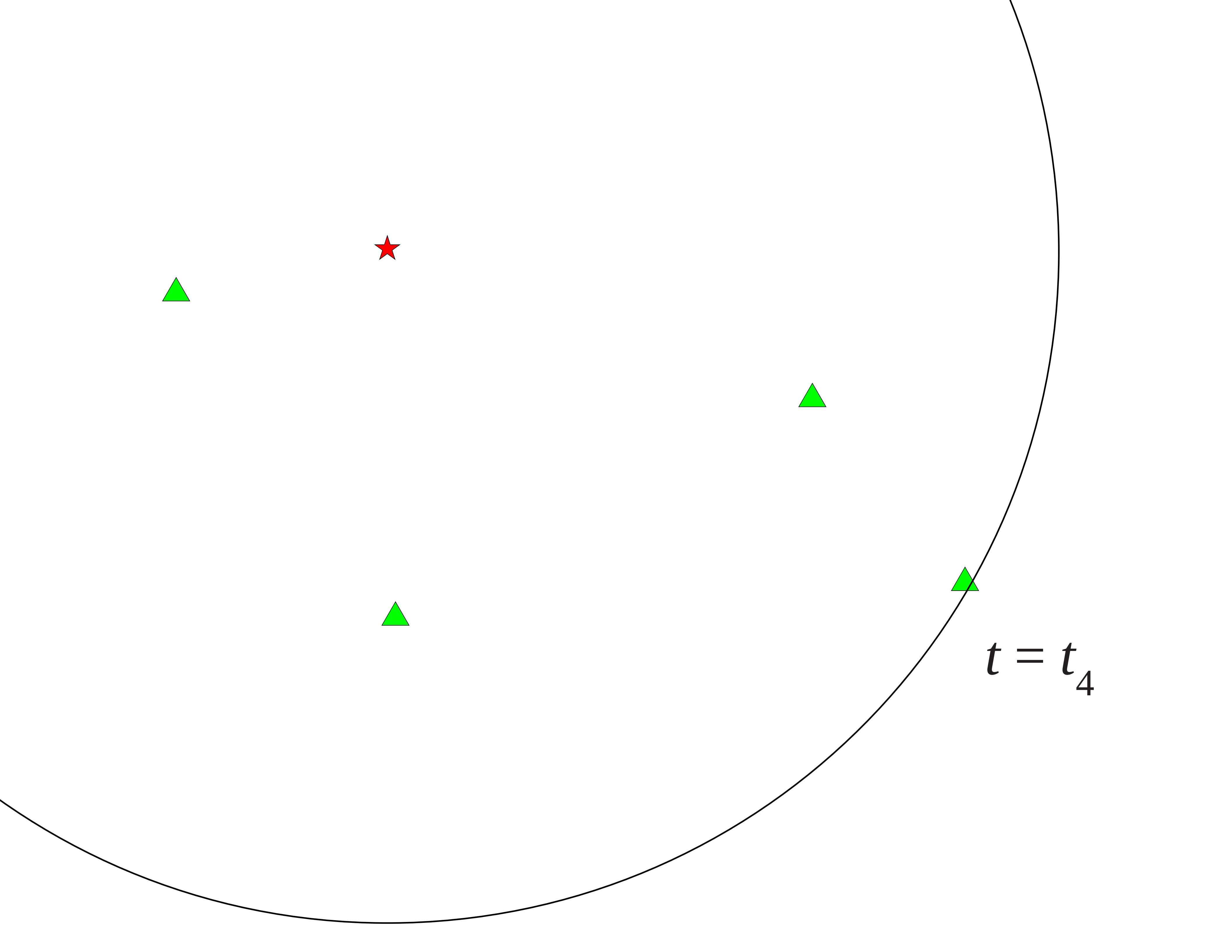


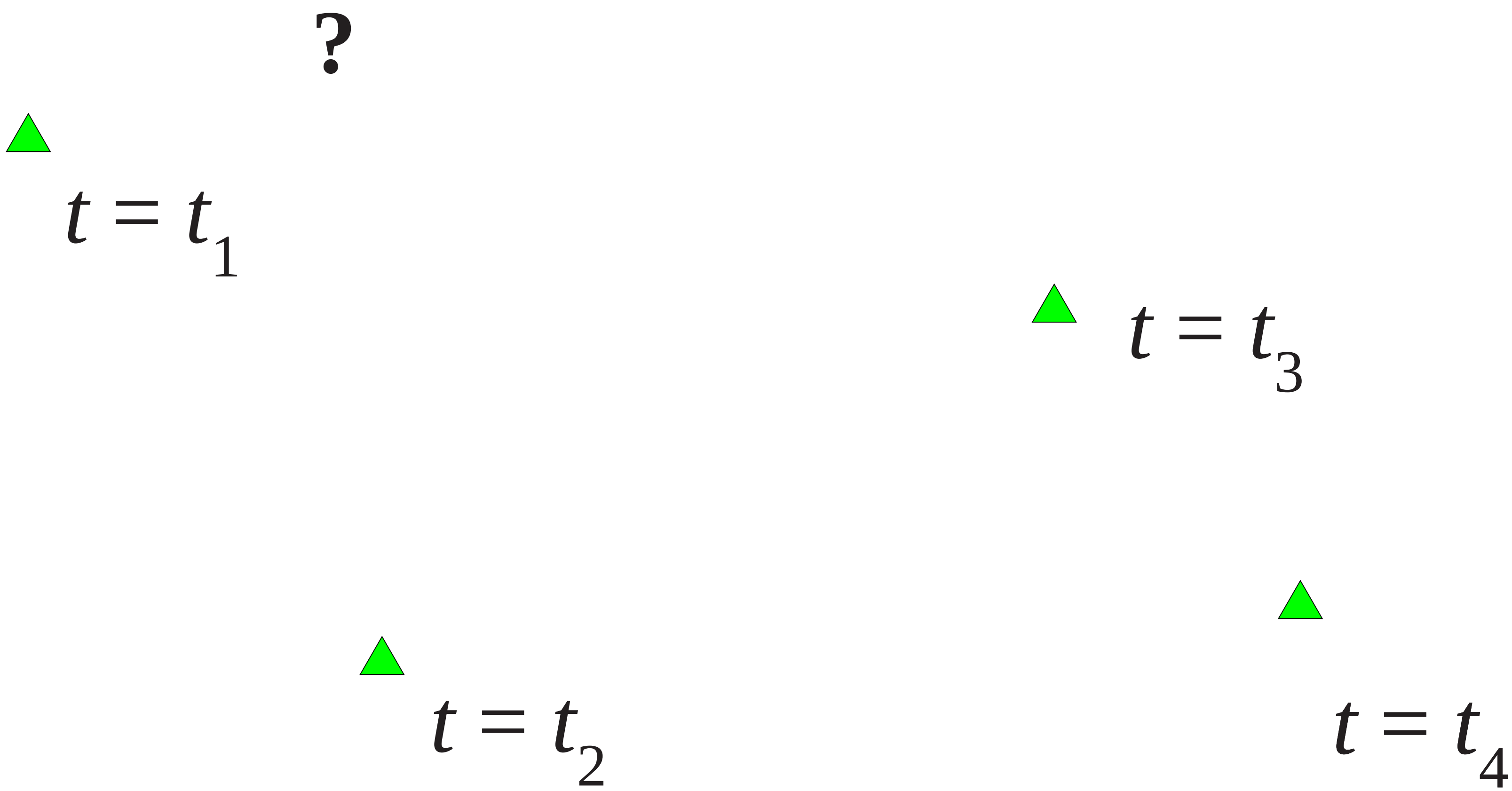









$t = t_4$



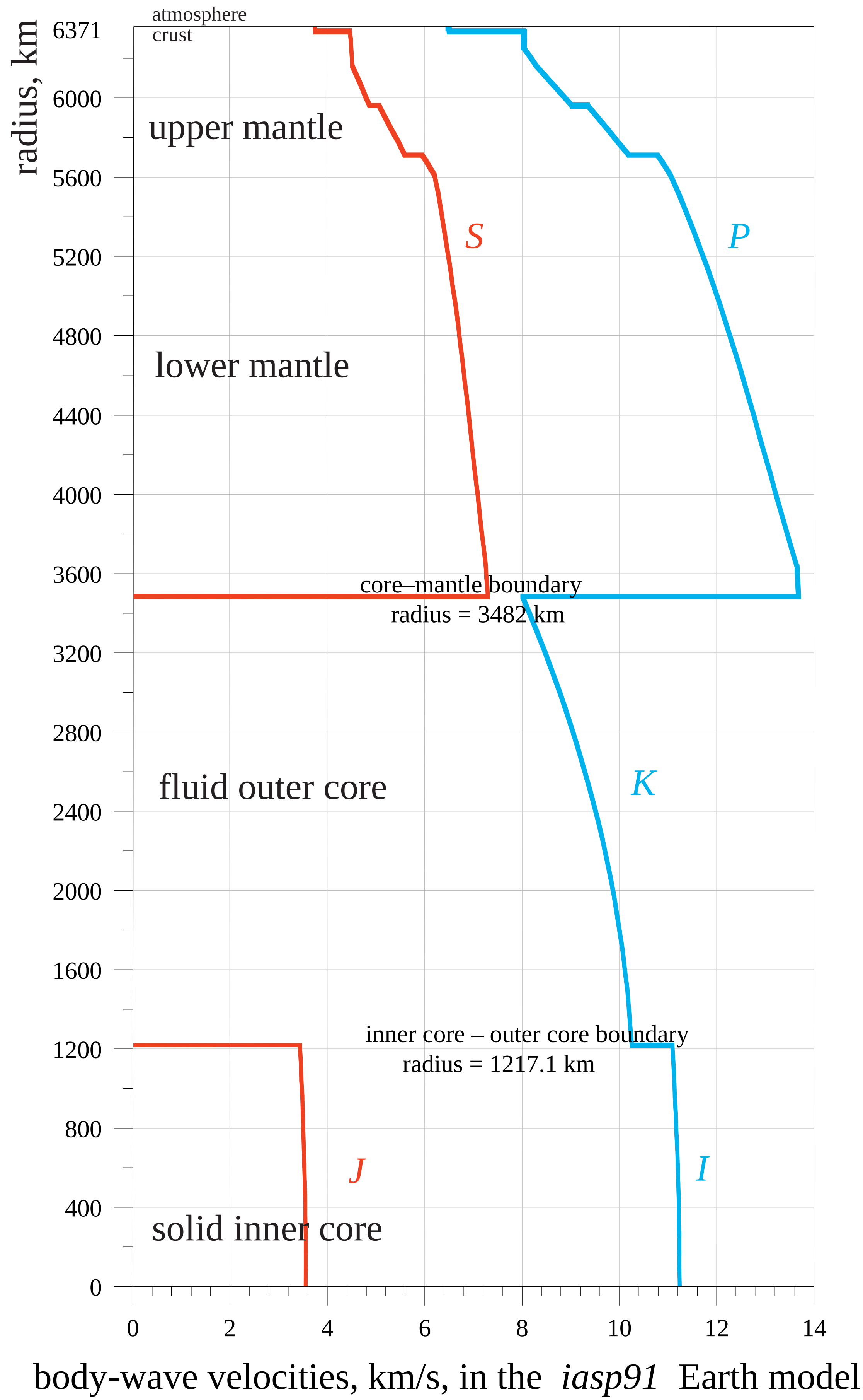
Four pieces of information, to determine location and origin time

Three problems with this simple explanation:

the waves spread in 3D not 2D
(easy to fix – with a standard Earth model)

we don’t know the exact model
(“model error”)

we can’t pick the arriving signals accurately
(“pick error”)


radius, km
atmosphere
crust
6371
6000
5600
5200
4800
4400
4000
3600
3200
2800
2400
2000
1600
1200
800
400
0
upper mantle
lower mantle
fluid outer core
solid inner core
S
P
K
J
I
core–mantle boundary
radius = 3482 km
inner core – outer core boundary
radius = 1217.1 km
0
2
4
6
8
10
12
14
body-wave velocities, km/s, in the *iasp91* Earth model

Pn - wave path
(travels mostly in the mantle)

Pg - paths, in the crust,
all with similar travel times

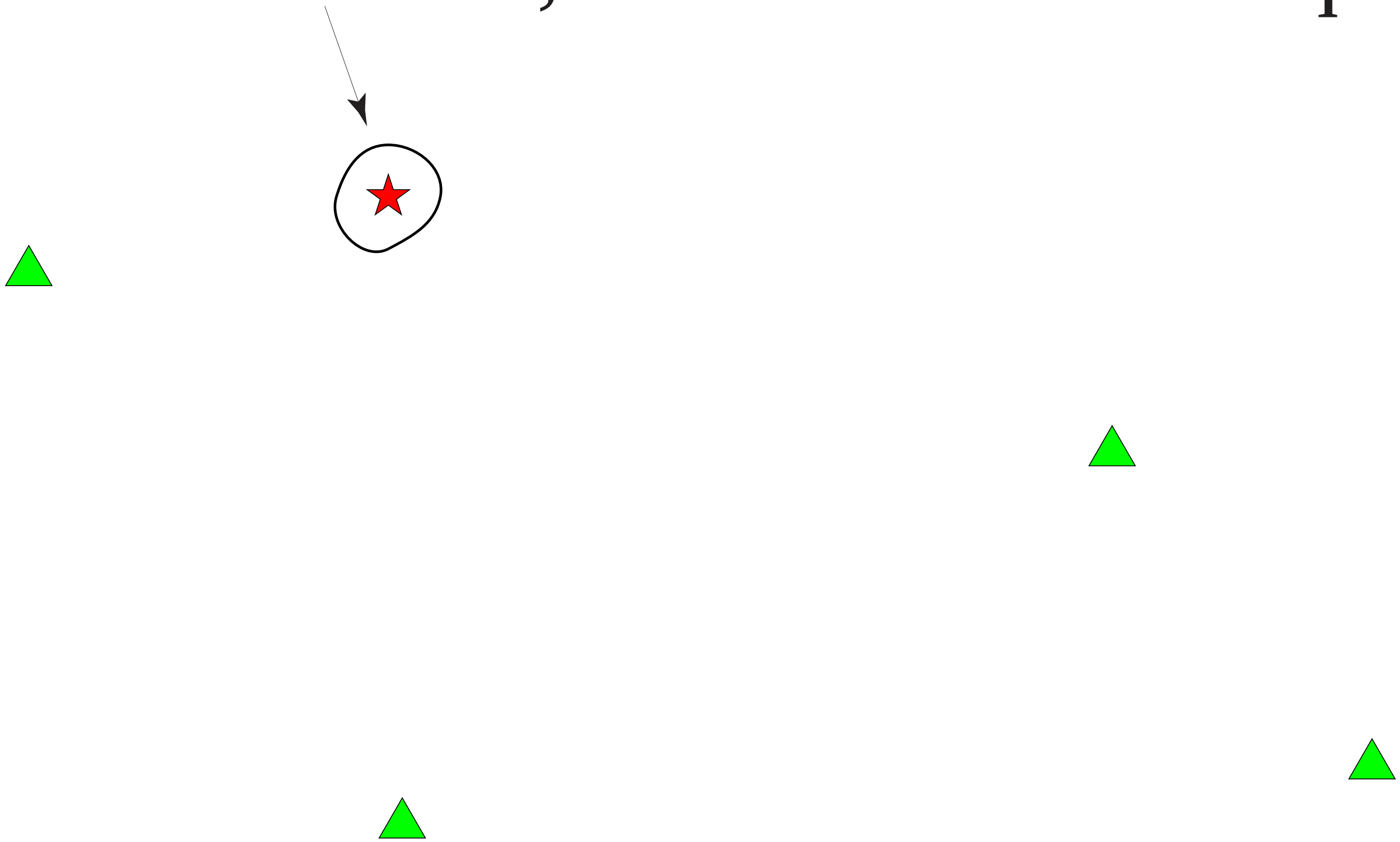
Three problems, one solved:

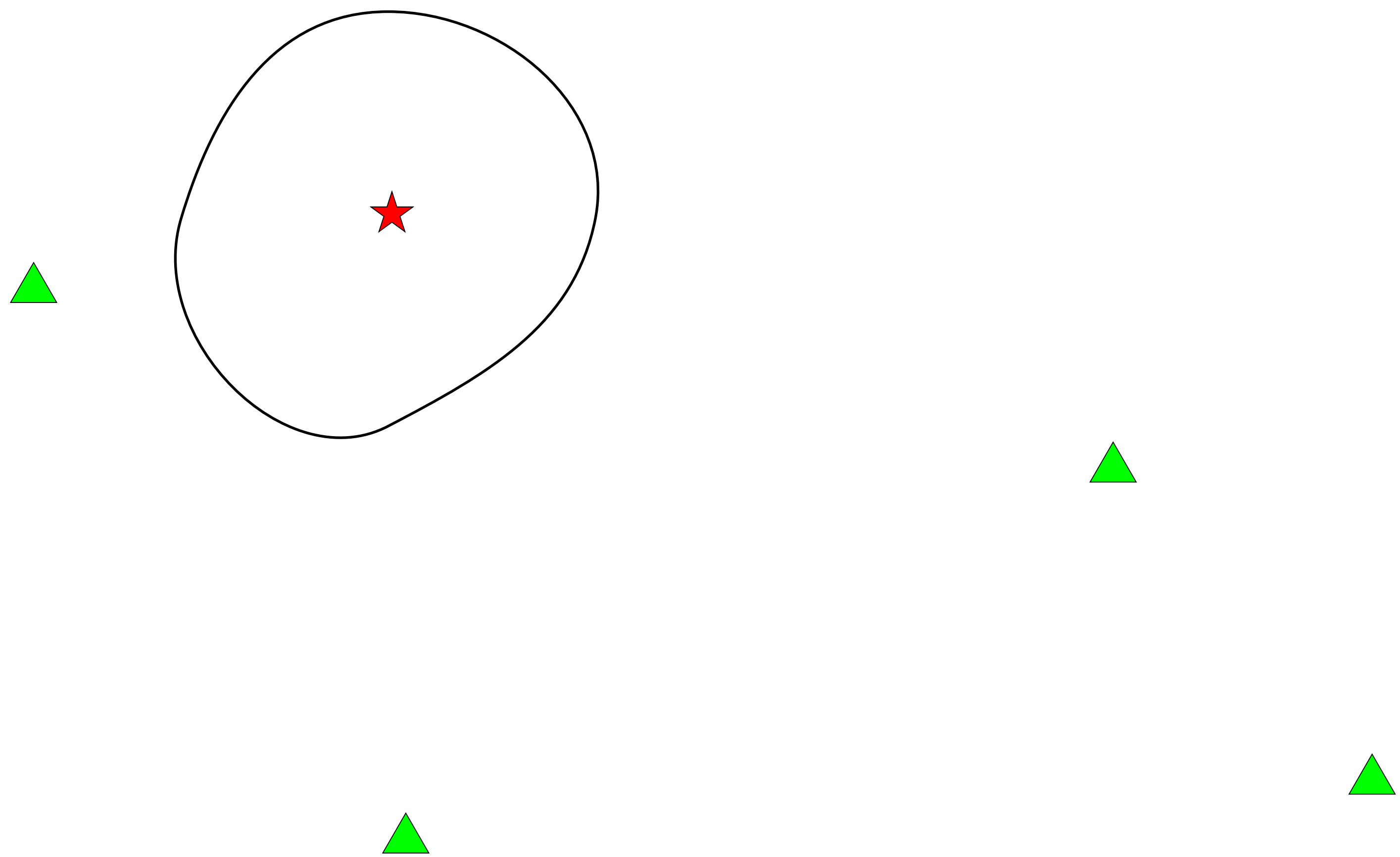
the waves spread in 3D not 2D √
(easy to fix – with a standard Earth model)

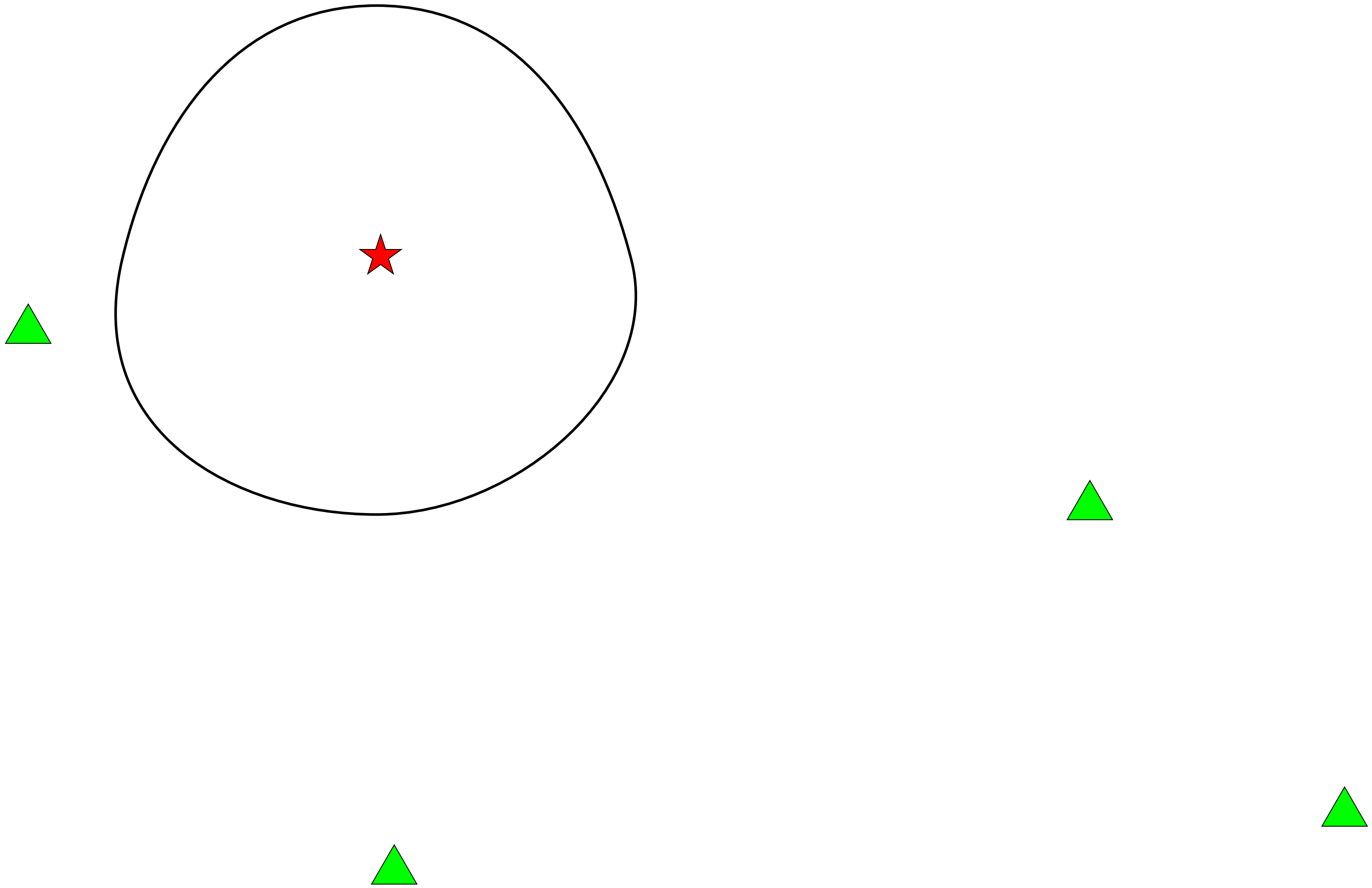
we don’t know the exact model
(“model error”)

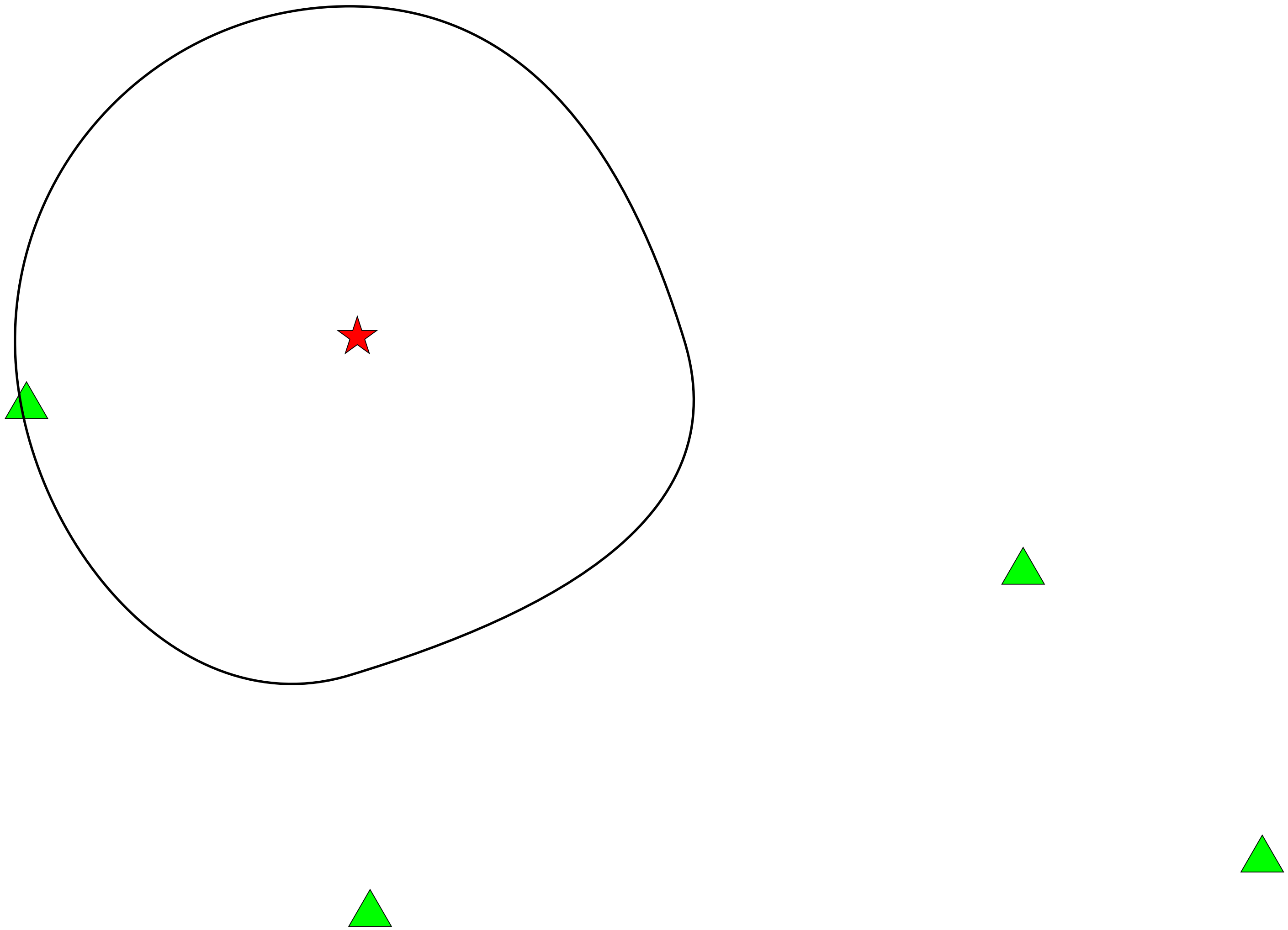
we can’t pick the arriving signals accurately
(“pick error”)

Seismic wavefront, soon after an earthquake starts

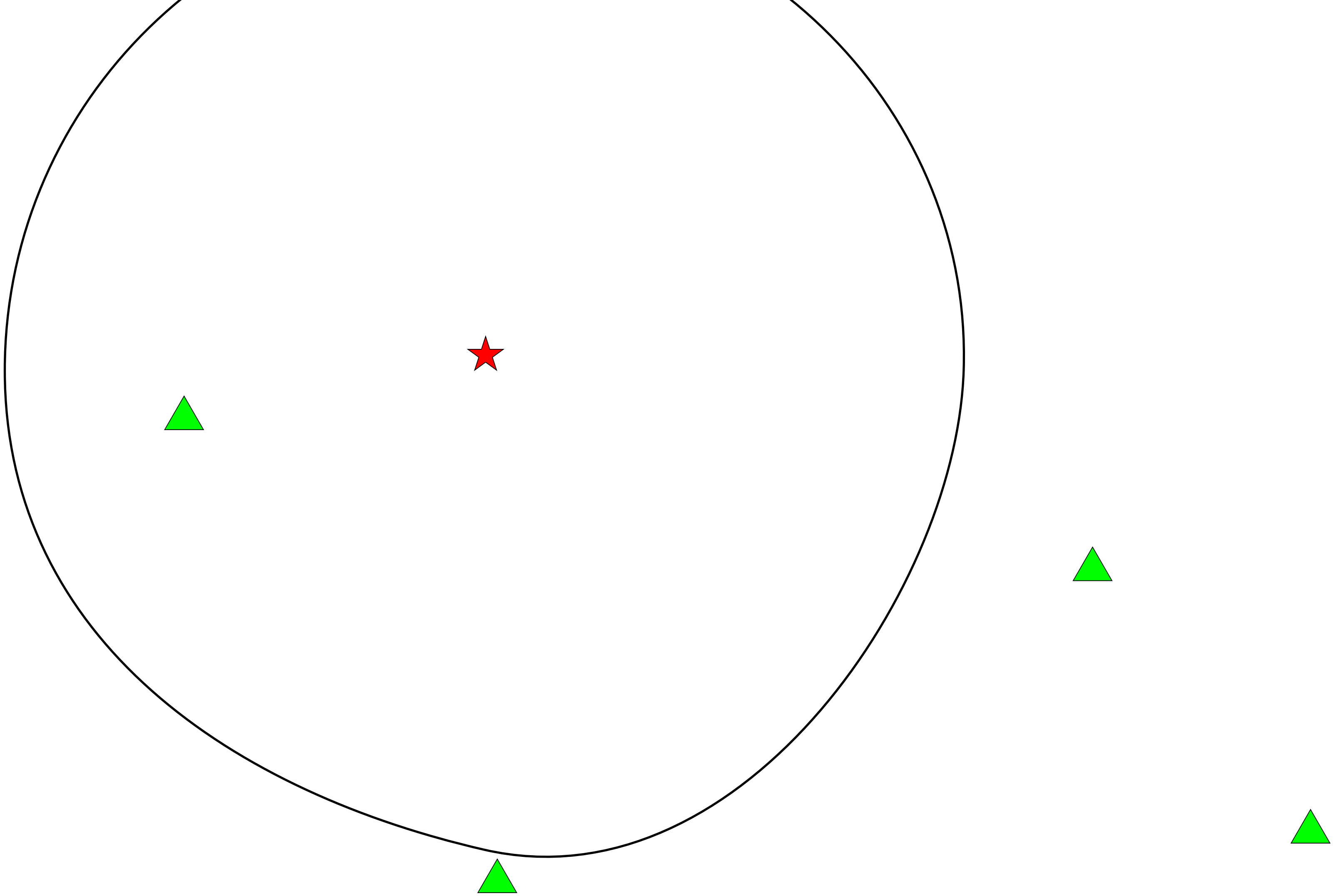


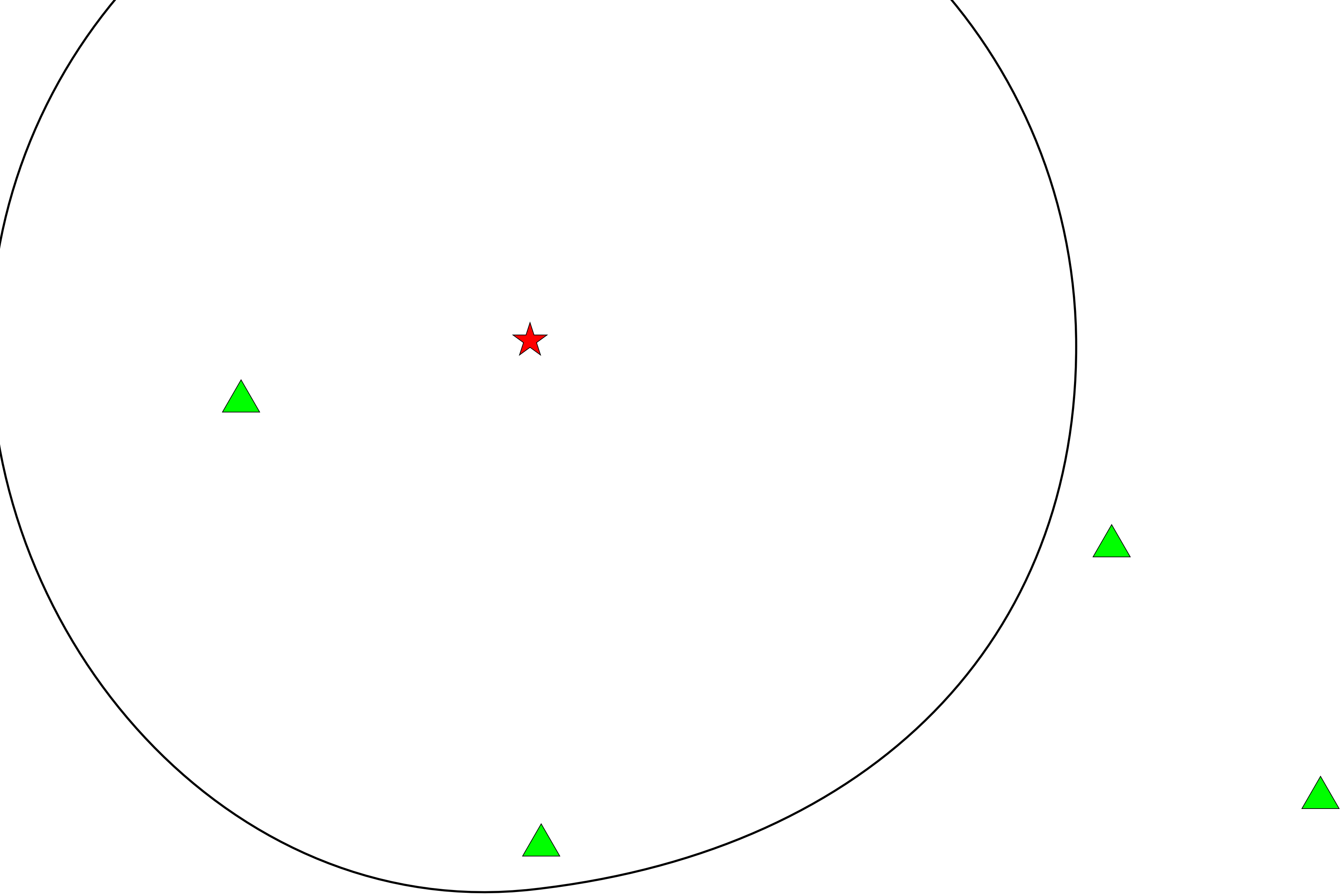


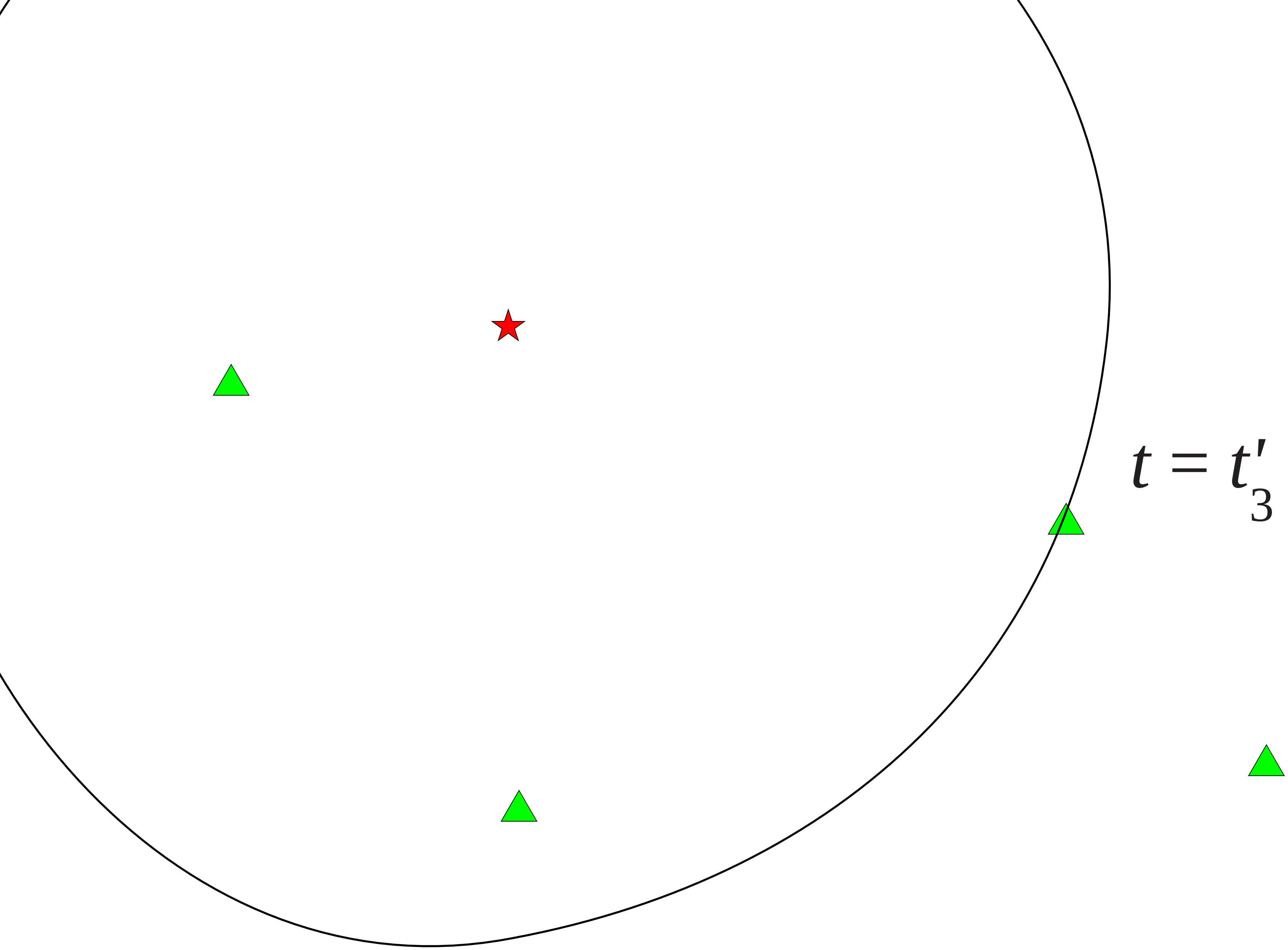


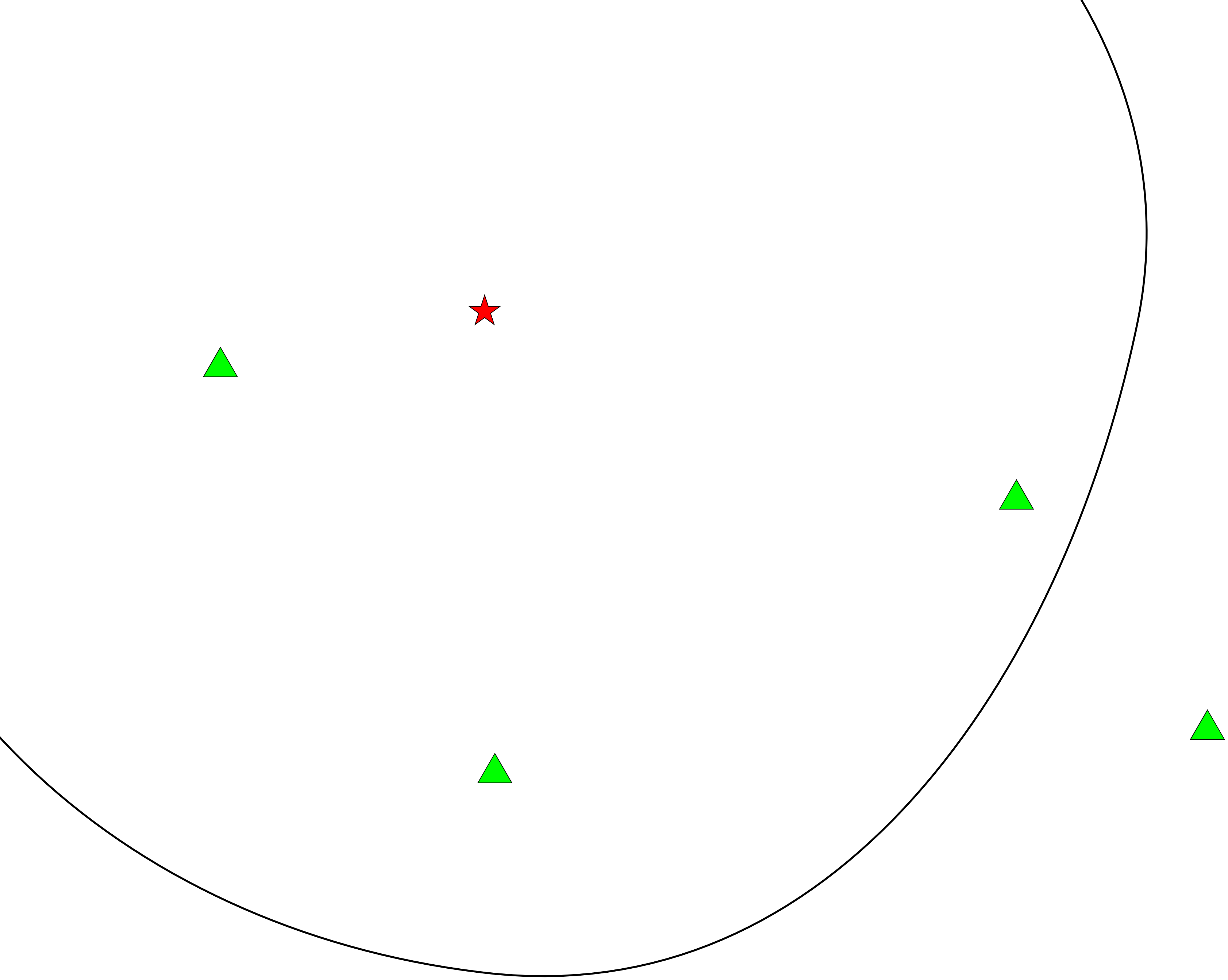


The nearest station gets a signal, at time $t = t_1'$






$t = t'_3$



How to solve this second problem, of unmodelled perturbations to standard travel times?

Better 3D model of the whole Earth?
(Will take too long.)

Empirical methods?
(This approach is the basis of a Lamont consortium effort.)

Location Calibration for 30 IMS Stations in East Asia

A consortium project, began March 2000.
The consortium members are:

URS Greiner Woodward Clyde

Chandan Saikia, Gene Ichinose

University of Connecticut

Vernon Cormier, Anastasia Stroujkova

Lamont-Doherty Earth Observatory of Columbia University

Paul Richards, Vitaly Khalturin, Won-Young Kim,
Felix Waldhauser, David Schaff, John Armbruster

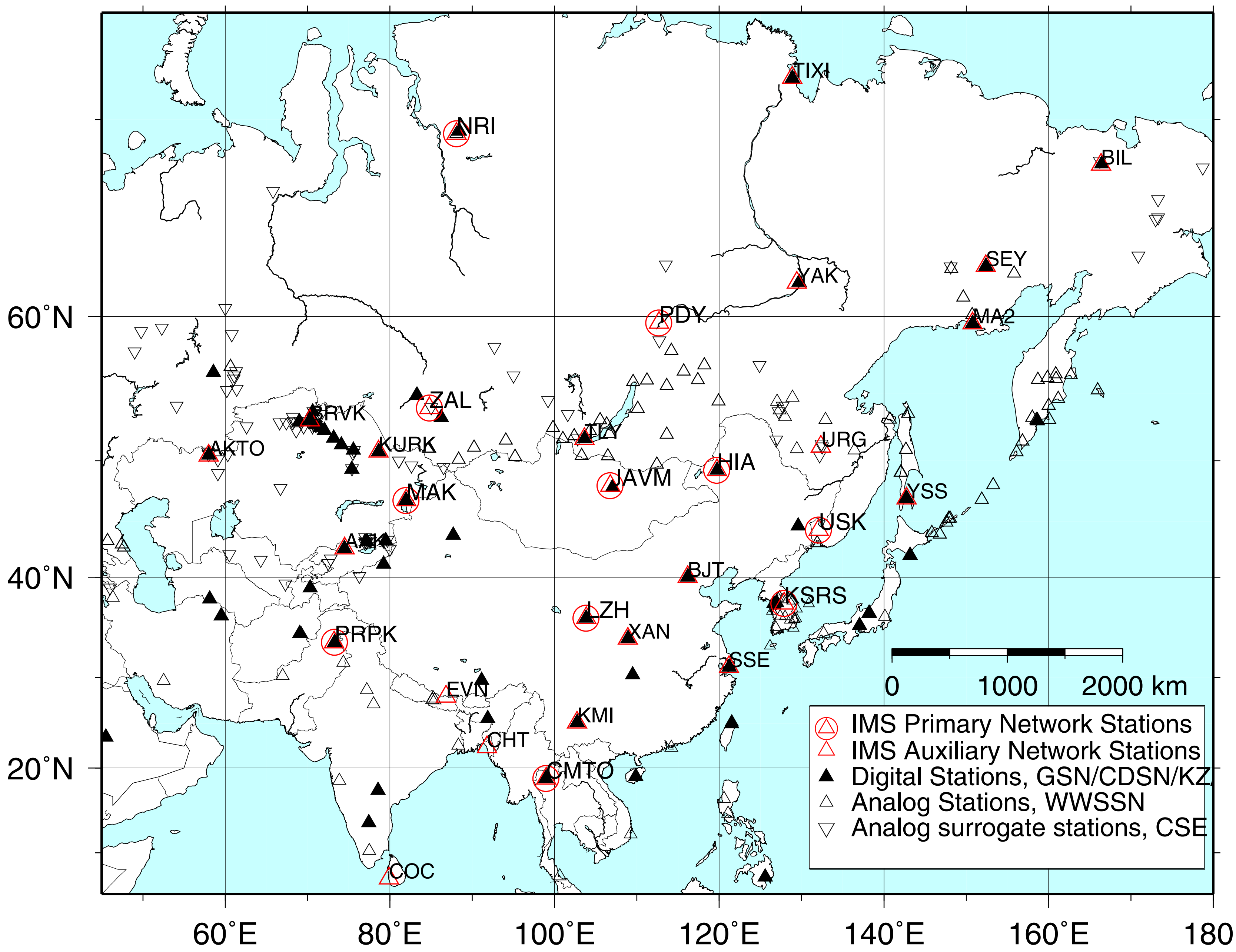
Mission Research Corporation

Mark Fisk, Relu Burlacu

University of Wyoming

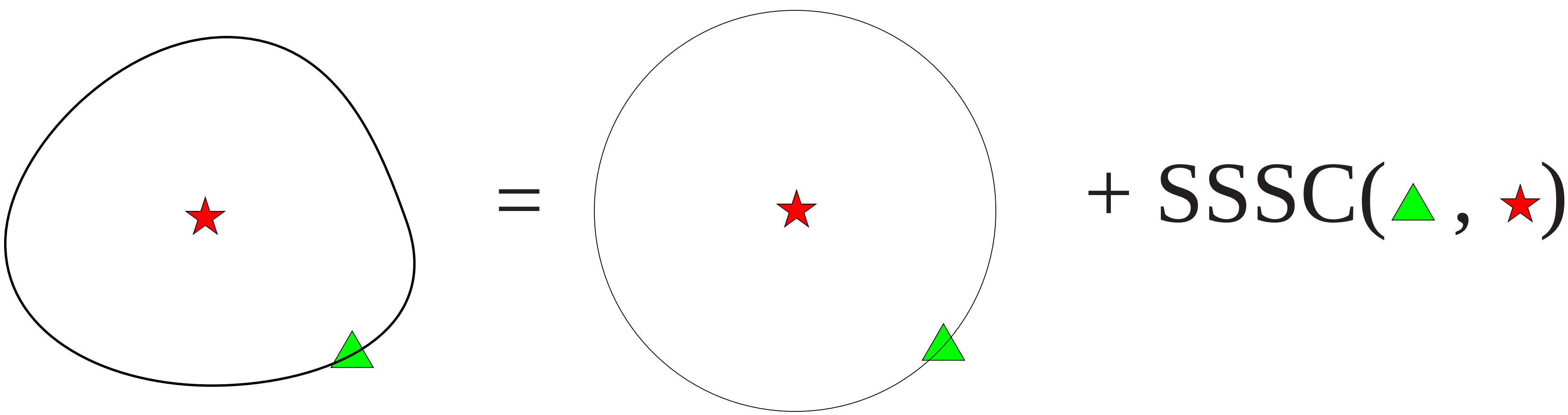
Igor Morozov, Elena Morozova

IMS Primary & Auxiliary Network Stations



Jargon:
"Source-Specific Station Corrections" (SSSC)

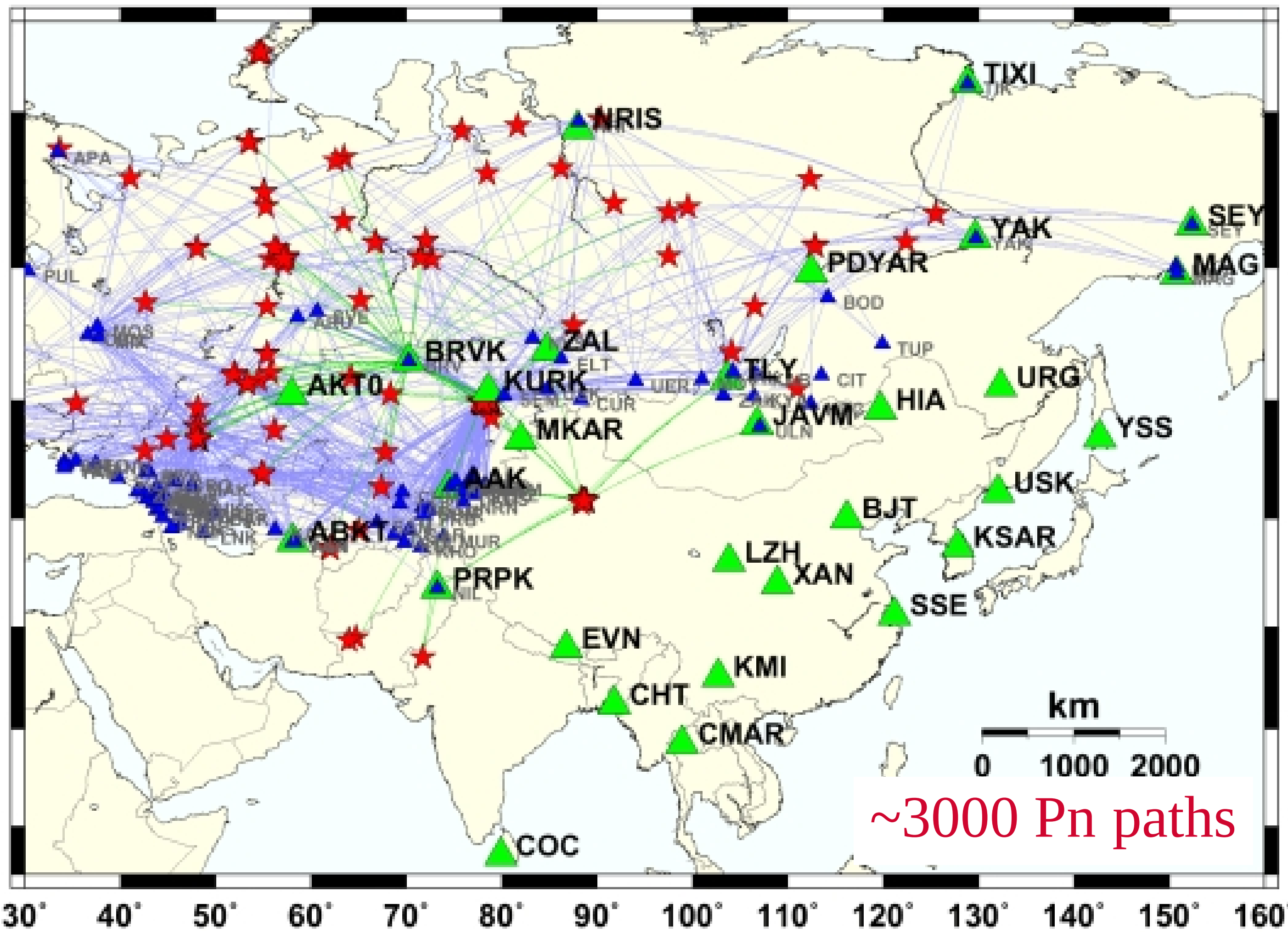
These are the corrections in travel time, needed
to get the *actual* system of expanding non-circular wavefronts,
from the *predicted* system of expanding circular wavefronts
based on the iasp91 standard model:



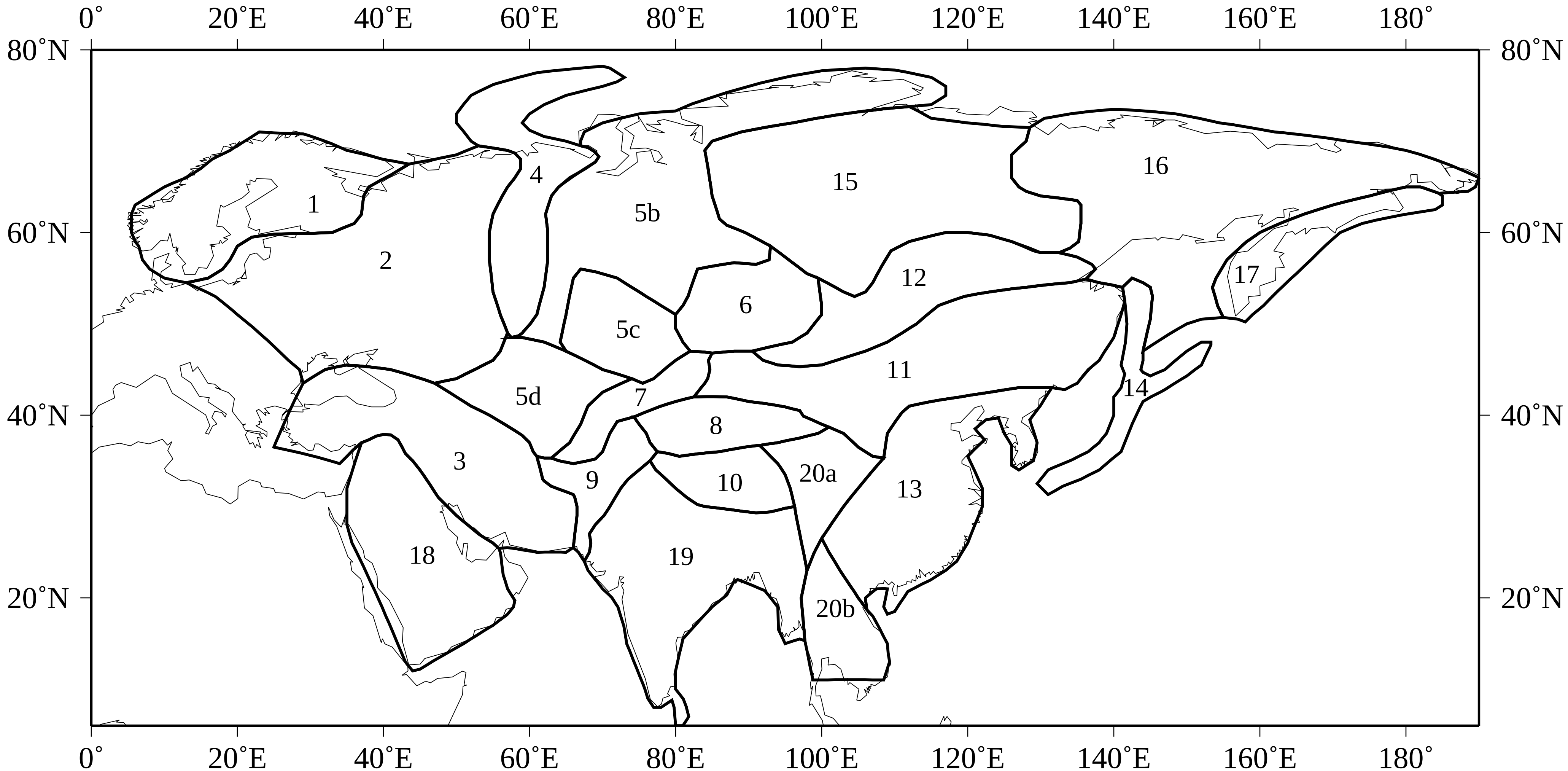
iasp91 prediction

Travel time (source to station)

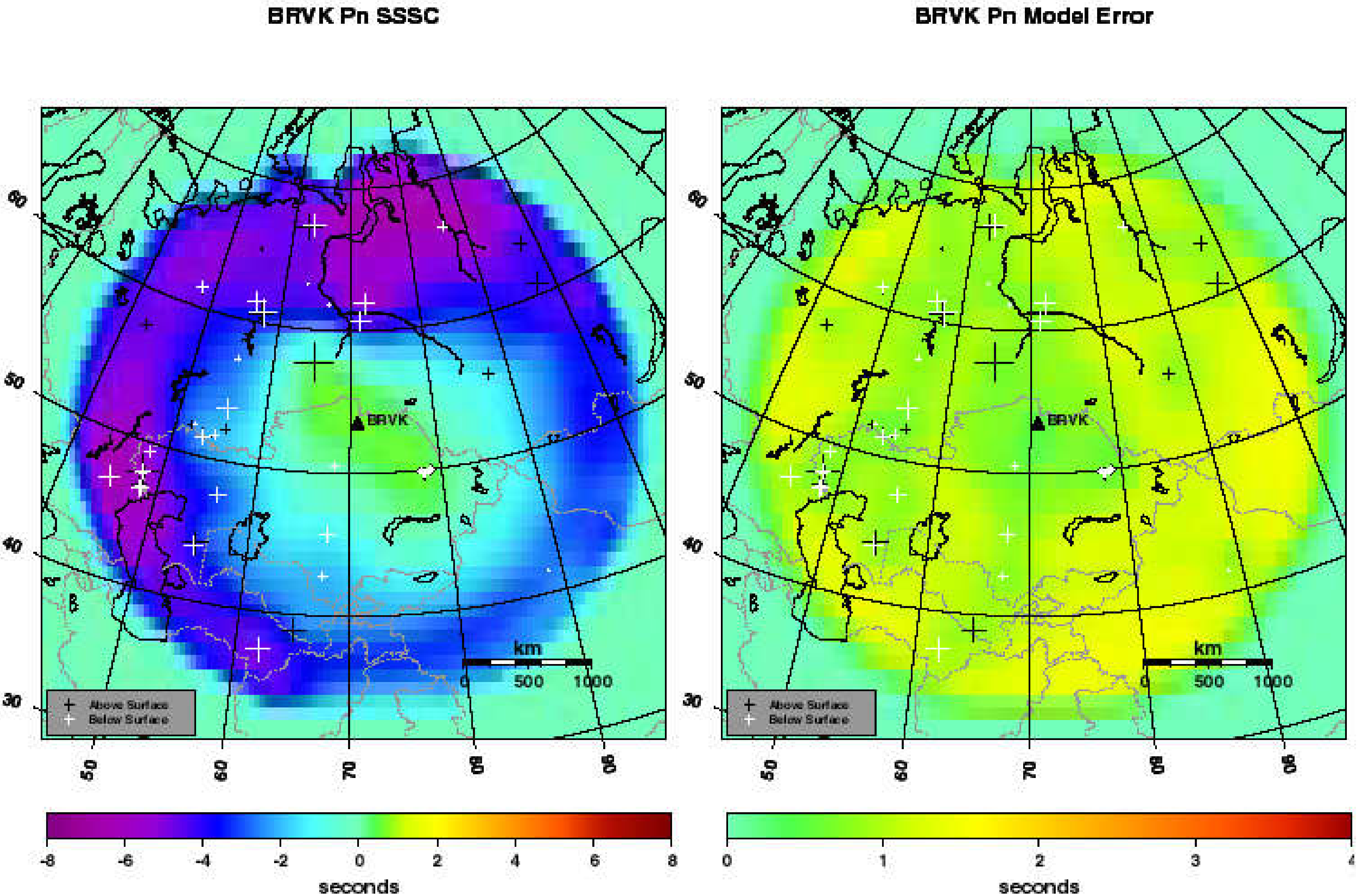
= Standard value + SSSC



174 GT explosions (stars) and the recording seismographic stations (triangles) used for validation tests. Good news, bad news: dense regions, blank regions (but, with earthquakes)

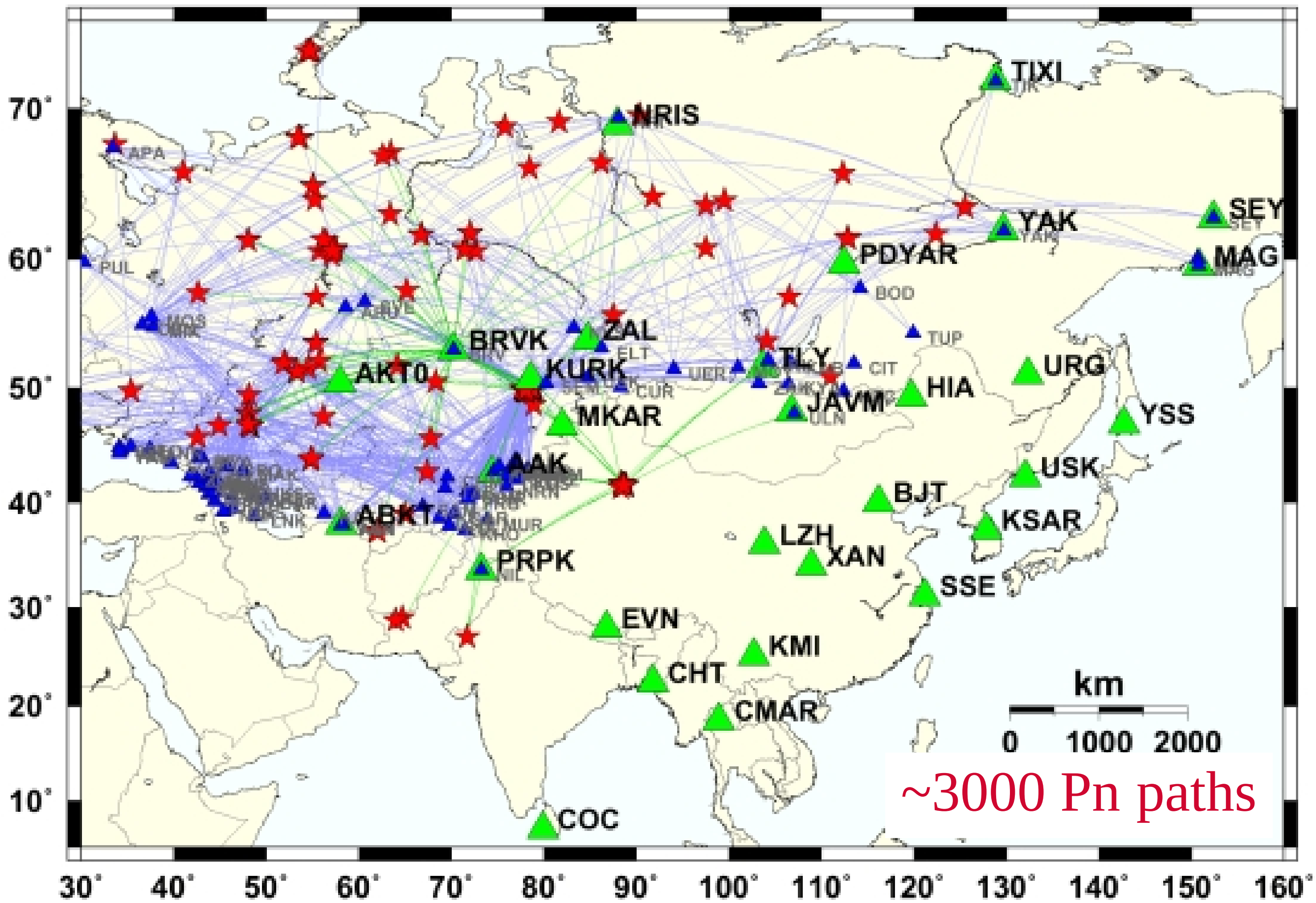


0°
20°E
40°E
60°E
80°E
100°E
120°E
140°E
160°E
180°
80°N
60°N
40°N
20°N
1
2
3
4
5b
5c
5d
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20a
20b

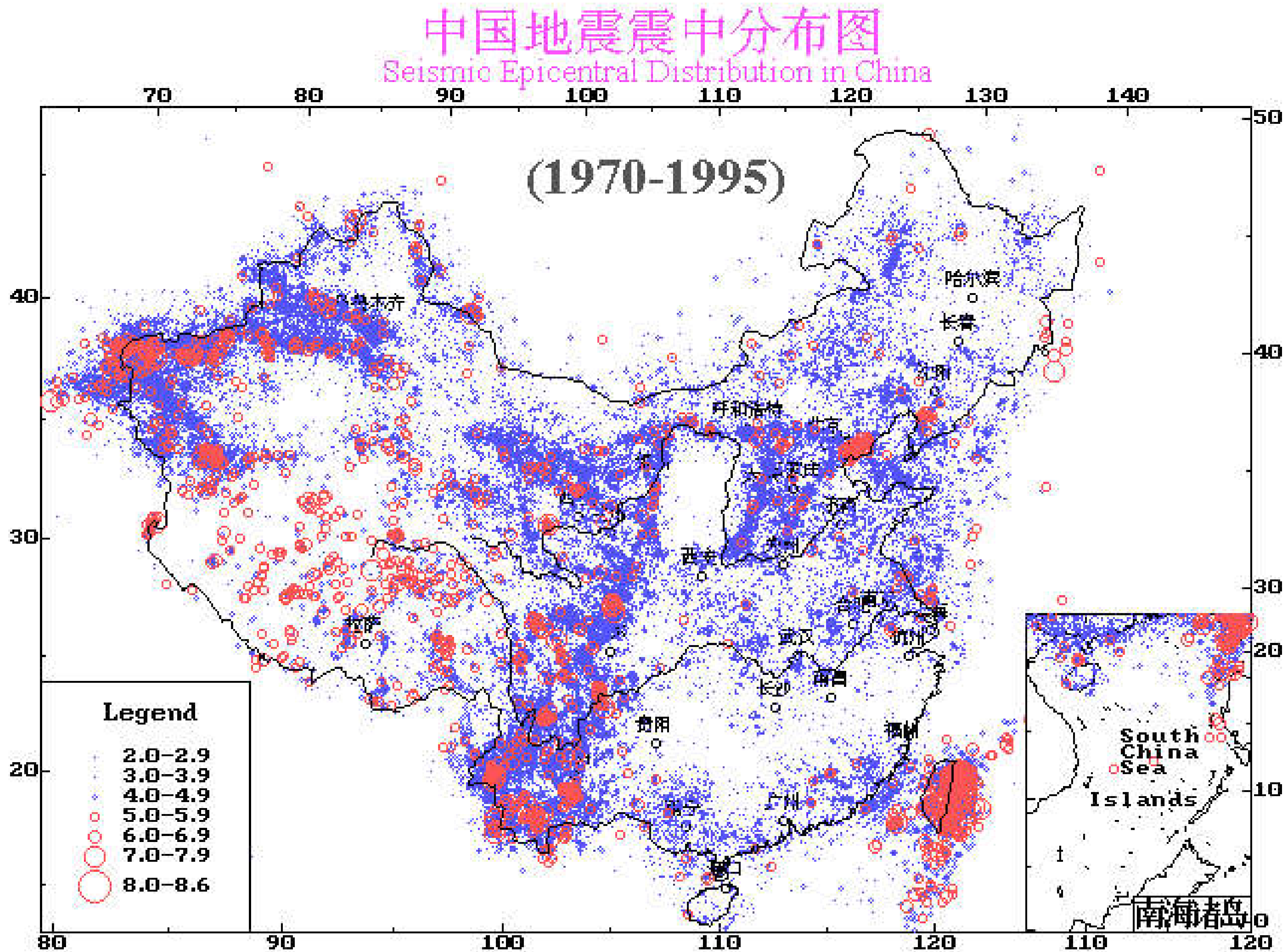

BRVK Pn SSSC
BRVK Pn Model Error
BRVK
km
0
500
1000
Above Surface
Below Surface
60
50
40
30
70
80
90
-8
-6
-4
-2
0
2
4
6
8
seconds
0
1
2
3
4
seconds

Use of kriged SSSCs, for 14 IMS stations in Russia and Central Asia, has led us to the following preliminary results:

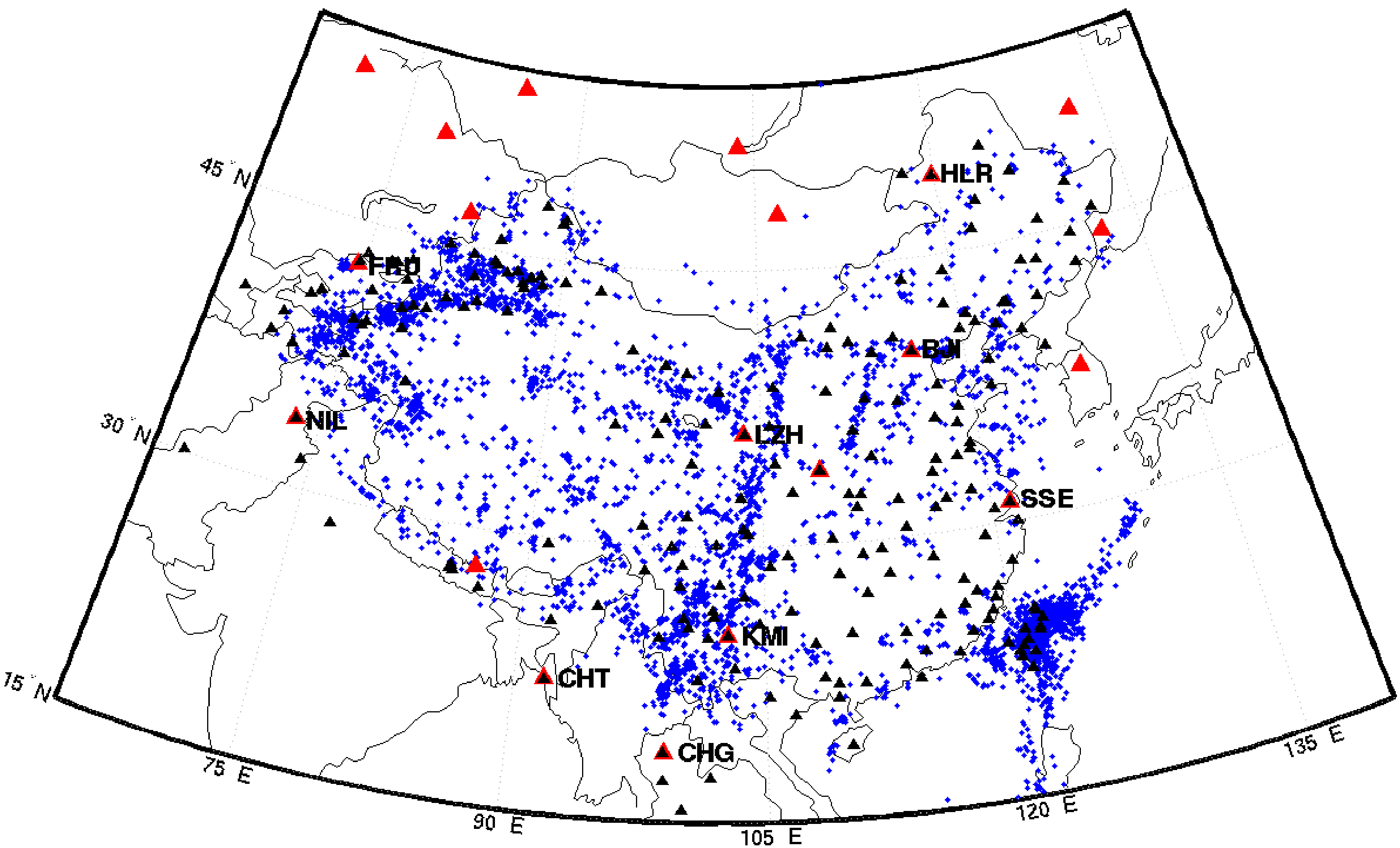
- median mislocation error reduced from 12.2 km to 2.7 km,
- error ellipse areas reduced by 20% or more for 97% of events,
- median error ellipse reduced from 1,596 to 196 km^2, while achieving 100% coverage.



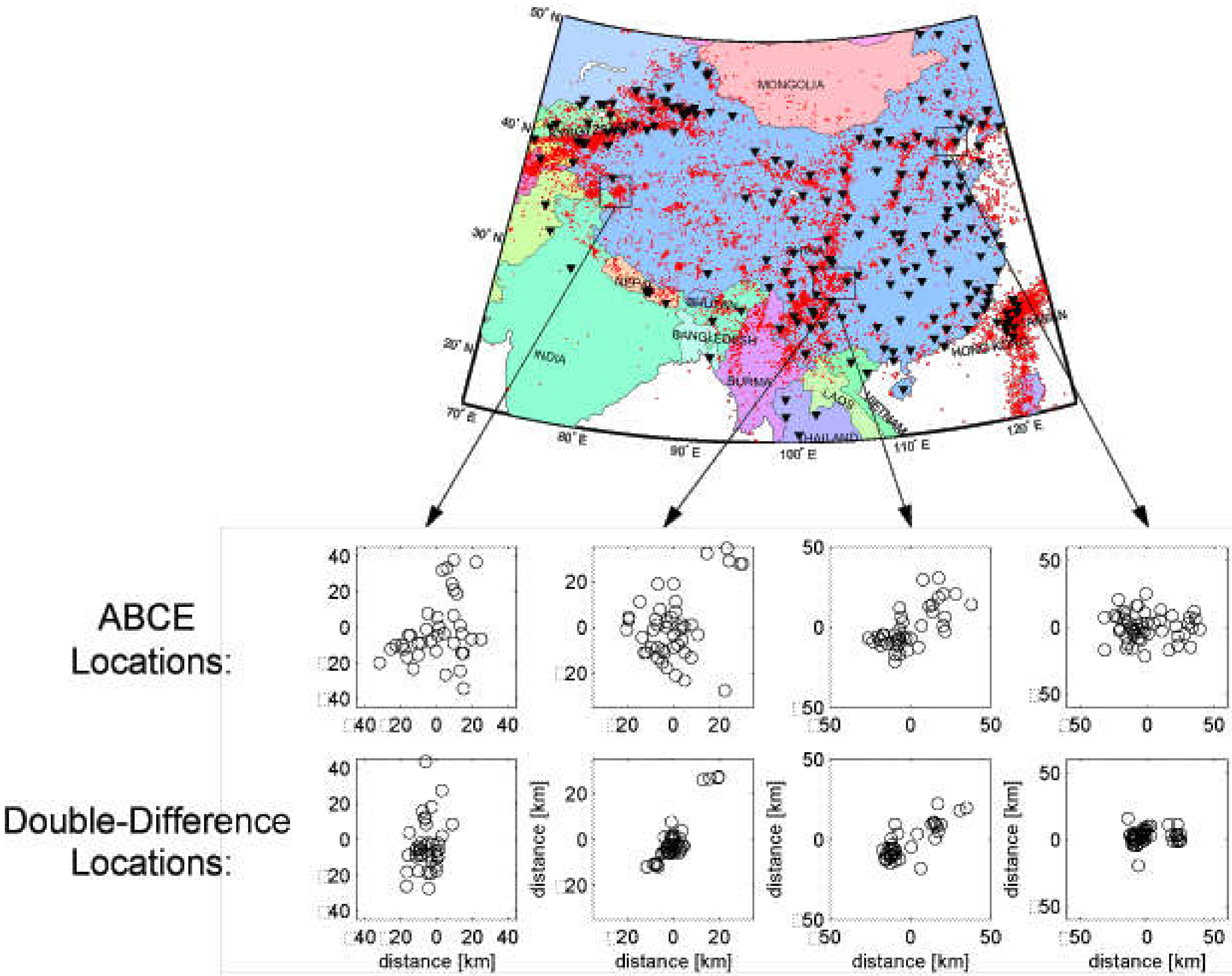
174 GT explosions (stars) and the recording seismographic stations (triangles) used for validation tests. Good news, bad news: dense regions, blank regions (but, with earthquakes)



downloaded March 30, 2000, from http://gt.csdi.ac.cn/w7/veq7095.gif

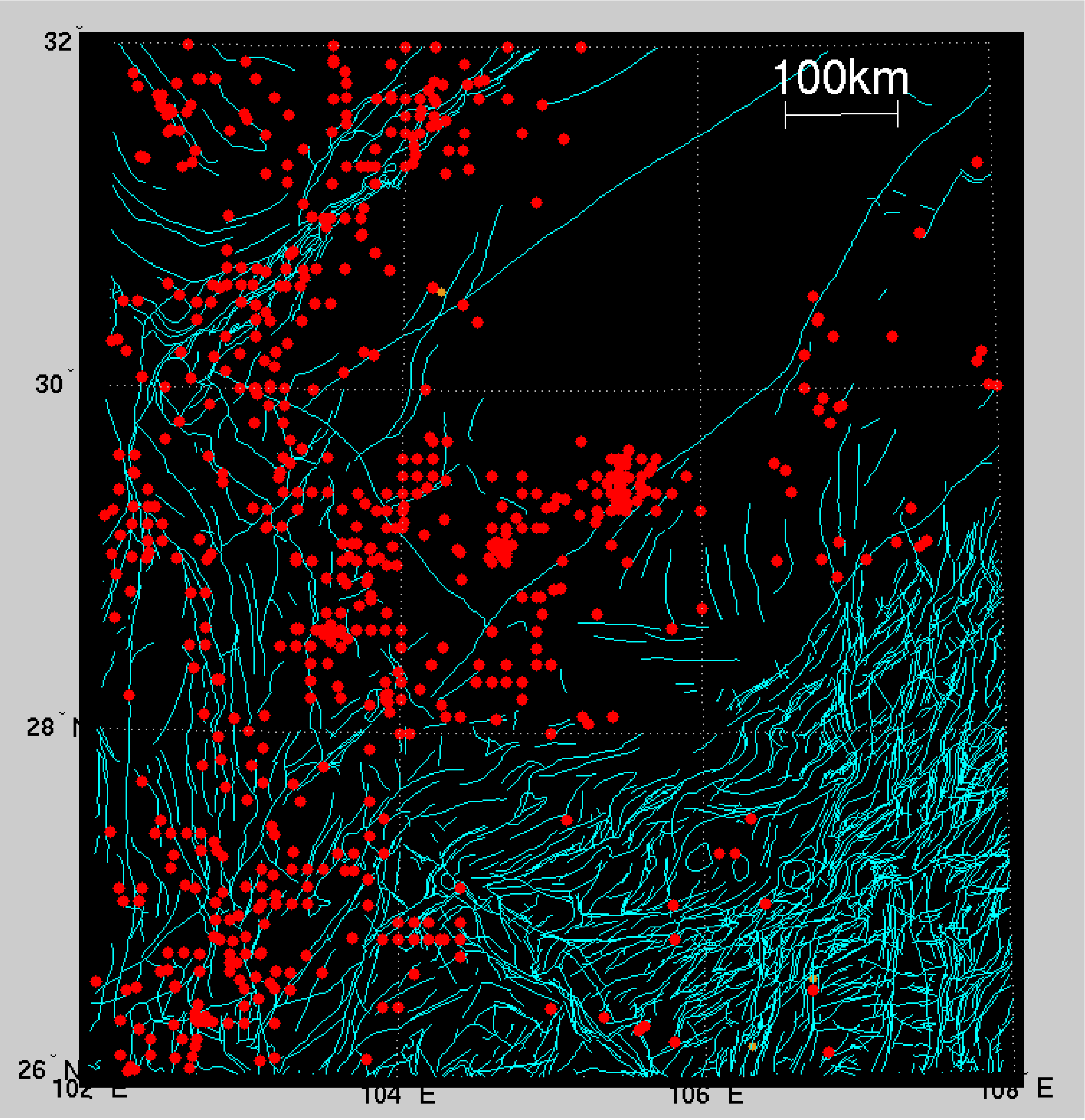

45 N
30 N
15 N
75 E
90 E
105 E
120 E
135 E
HLR
FRU
BJI
NIL
LZH
SSE
KMI
CHT
CHG

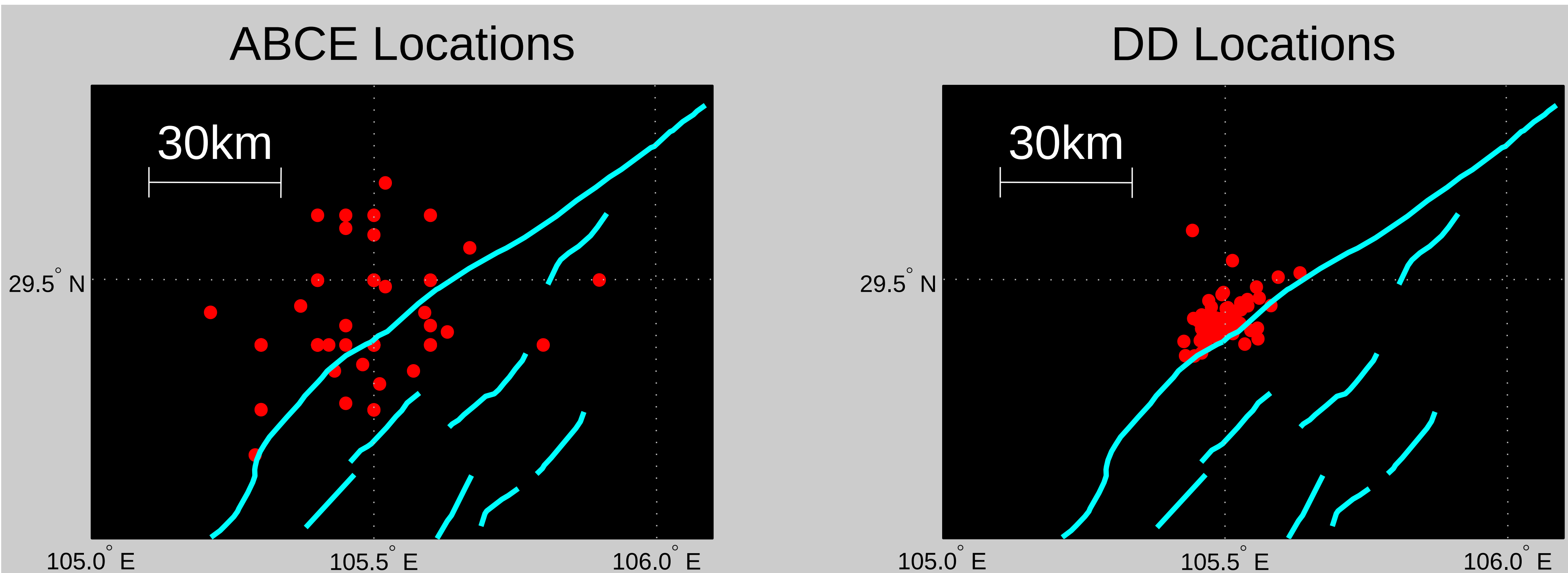
Relocation of Chinese Earthquakes

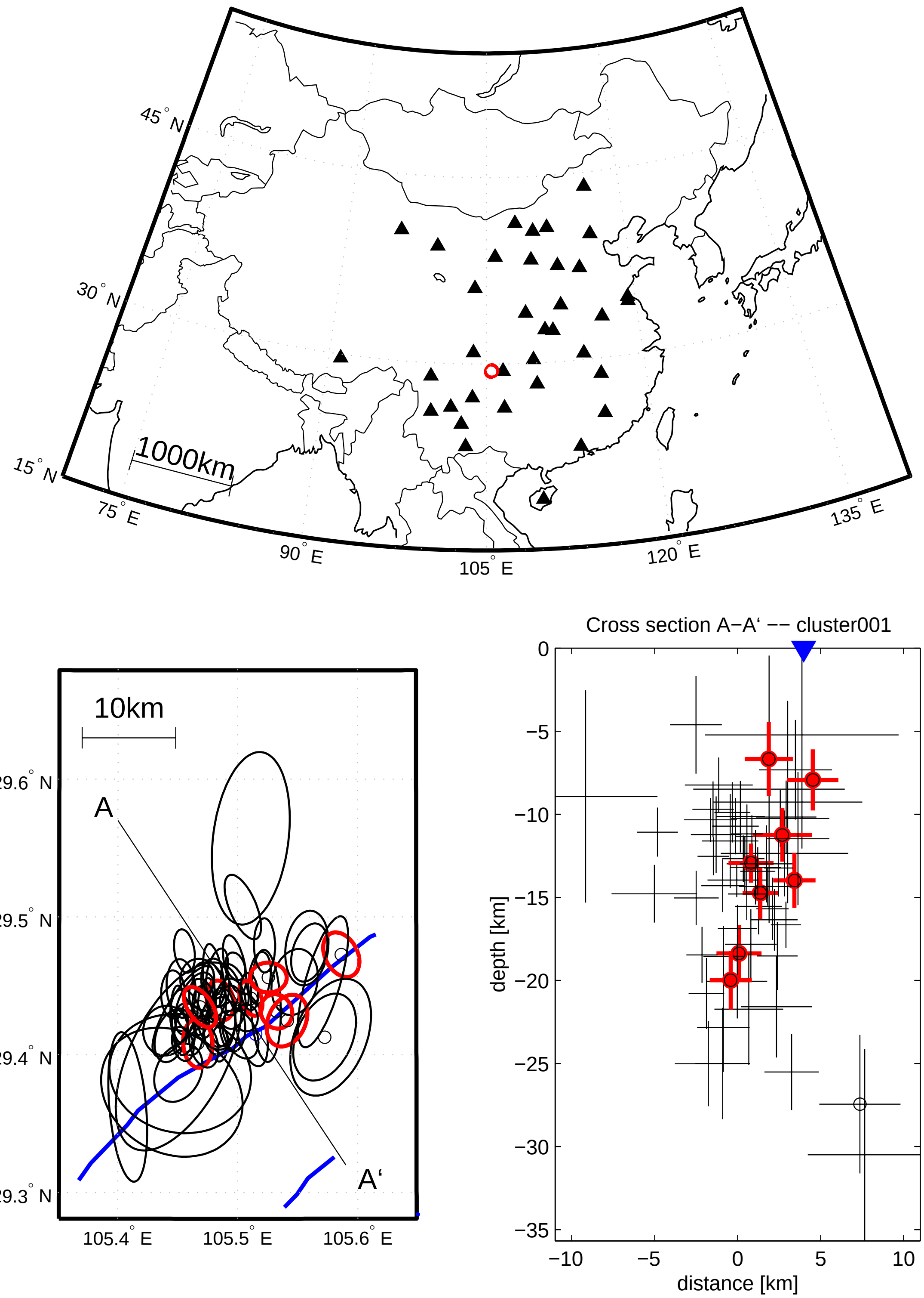


Digital Fault Map

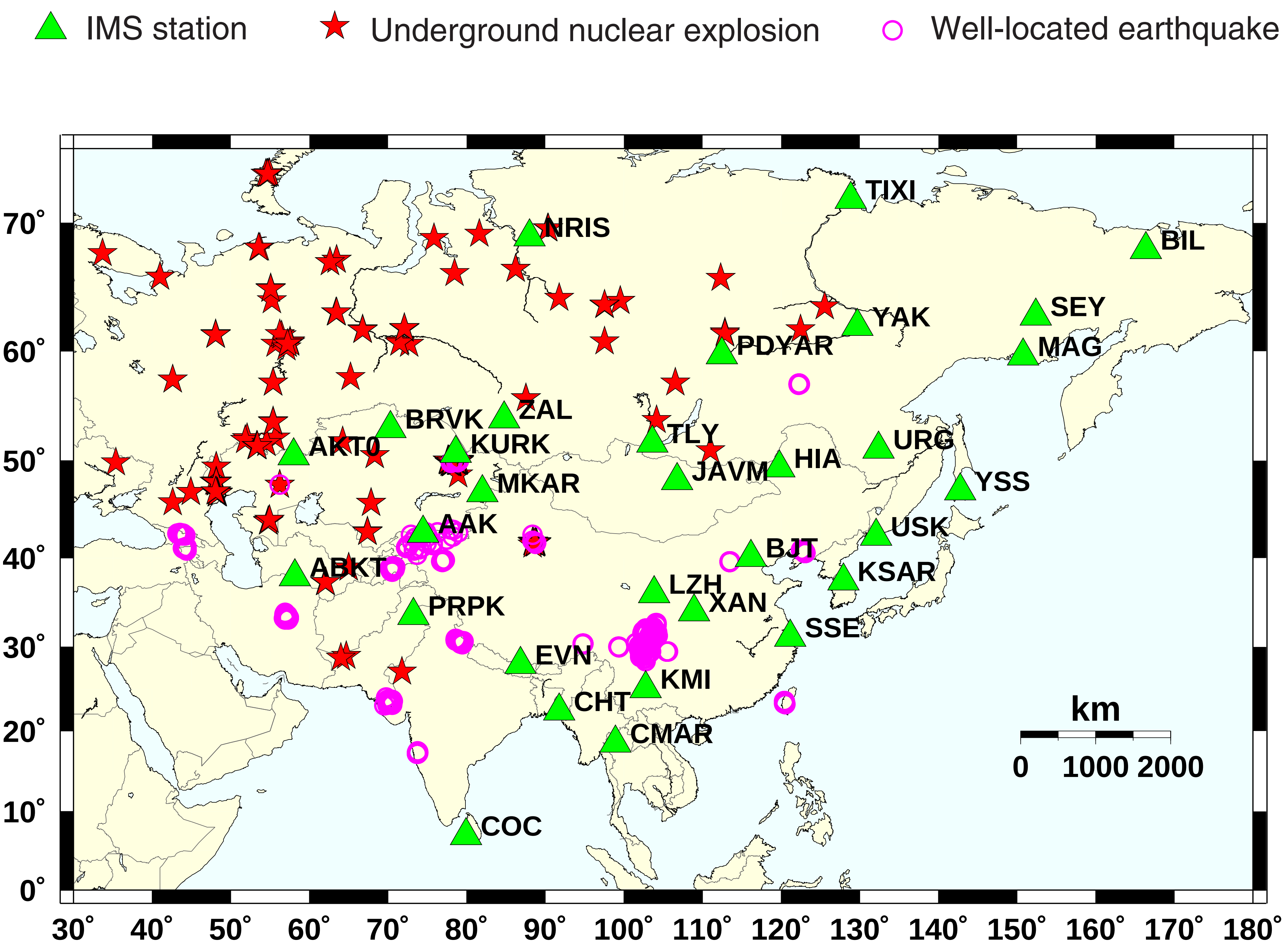
(from USGS, based on Chinese Publ. on regional geology, GPH, Bejing 1984-1993)




ABCE Locations
30km
29.5° N
105.0° E
105.5° E
106.0° E
DD Locations
30km
29.5° N
105.0° E
105.5° E
106.0° E



Double-difference locations for events in cluster 001 near Neijiang.


IMS station
Underground nuclear explosion
Well-located earthquake
TIXI
NRIS
BIL
SEY
YAK
MAG
PDYAR
ZAL
BRVK
TLY
URG
AKT0
KURK
HIA
JAVM
YSS
MKAR
AAK
USK
BJT
ABKT
KSAR
LZH
XAN
PRPK
SSE
EVN
KMI
CHT
CMAR
COC
km
0
1000
2000
70°
60°
50°
40°
30°
20°
10°
0°
30°
40°
50°
60°
70°
80°
90°
100°
110°
120°
130°
140°
150°
160°
170°
180°

Three problems, two fixed:

the waves spread in 3D not 2D √

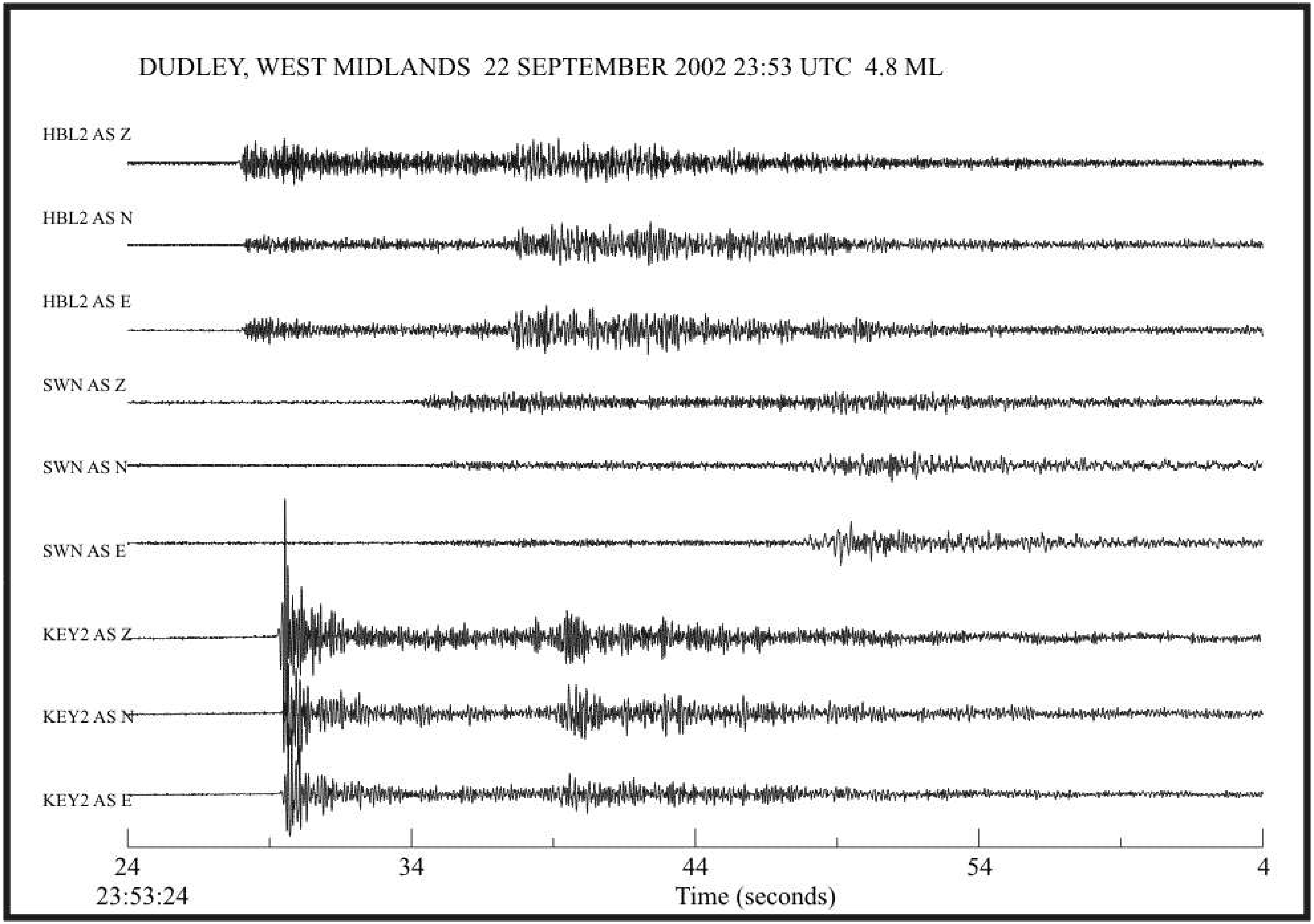
(easy to fix – with a standard Earth model)

we don’t know the exact model √

(“model error” — use SSSCs, use DD)

we can’t pick the arriving signals accurately

(“pick error”)


DUDLEY, WEST MIDLANDS 22 SEPTEMBER 2002 23:53 UTC 4.8 ML
HBL2 AS Z
HBL2 AS N
HBL2 AS E
SWN AS Z
SWN AS N
SWN AS E
KEY2 AS Z
KEY2 AS N
KEY2 AS E
24
34
44
54
4
23:53:24
Time (seconds)

Waveform cross-correlation of two signals $s_1(t)$ and $s_2(t)$

$$= WCC(t)$$

$$= \int_{-\infty}^{\infty} s_1(\tau)\, s_2(t+\tau)\, d\tau \qquad \text{for continuous signals}$$

$$= \Delta\tau \sum_{i=\infty}^{\infty} s_1(\tau_i)\, s_2(\tau_i + t) \qquad \text{for digital signals (with discrete time steps, } \Delta\tau\text{).}$$

$$(\tau_{i+1} = \tau_i + \Delta\tau)$$

In practice, this means:
"shift one signal with respect to the other, by an amount *t*,
then multiply all the points together (many of them have zero value if the shift is big),
then add up all the products.
You have to do all this arithmetic for every different value of *t*."

Such work is what computers are for:
~10,000 to 100,000 multiplications and additions for each cross-correlation.

We can consider two extreme examples:

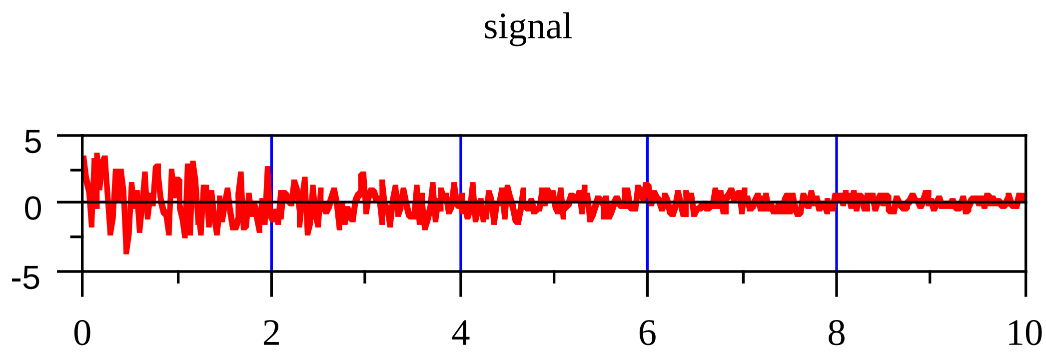
(1) If $s_1(t)$ is random noise, $s_1(t) = n(t)$, and $s_2(t)$ is a signal of interest (with frequency content different from noise), then

$$WCC(t) = \int n(\tau)\, s(t+\tau)\, d\tau = 0.$$

(2) If $s_1(t)$ is a broadband signal $s(t)$, and $s_2(t)$ is the same signal but delayed by a time T, then $s_2(t) = s_1(t - T)$ and

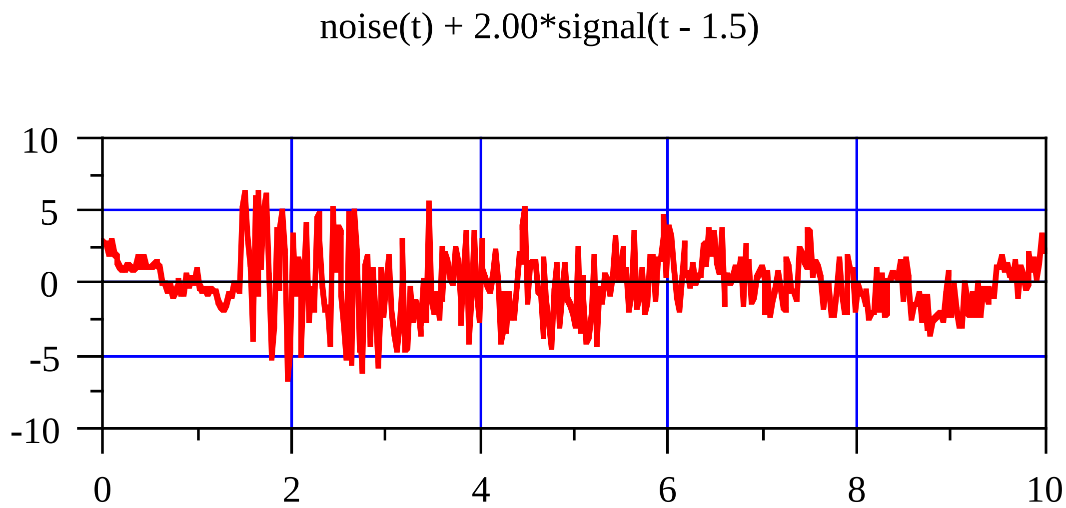
$$WCC(t) = 0 \qquad \text{if} \quad t \neq T; \qquad \text{and}$$

$$WCC(t) = 1 \qquad \text{if} \quad t = T.$$



This shows a digital signal, lasting 10 seconds. The horizontal scale is time, and the vertical scale gives the amplitude. The signal is zero before $t = 0$.

Suppose we have a recording of this same signal, with a different amplitude, superimposed on noise, and shifted in time:

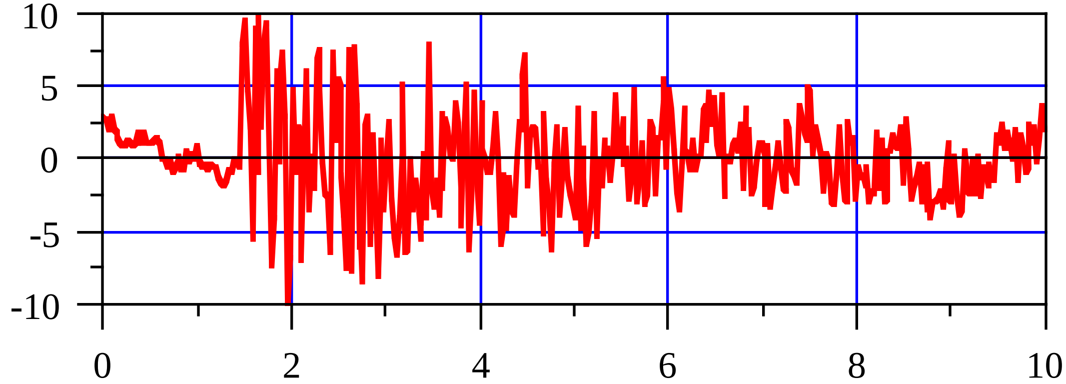


Here, the signal shown previously is doubled in amplitude, delayed 1.5 seconds, and added to noise. (Noise and signal have the same RMS amplitude, in these examples.)

How can we tell when the signal begins? And how is our detection ability influenced by changes in the relative amplitude of the signal and noise?

If the signal is strong enough, we can easily pick the arrival of the impulsive onset — above, or in the next example:

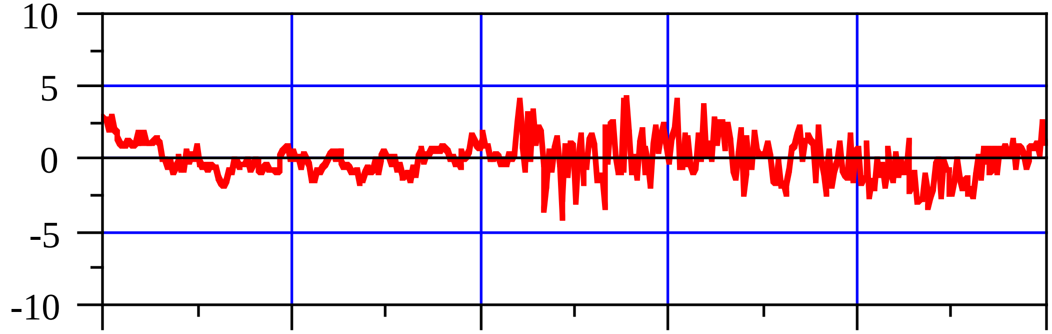
noise(t) + 3.00*signal(t - 1.5)



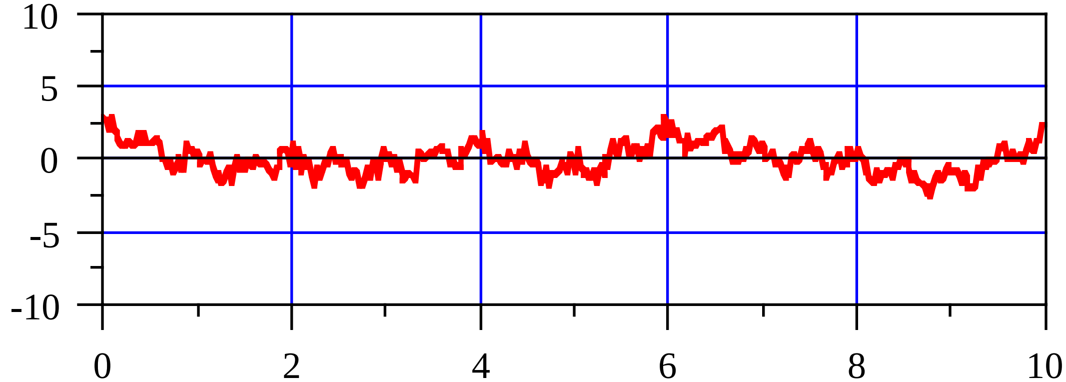
Next, let's look at a couple of examples of signal added to noise where the signal amplitude is made smaller and smaller compared to the noise levels, and the signal is shifted to different times.

In these next cases, the correlation method is the way to go.

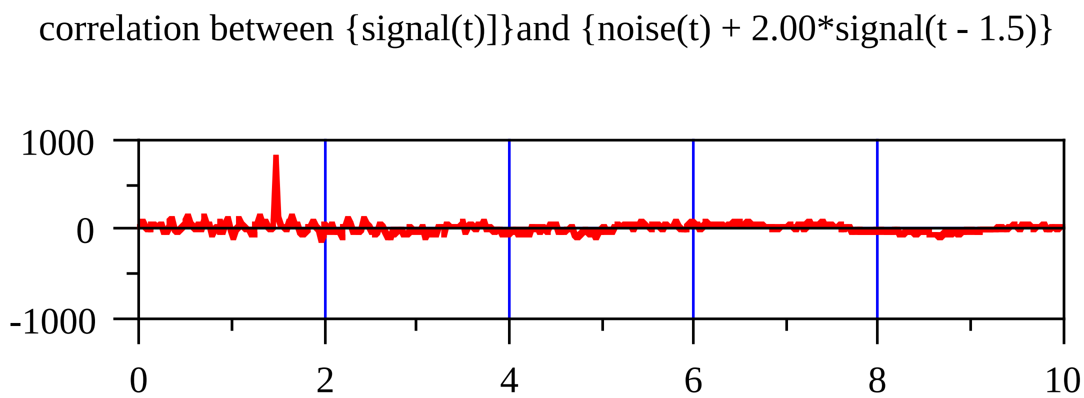
noise(t) + 1.00*signal(t - 4.4)



noise(t) + 0.20*signal(t - 0.9)



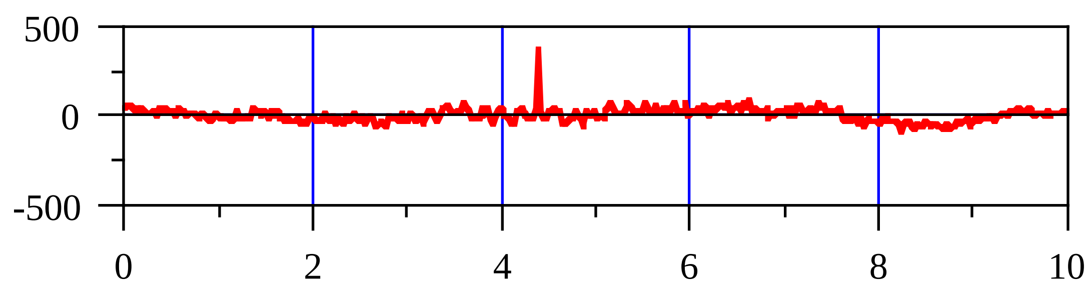
When the correlation method is applied to one of these examples of noise and signal where the signal is strong, the result is



[In the ideal situation, the correlation between the signal and the noise is zero, and the correlation of the signal with itself is just a single spike. This computation with 40 points per second and 10 seconds of data needed 160,000 multiplications and 160,000 additions on my Mac.]

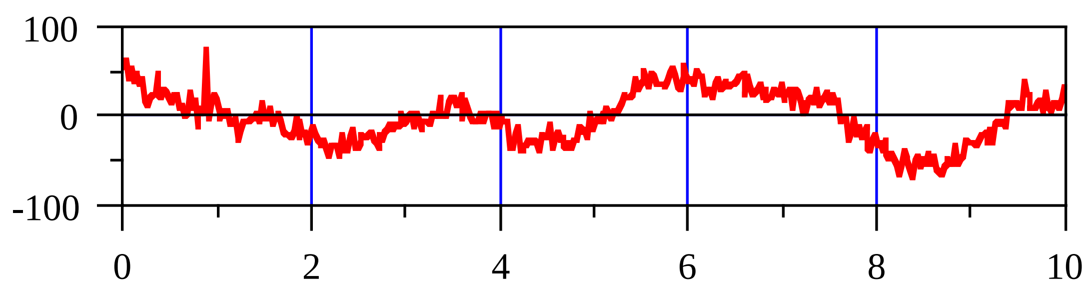
The correlation method successfully indicates the arrival times of signals much smaller than the noise, as shown below. The timing of the correlation spikes, shown in these two cases, indicates the times when signals arrive (at time 4.4 with signal-to-noise ratio of 1 in example A; and at time 0.9 with SNR as small as 0.2 in example B).

correlation between {signal(t)}and {noise(t) + 1.00*signal(t - 4.4)}



A

correlation between {signal(t)}and {noise(t) + 0.20*signal(t - 0.9)}



B

Three problems, all three fixed:

the waves spread in 3D not 2D √

(easy to fix – with a standard Earth model)

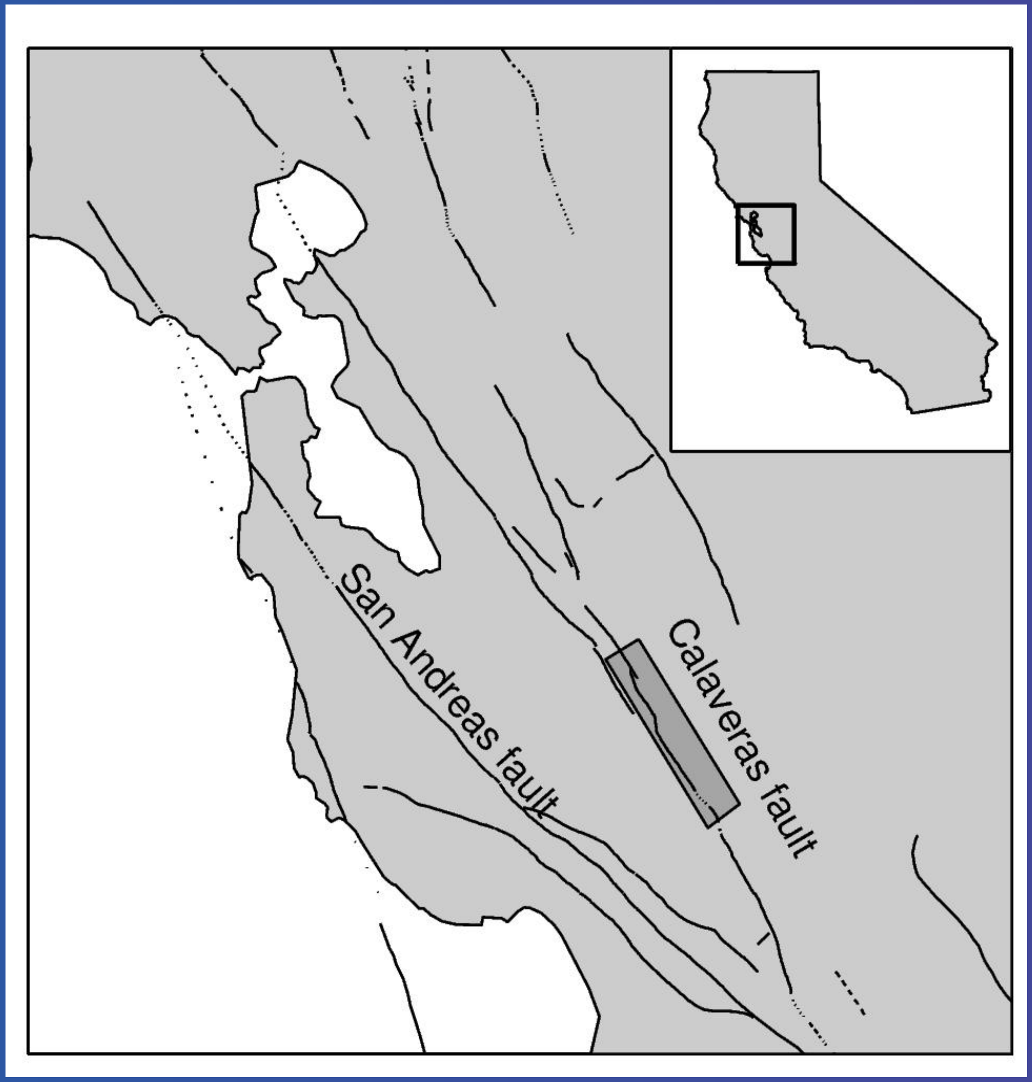
we don't know the exact model √

("model error")

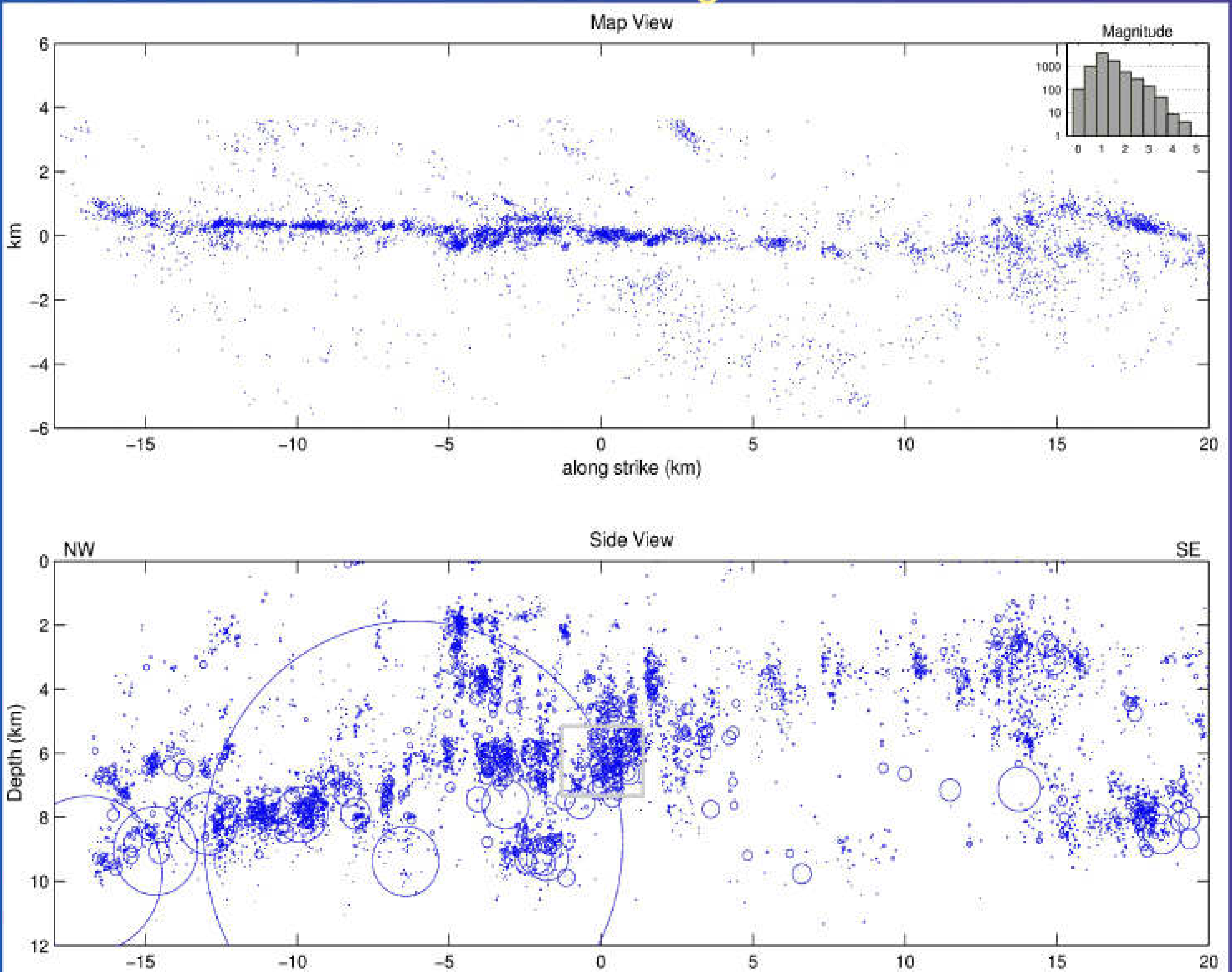
we can't pick the arriving signals accurately

("pick error") √

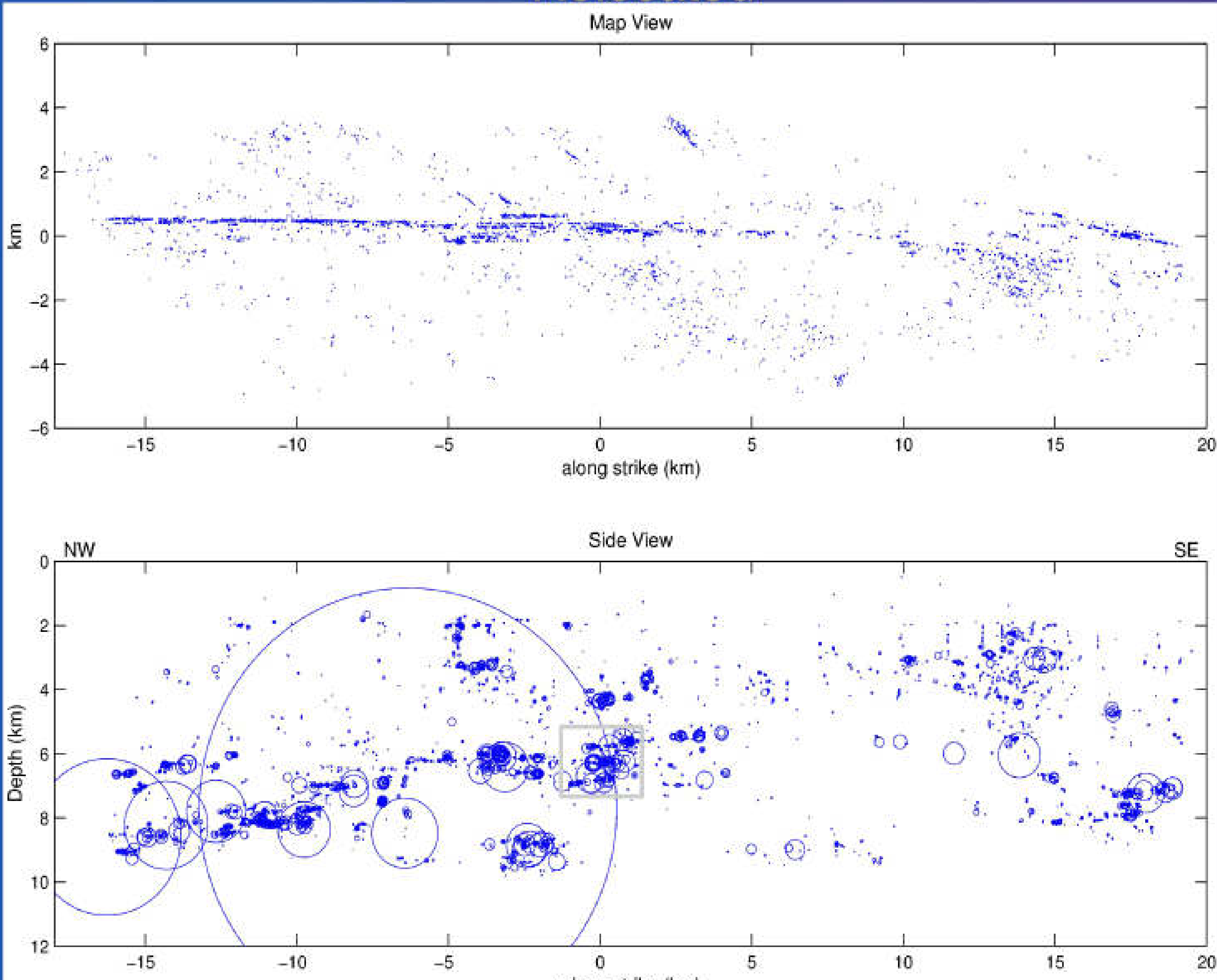
Study Area for Relocation



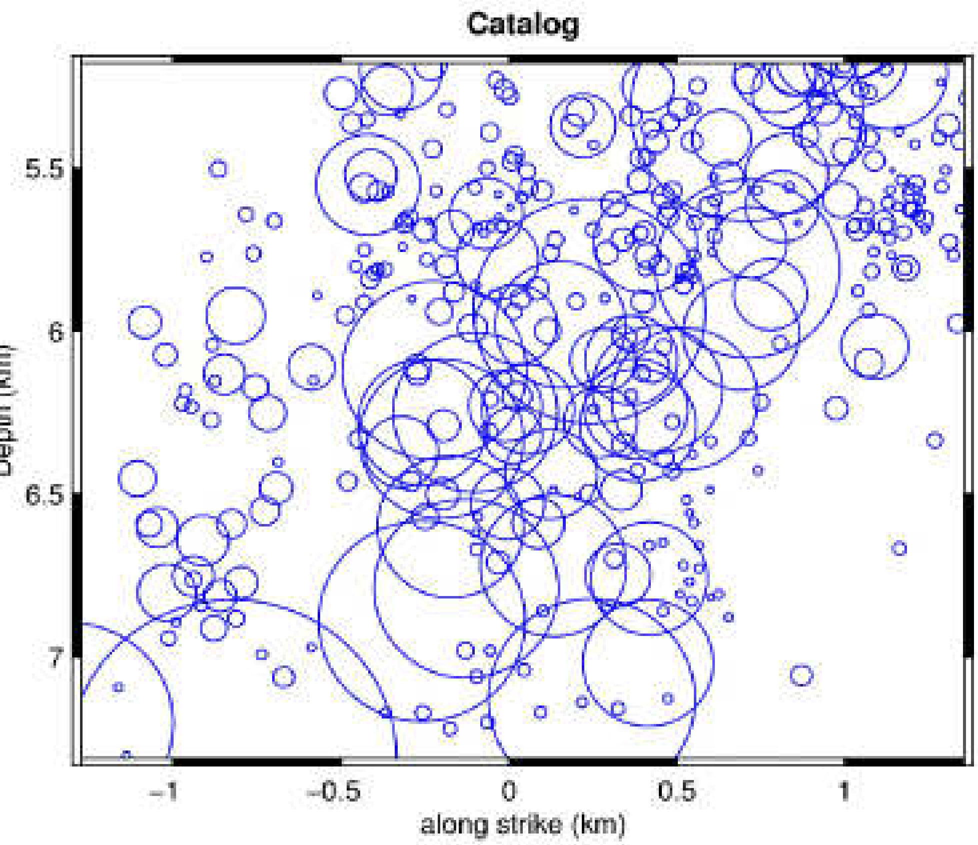
Catalog

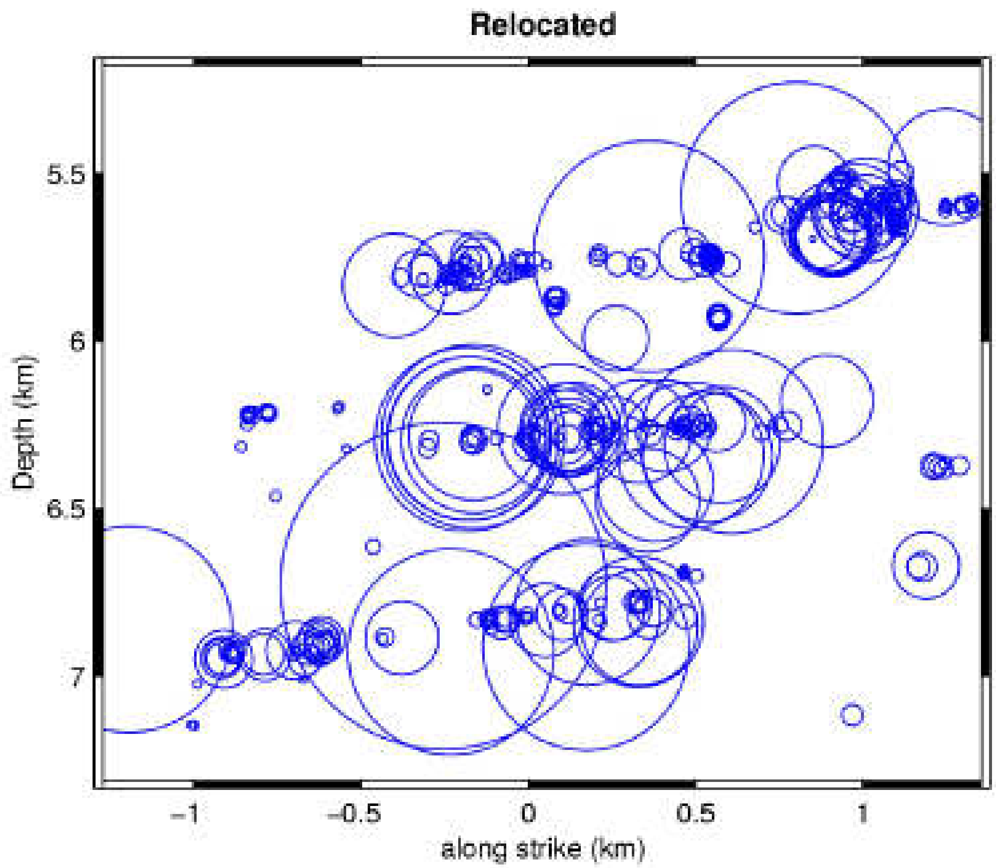

Map View
Magnitude
1000
100
10
1
0
1
2
3
4
5
6
4
2
0
−2
−4
−6
km
−15
−10
−5
0
5
10
15
20
along strike (km)
Side View
NW
SE
0
2
4
6
8
10
12
Depth (km)
−15
−10
−5
0
5
10
15
20

Relocated

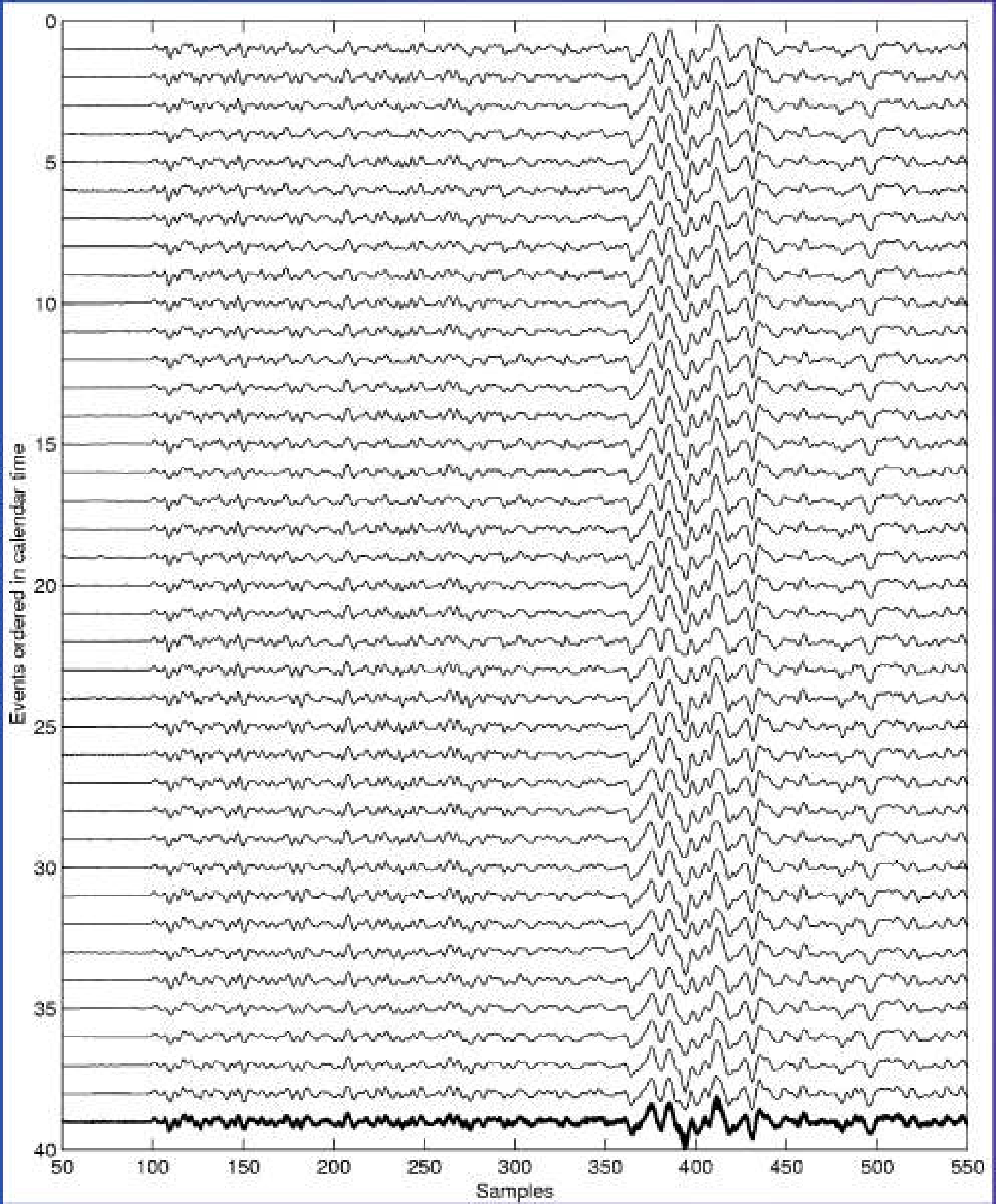


Fine-scale structure





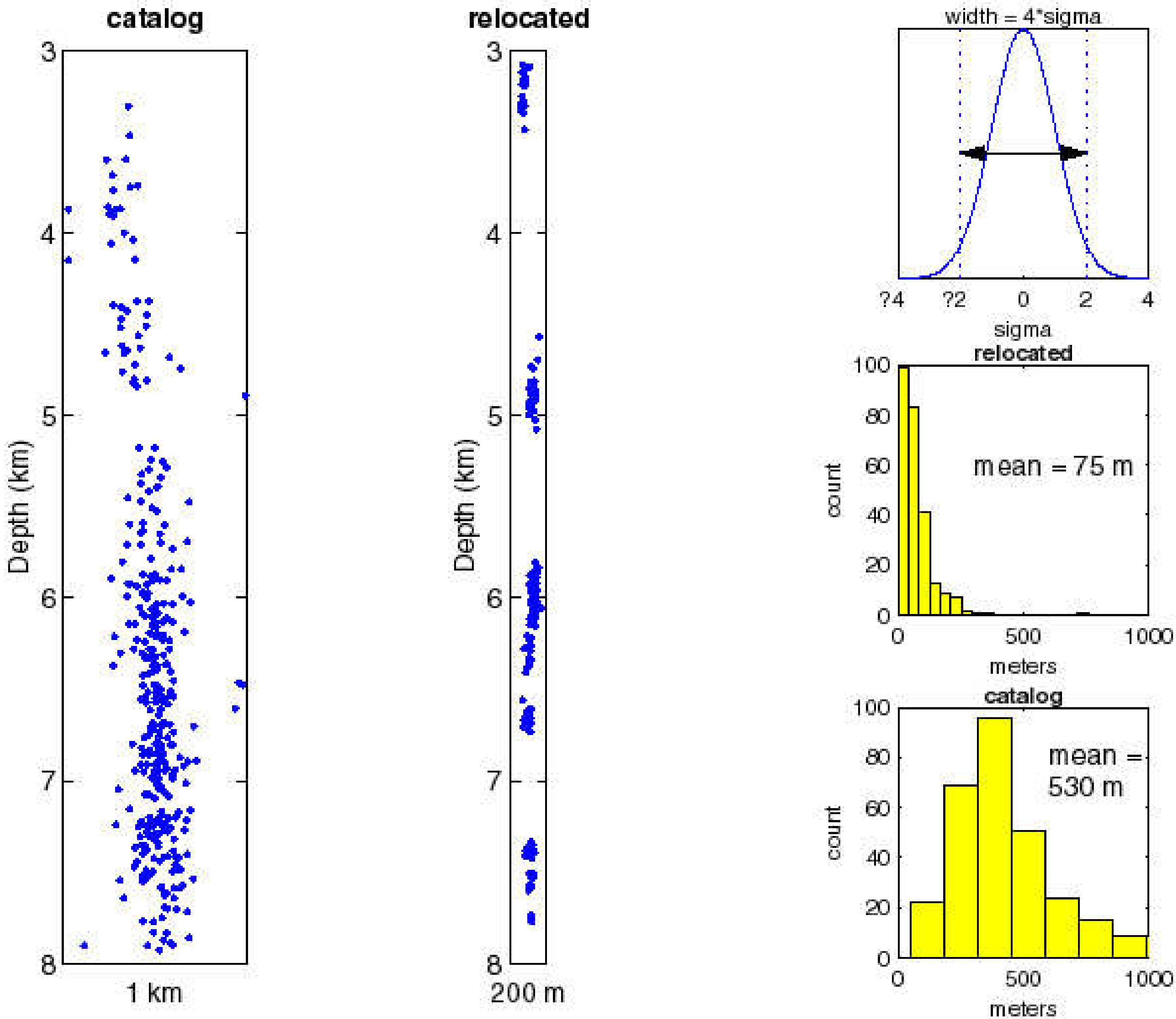
Super multiplet (Calaveras)



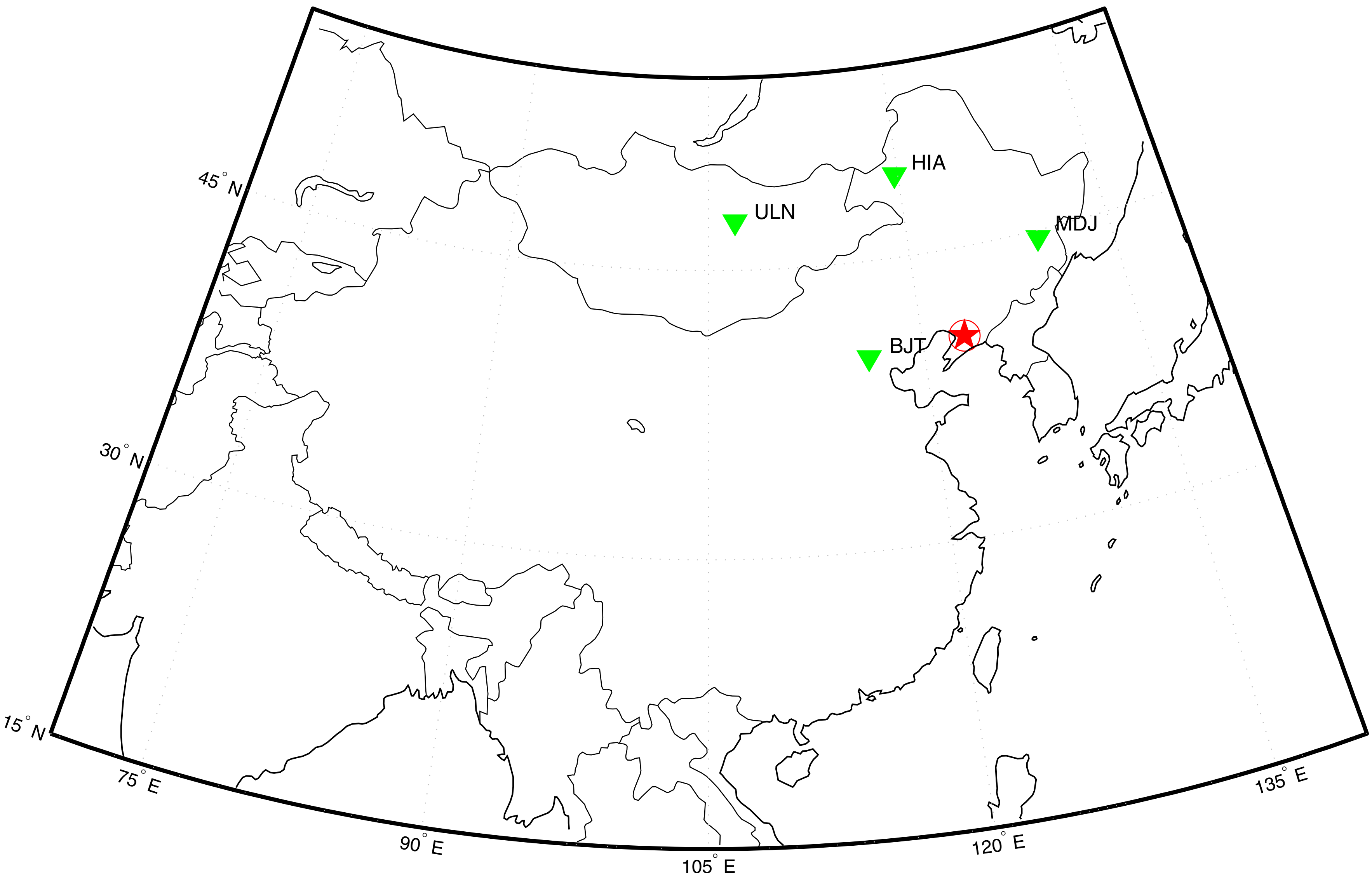
38 different events

events superposed

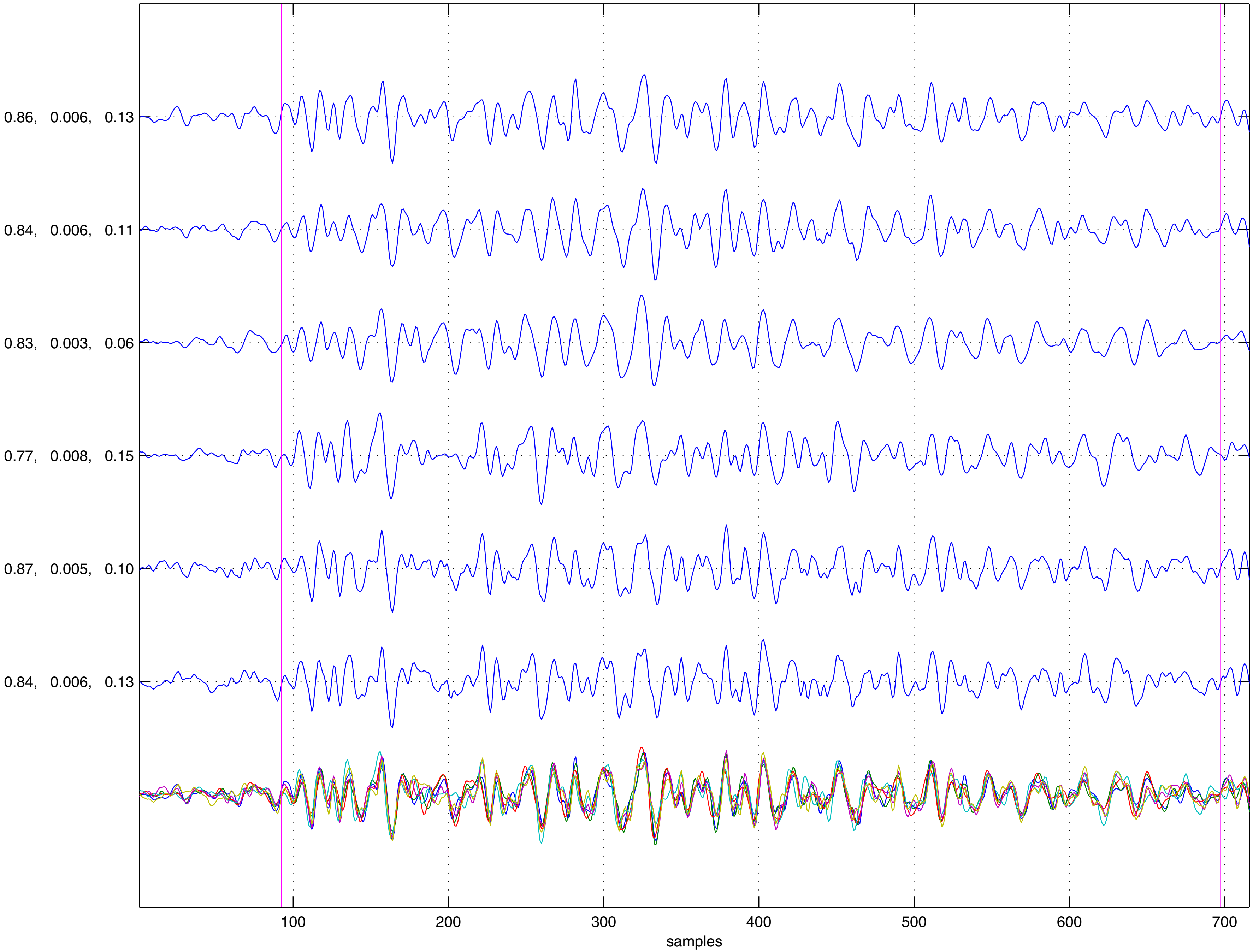
Fault Zone Width



Xiuyan cluster and stations with Lg correlations

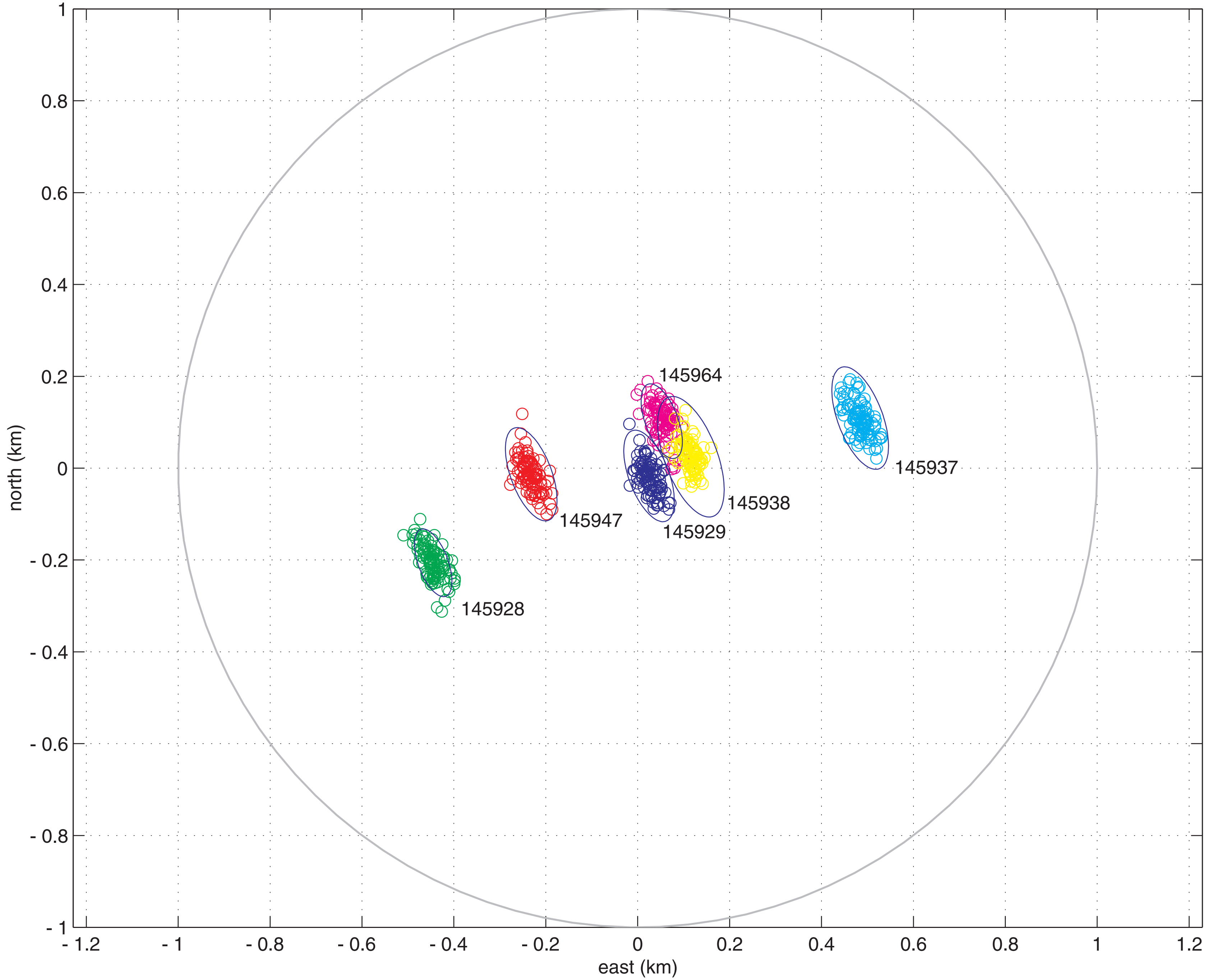


Clust2, IC.MDJ



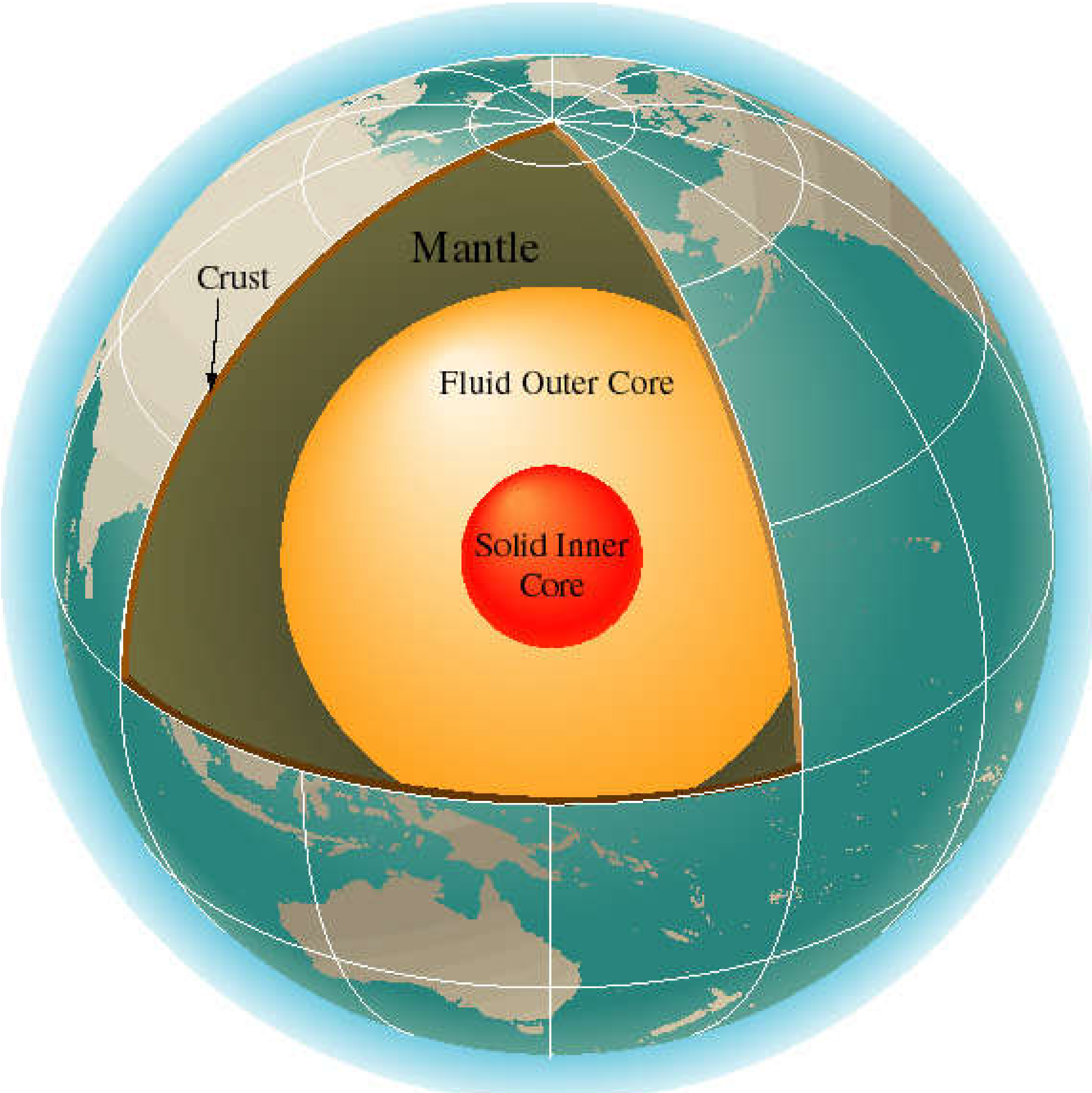
bpfilt .5 to 5 Hz, delta = 0.05 sec, stadist = 750 km, 145929 ... 145938.

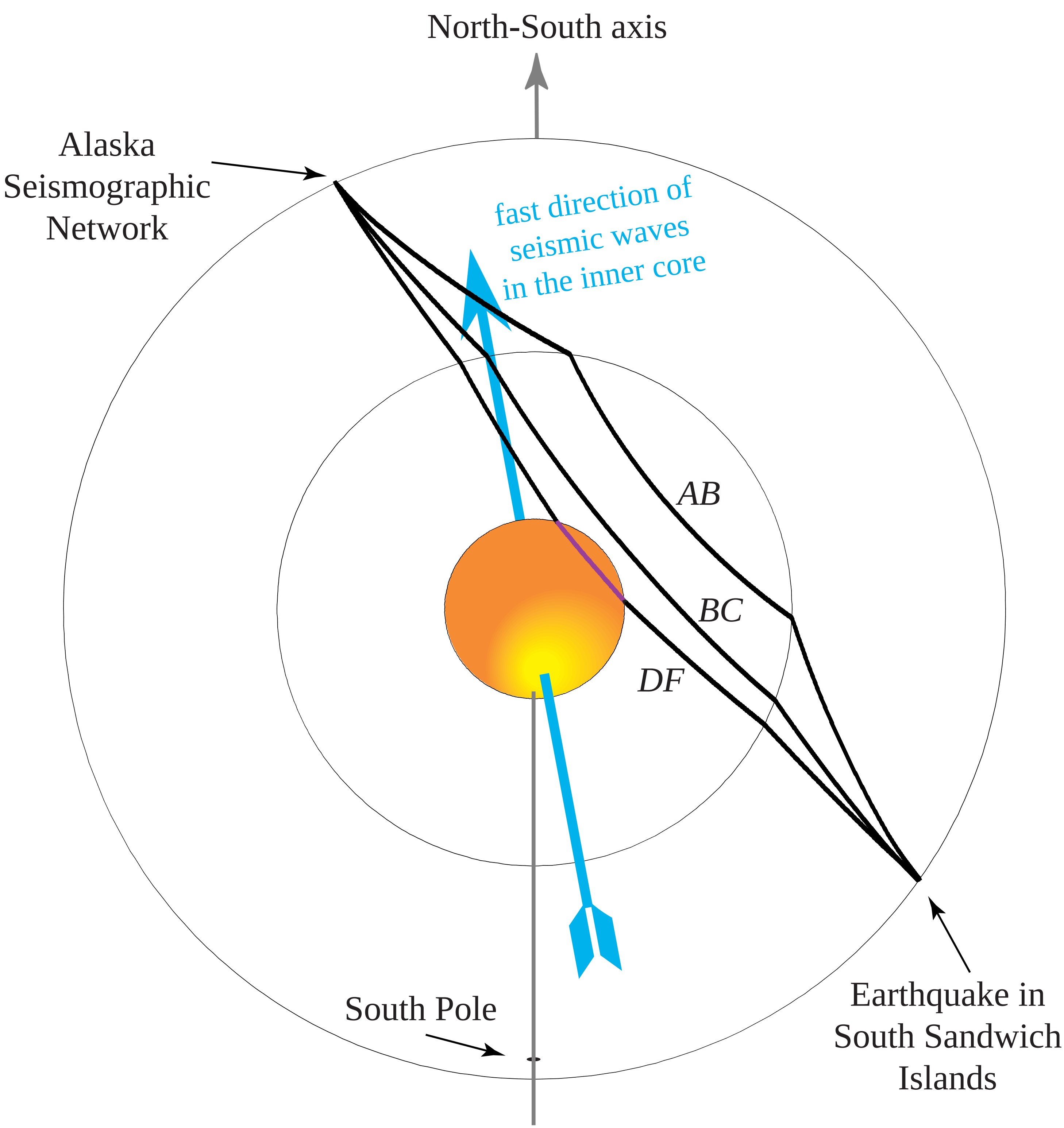
Lg correlations, Xiuyan, China (clust2)

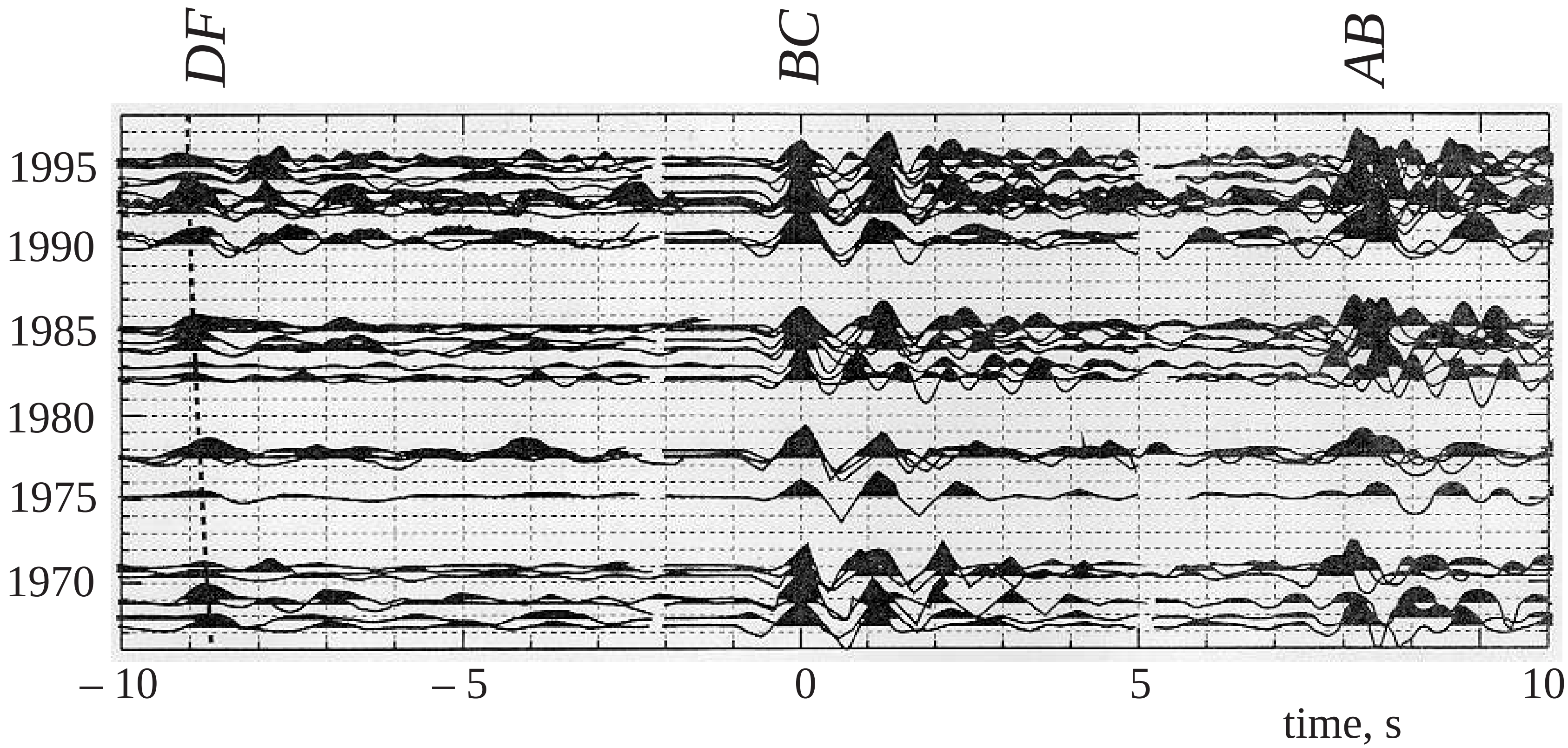


Bootstrap errors and 95% confidence ellipses from formal errors shown. Reference circle in gray has radius of 1 km.

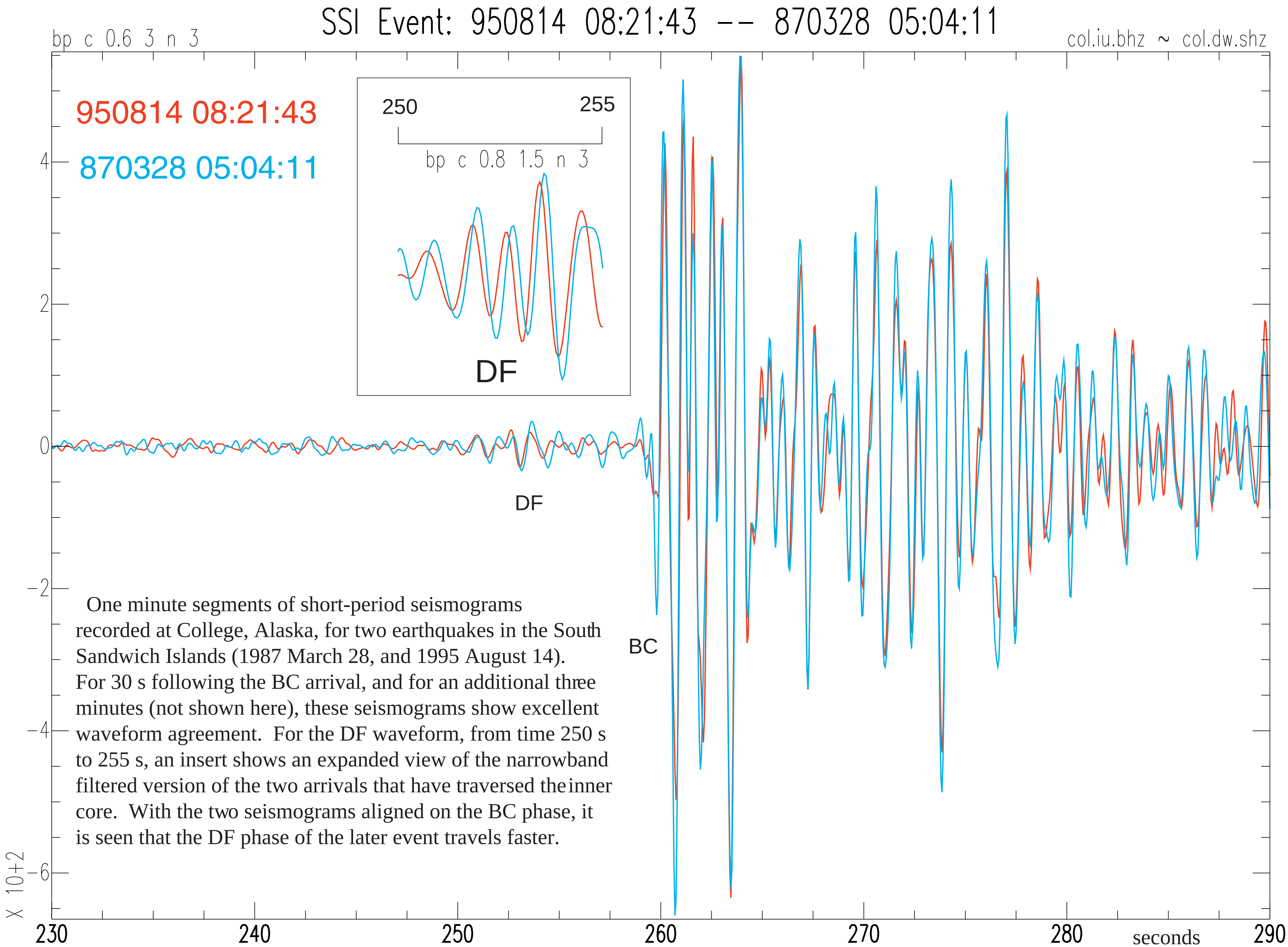
13 Aug 2002 /turf/fdny/dschaff/china/clust2/corr1 reloc1.m, lg1.ps


Mantle
Crust
Fluid Outer Core
Solid Inner Core


North-South axis
Alaska Seismographic Network
fast direction of seismic waves in the inner core
AB
BC
DF
South Pole
Earthquake in South Sandwich Islands



DF
BC
AB
1995
1990
1985
1980
1975
1970
– 10
– 5
0
5
10
time, s



One minute segments of short-period seismograms recorded at College, Alaska, for two earthquakes in the South Sandwich Islands (1987 March 28, and 1995 August 14). For 30 s following the BC arrival, and for an additional three minutes (not shown here), these seismograms show excellent waveform agreement. For the DF waveform, from time 250 s to 255 s, an insert shows an expanded view of the narrowband filtered version of the two arrivals that have traversed the inner core. With the two seismograms aligned on the BC phase, it is seen that the DF phase of the later event travels faster.

What are the issues for the future
(in seismic location capability)**?**

Note that achievement of more accurate location (if not detection) is of broad interest in scientific studies of the Earth and of earthquake physics, and in mitigation of earthquake hazard.

1. Emphasize superGT (preferably **without** resumption of nuclear testing). Use

$S - P$ of a few tenths of a second.
Local network operations in a well-studied region.
Mapped surface faulting.
Synthetic Aperture Radar
……

2. Develop/take opportunities for international cooperation with the two most populous countries in the world — in the context of earthquake hazard mitigation, and scientific studies (if not for explosion monitoring). For example, we need to establish an effort to document (certify?) the quality of station locations.

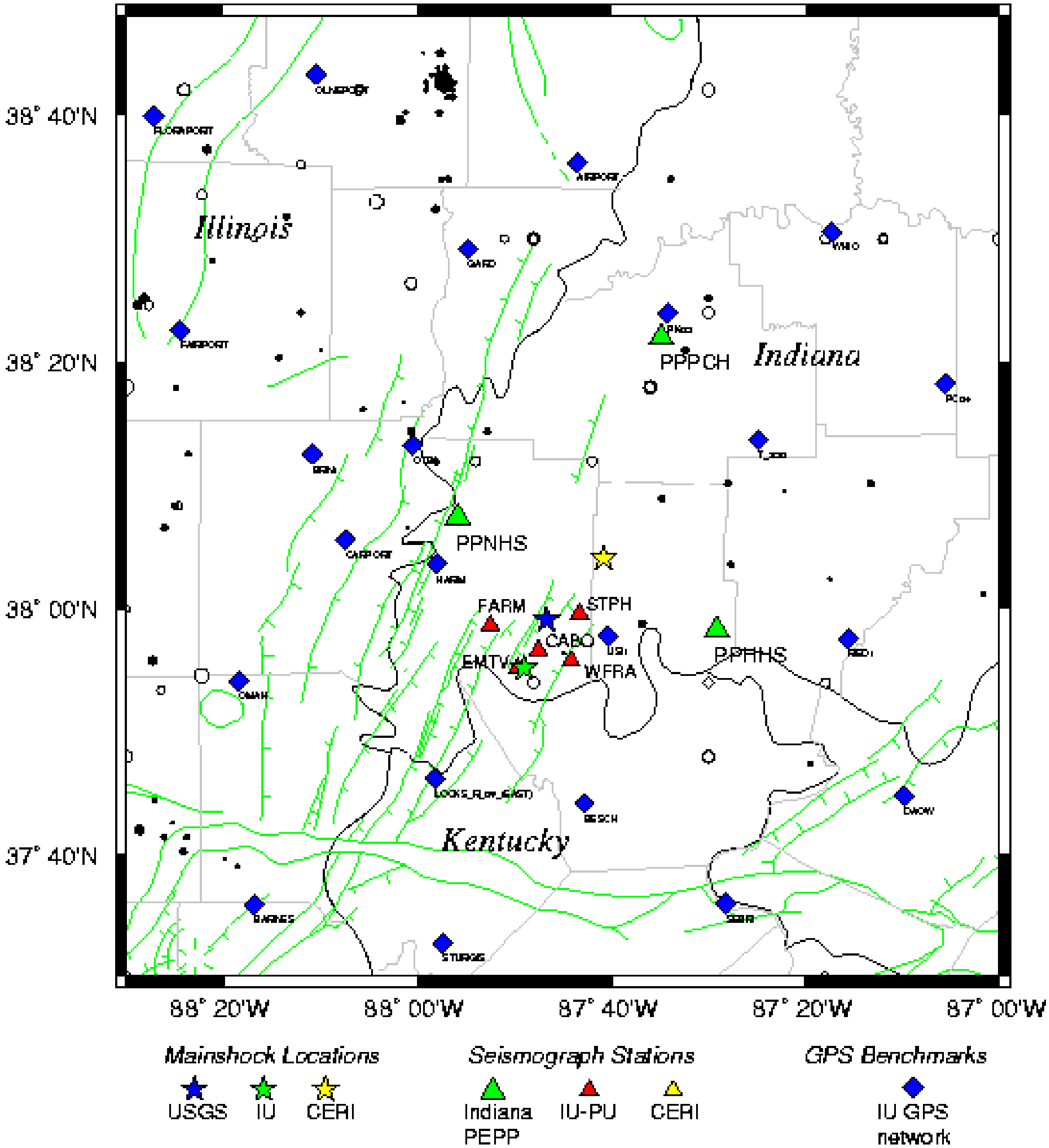
(Check station coordinates with GPS receivers.)

3. **To remove pick error, we must make conventional phase picks irrelevant.**

Instead, go with massive waveform databases, and waveform cross-correlation or some type of envelope matching/stretching. The key resource will be long-running stations with archived waveforms that are high-quality/easily accessed .

Location estimates for the Evansville, Indiana, earthquake of 2002 June 18

Figure downloaded 2002 June 28 from http://www.indiana.edu/~pepp/eqs/darmstadt_seis_map.gif



"Earthquake
location,
location,
location"

— we know what to do,
and we must do better