APPLICATION OF AN IMPROVED ALGORITHM TO HIGH-PRECISION TELESEISMIC RELOCATION OF THE ISC TEST EVENTS

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The Problem

The main problem is the varying level of mislocation, particularly focal depth, introduced largely by errors in the reference Earth model, unaccounted for effects of lateral heterogeneity, and phase misidentification. The result is a loss of structural signal in the residuals.

The Solution

The bias in hypocenter determination can be significantly reduced and at least part of the lost structural signal recovered by

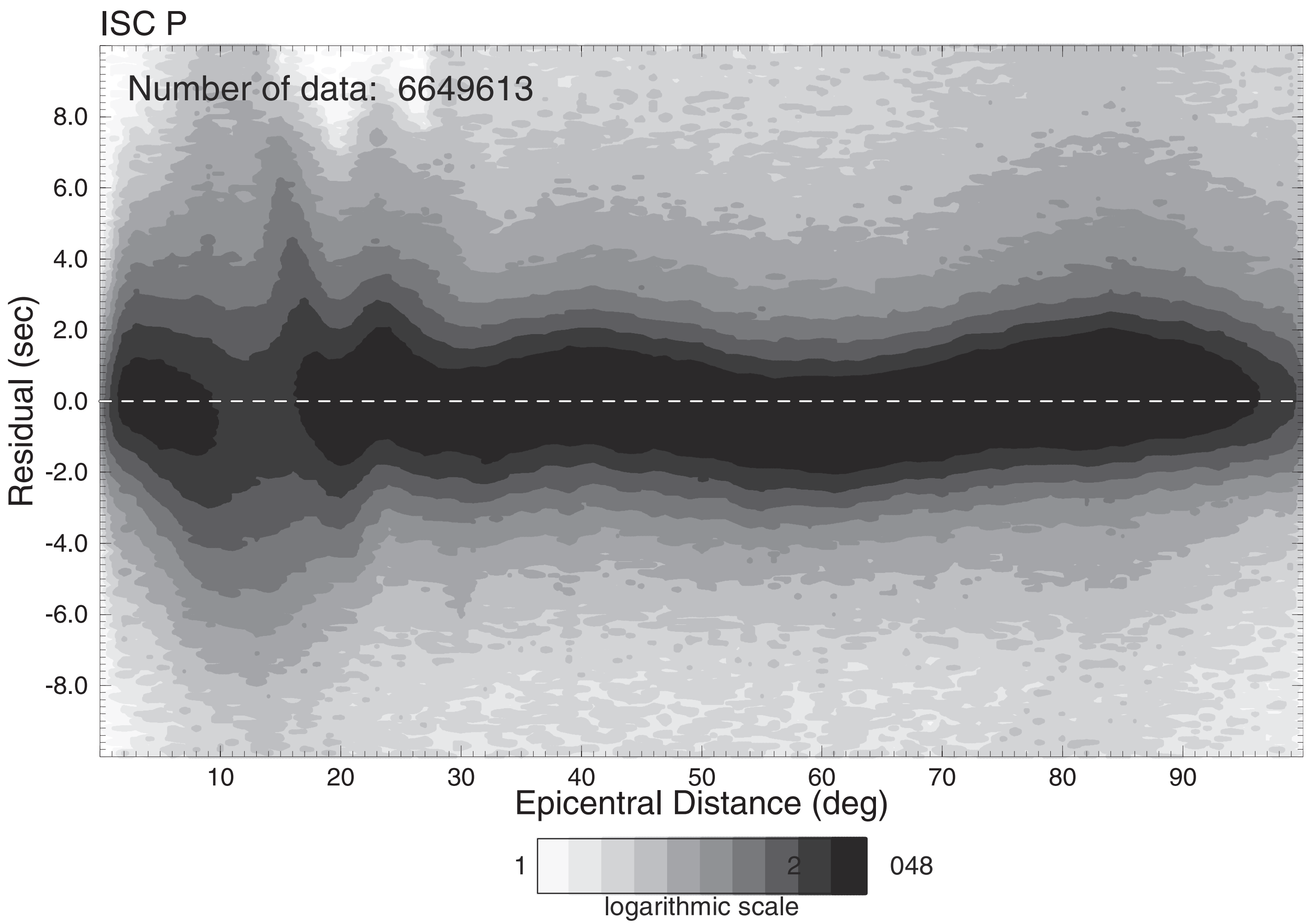
- Using an improved reference Earth model
- Using later arriving phases in the relocation procedure.
- Limiting the events of interest only to those that are well-constrained teleseismically

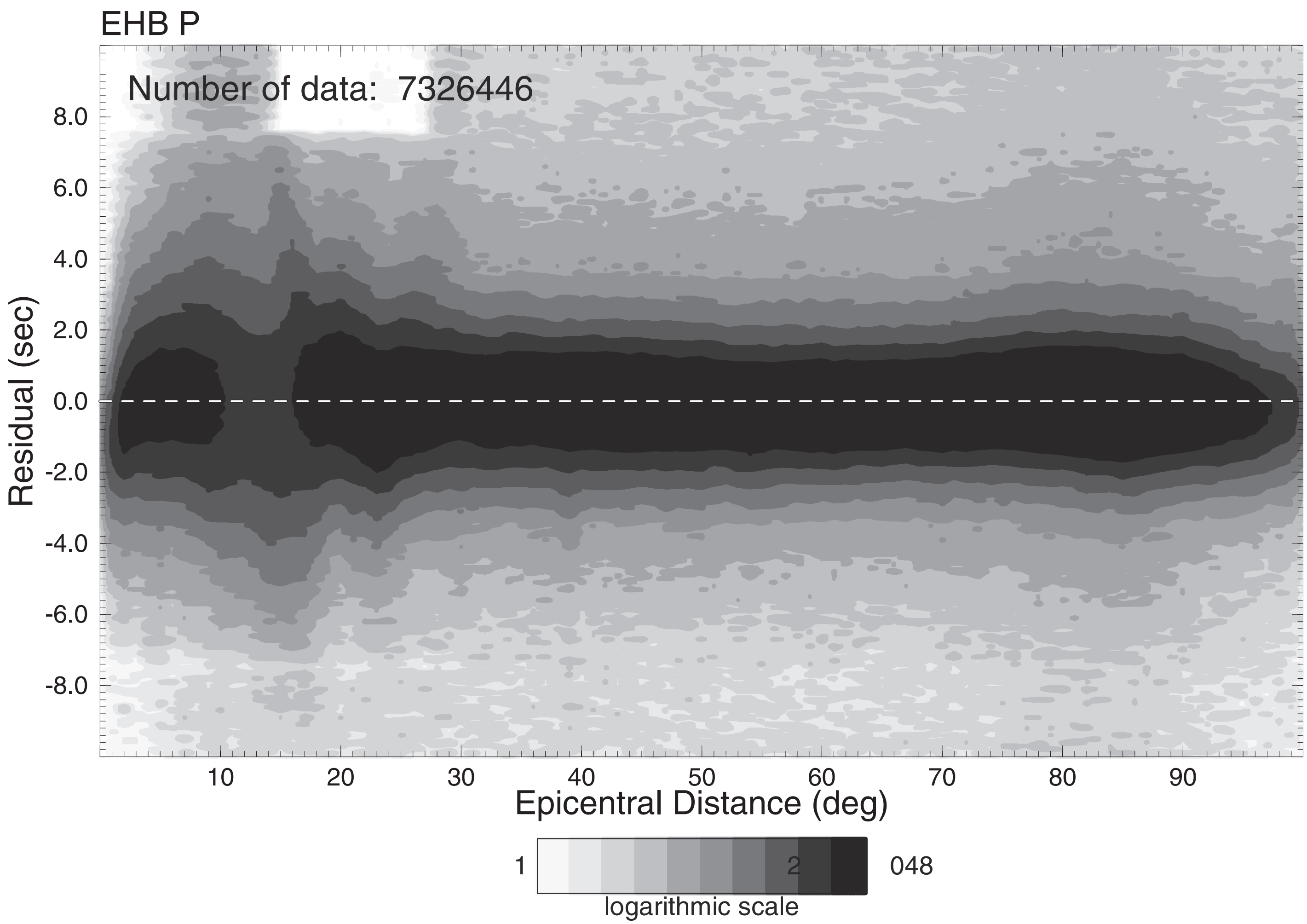
EHB* Methodology

*E.R. Engdahl, Van der Hilst, R.D., and Buland, R.P., 1998, Global teleseismic earthquake relocation with improved travel times and procedures for depth determination: Bulletin of the Seismological Society of America, v. 88, p. 3295-3314

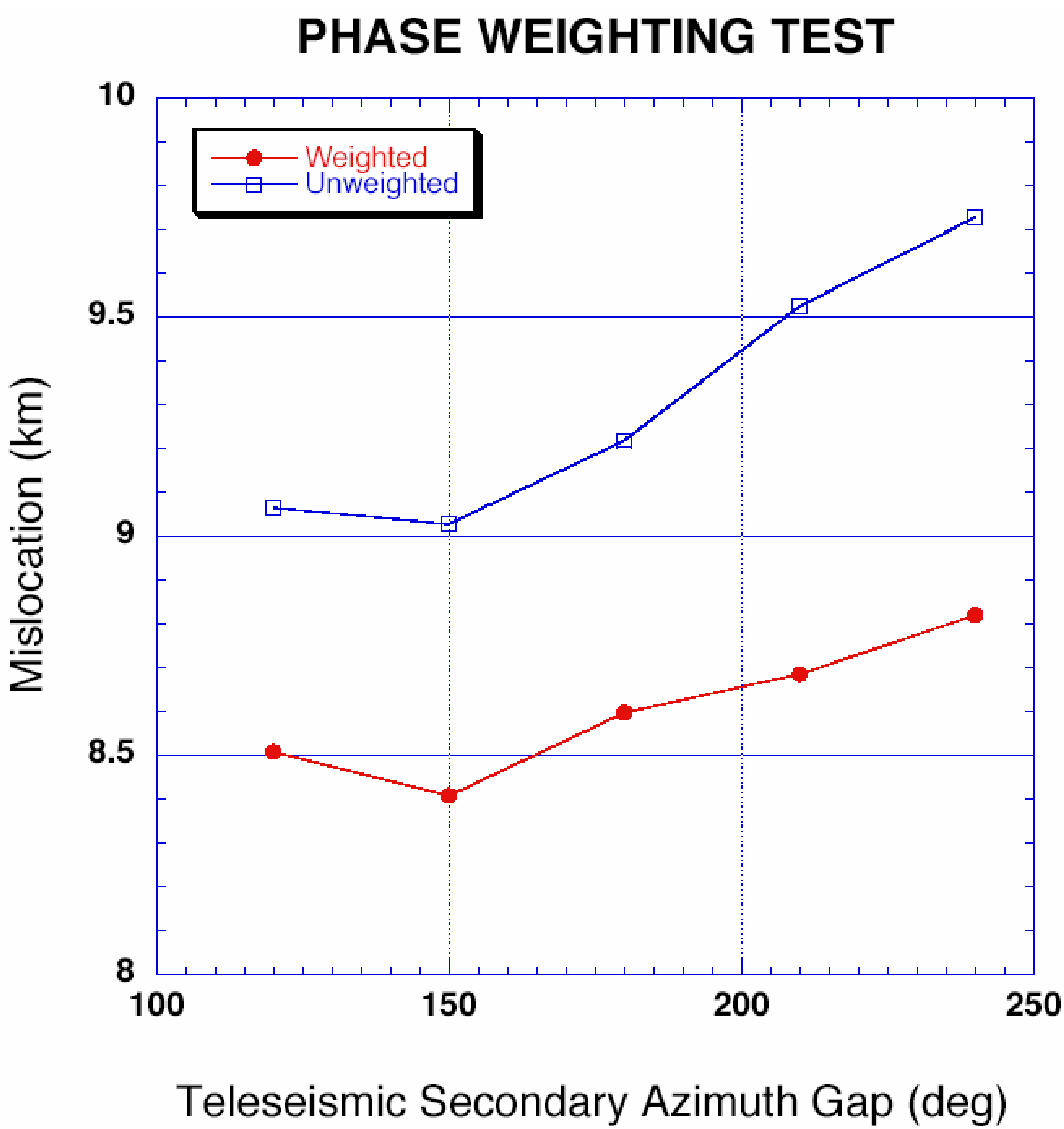
What makes EHB hypocenters better than ISS, ISC and PDE hypocenters?

- Use of an Improved 1-D Global Travel Time Model (ak135)
- Iterative Relocation With Dynamic Phase Identification
- Use of First Arriving P, S and PKP Phases
- Use of Teleseismic Depth Phases pP, pwP and sP (with PDF's and bounce point corrections)
- Ellipticity Corrections for ak135 Model
- Empirical Teleseismic "Station" Patch Corrections (5×5^{o} patches)
- Weighting by Phase Variance as a Function of Distance
- At Least 10 Teleseismic Observations
- Teleseismic Secondary Azimuth Gap $< 180^{o}$


ISC P
Number of data: 6649613
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
Residual (sec)
10
20
30
40
50
60
70
80
90
Epicentral Distance (deg)
1
2
048
logarithmic scale

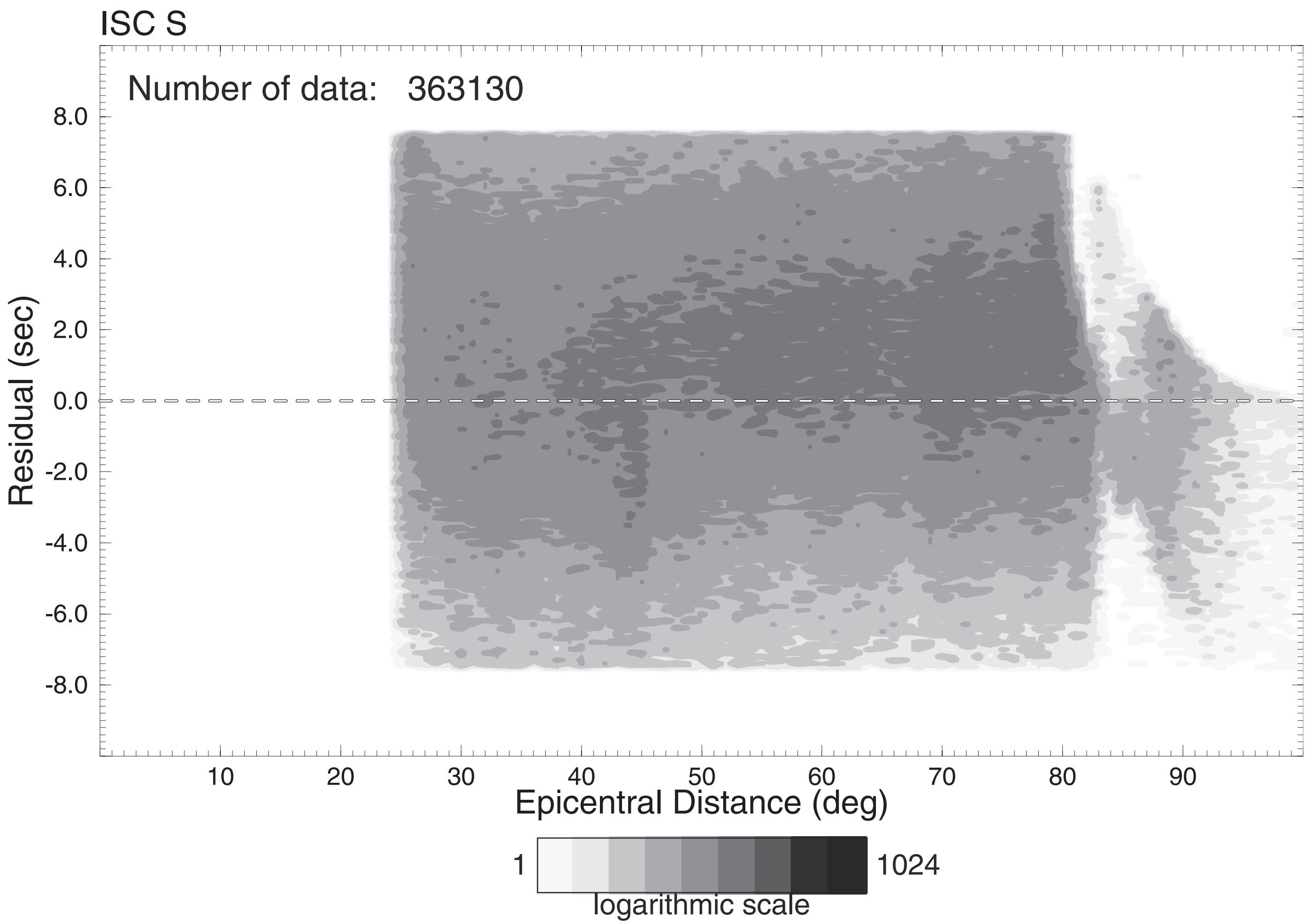


EHB P
Number of data: 7326446
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
Residual (sec)
10
20
30
40
50
60
70
80
90
Epicentral Distance (deg)
1
2
048
logarithmic scale

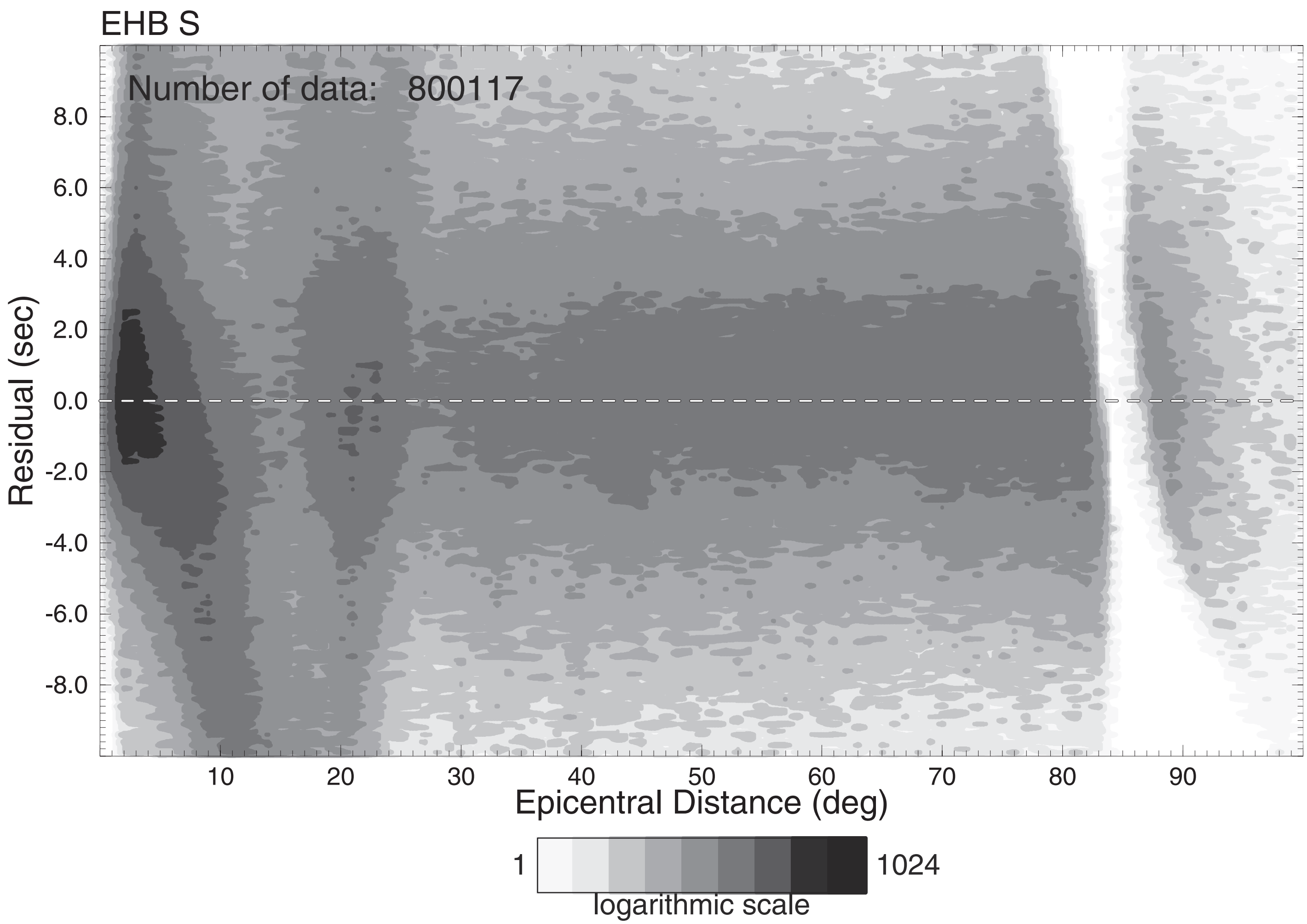

PHASE WEIGHTING TEST
Weighted
Unweighted
Mislocation (km)
10
9.5
9
8.5
8
100
150
200
250
Teleseismic Secondary Azimuth Gap (deg)

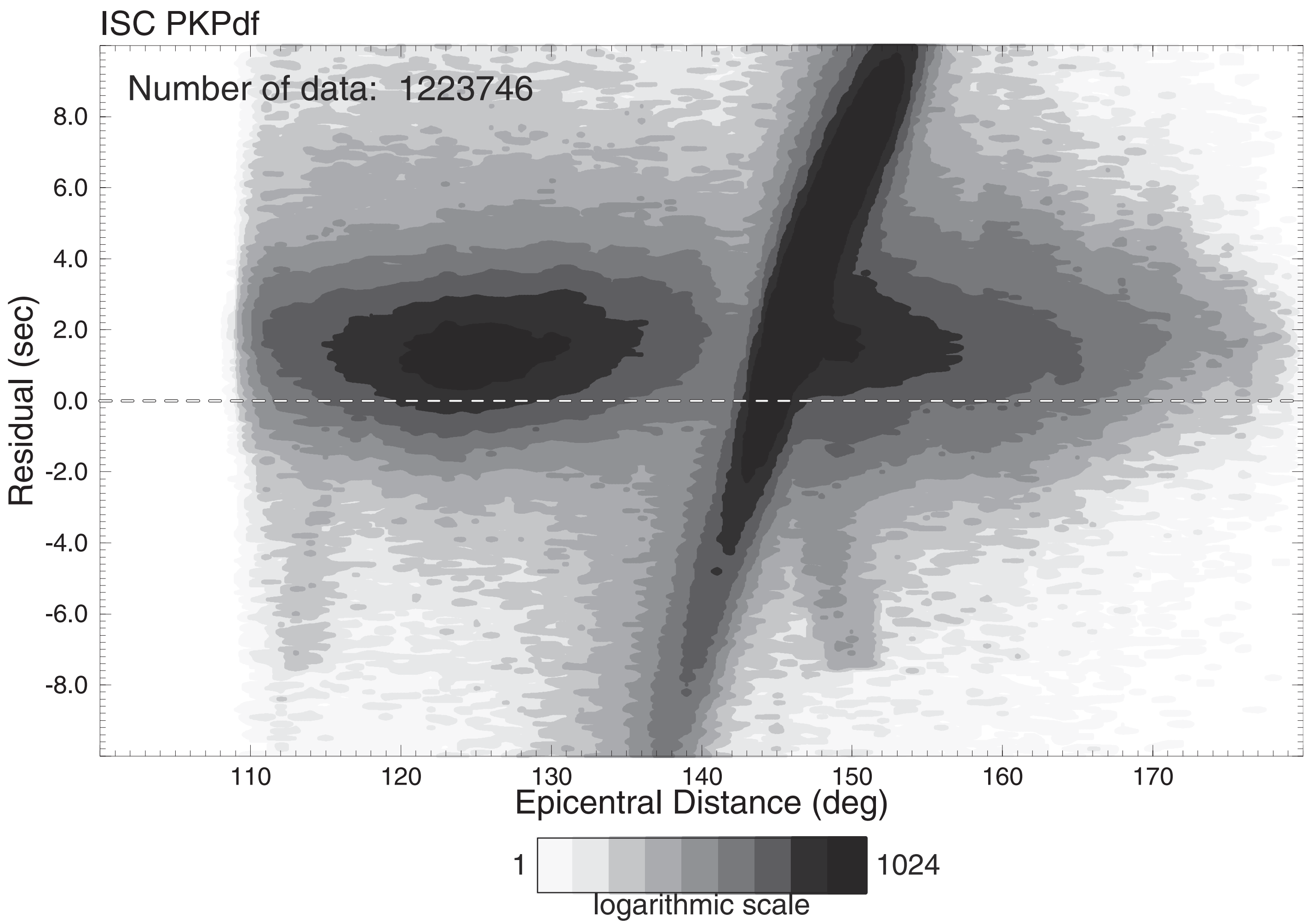
Improving Usage of Data

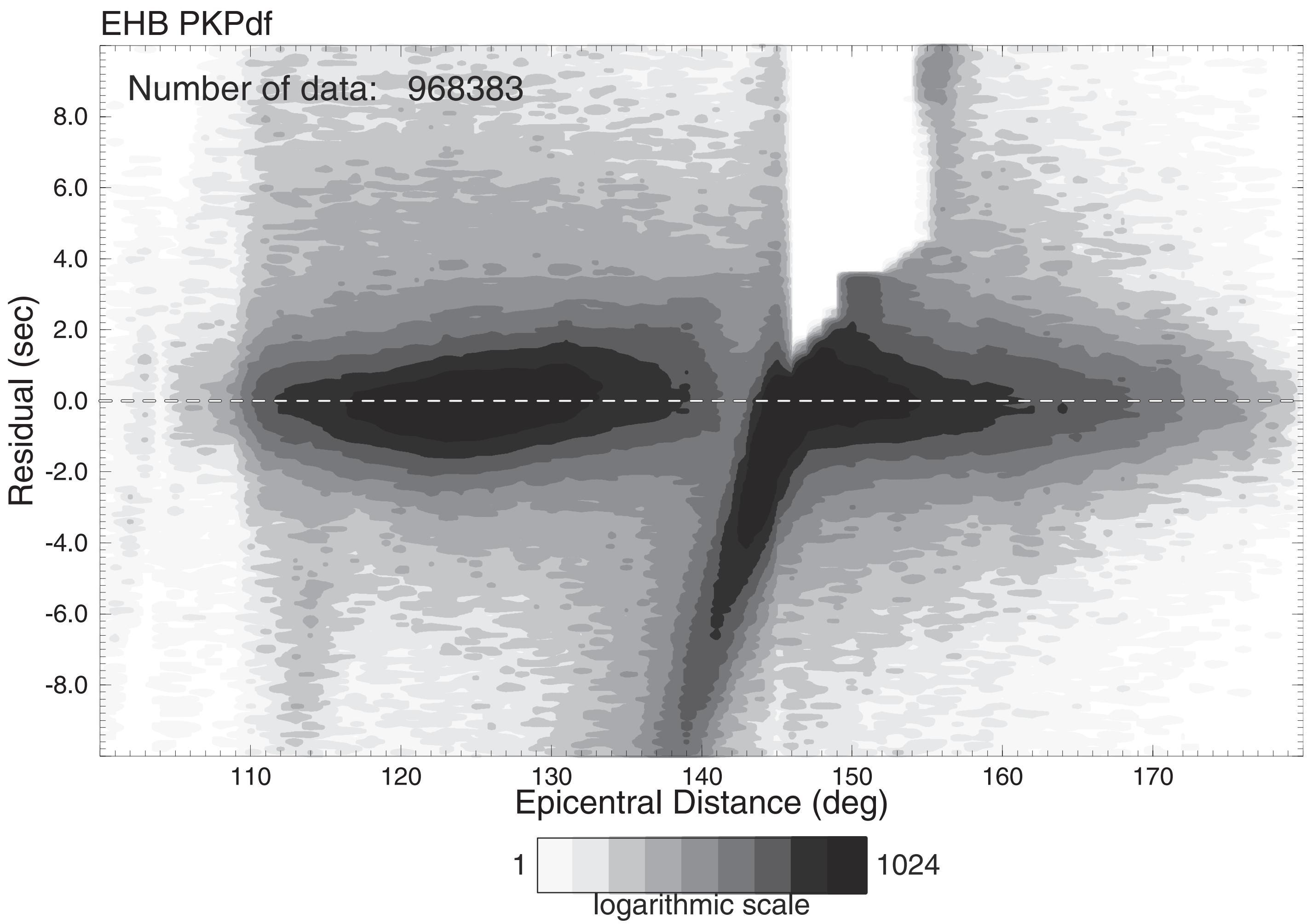
- One direct method to improve seismic event locations is by better utilization of the data.
- Standard teleseismic catalogs (ISC, NEIC) still rely almost entirely on first arriving P phases for locating events.
- Many studies have shown that the inclusion of later arriving phases can provide greater constraints on hypocenter parameters, especially focal depth.



ISC S
Number of data: 363130
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
Residual (sec)
10
20
30
40
50
60
70
80
90
Epicentral Distance (deg)
1
1024
logarithmic scale


EHB S
Number of data: 800117
Residual (sec)
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
10
20
30
40
50
60
70
80
90
Epicentral Distance (deg)
1
1024
logarithmic scale


ISC PKPdf
Number of data: 1223746
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
Residual (sec)
110
120
130
140
150
160
170
Epicentral Distance (deg)
1
1024
logarithmic scale



EHB PKPdf
Number of data: 968383
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
Residual (sec)
110
120
130
140
150
160
170
Epicentral Distance (deg)
1
1024
logarithmic scale

Model Conclusions

The model ak135 provides a very good fit to a wide range of seismic phases.

The mantle S wave bias of iasp91 has been removed.

Most core phase times are quite well matched and a baseline problem with ISC PKP phases removed.

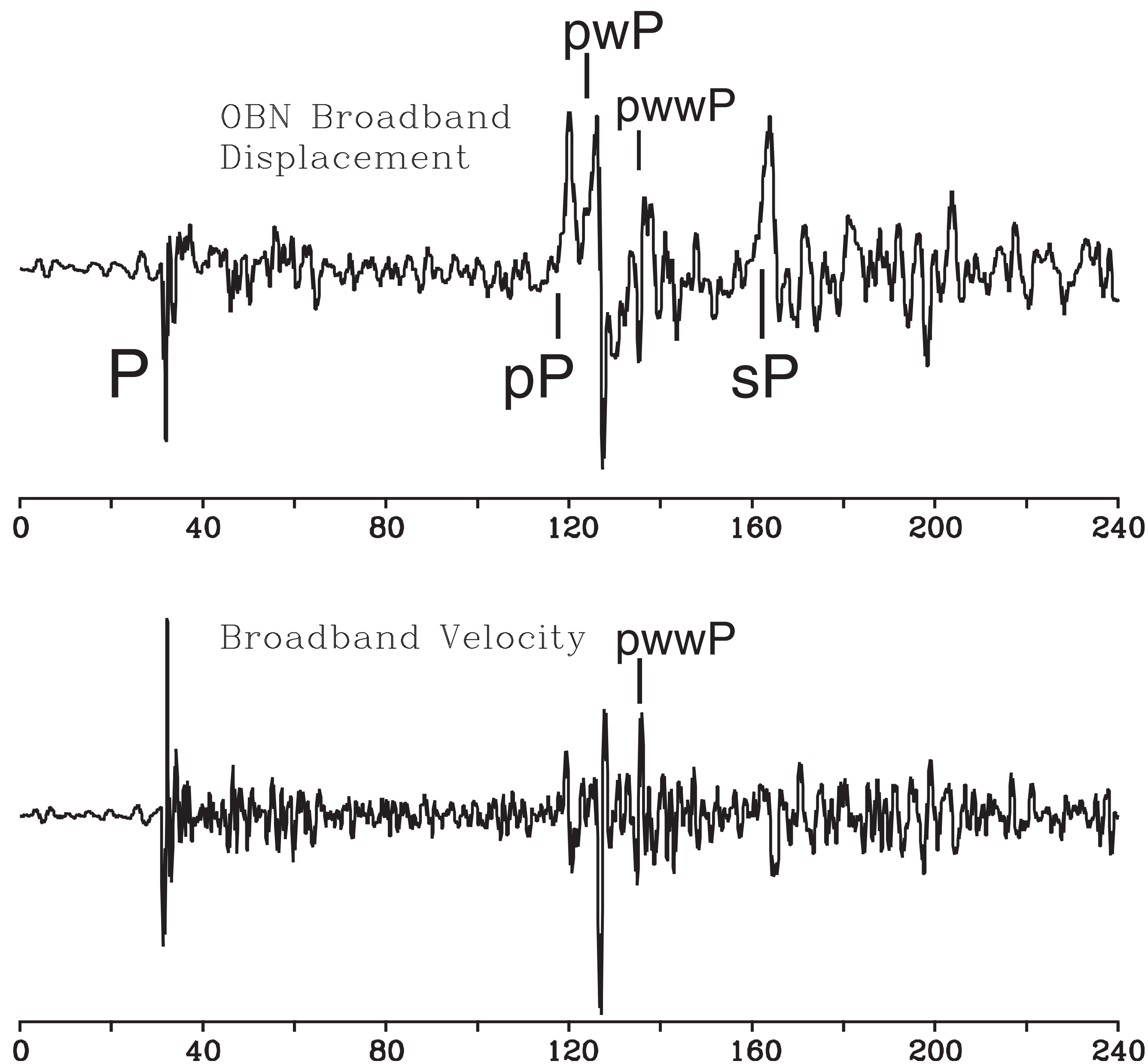
Thus, for global earthquake location there has been convergence on global, radially symmetric, P- and S-velocity Earth models that provide a good average fit to reported phase arrival times.

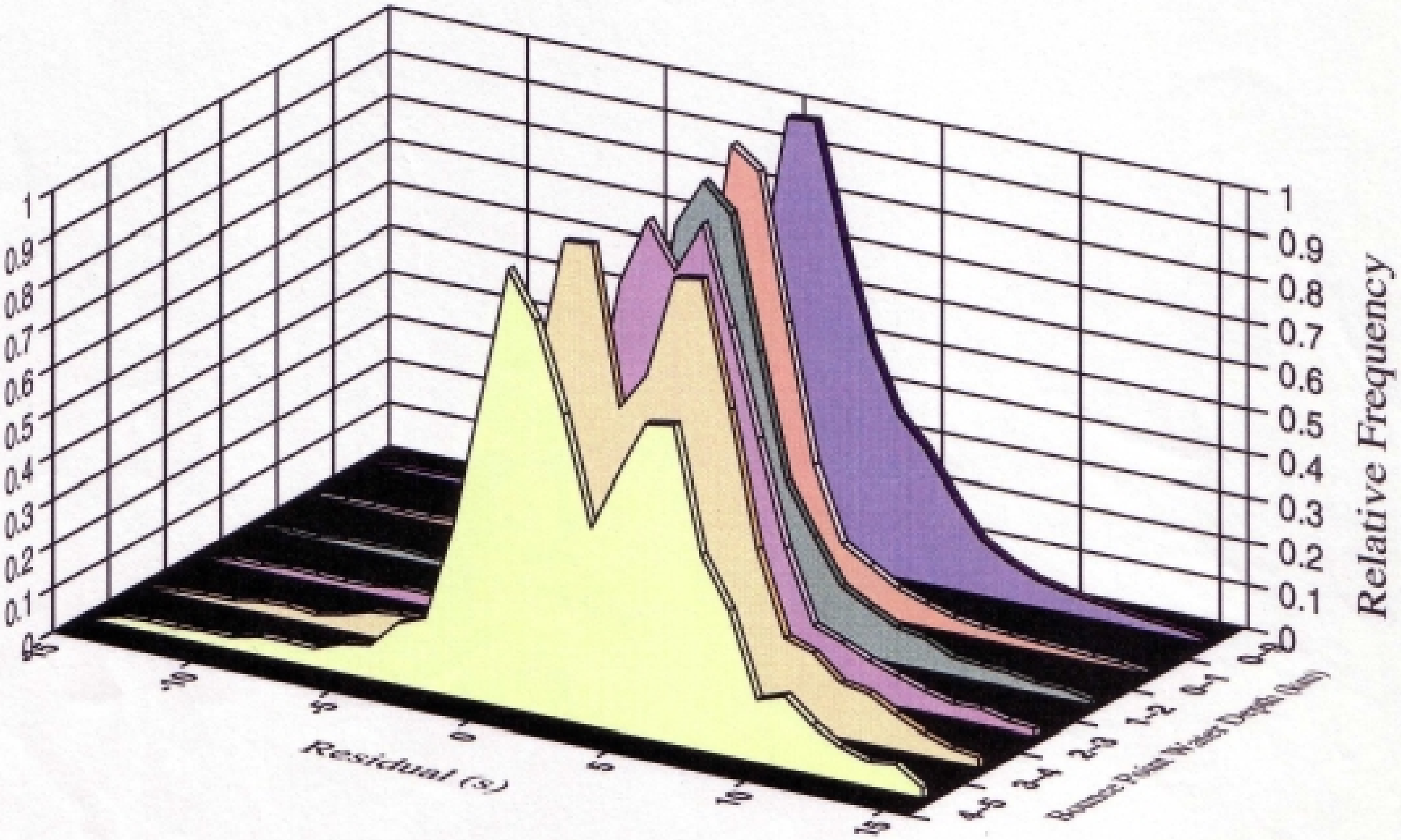
The phase arrival time residuals (observed minus calculated) are then related to hypocenter (latitude θ, longitude ϕ, depth z) and origin time (t_o) perturbations by a linearized equation of the form

$$r = -\sin\theta \sin\alpha \left(\frac{\partial T}{\partial \Delta}\right)(\Delta\phi) + \cos\alpha \left(\frac{\partial T}{\partial \Delta}\right)(\Delta\theta) + \left(\frac{\partial T}{\partial z}\right)(\Delta z) + \Delta t_o$$

where α is azimuth from the event to the station.

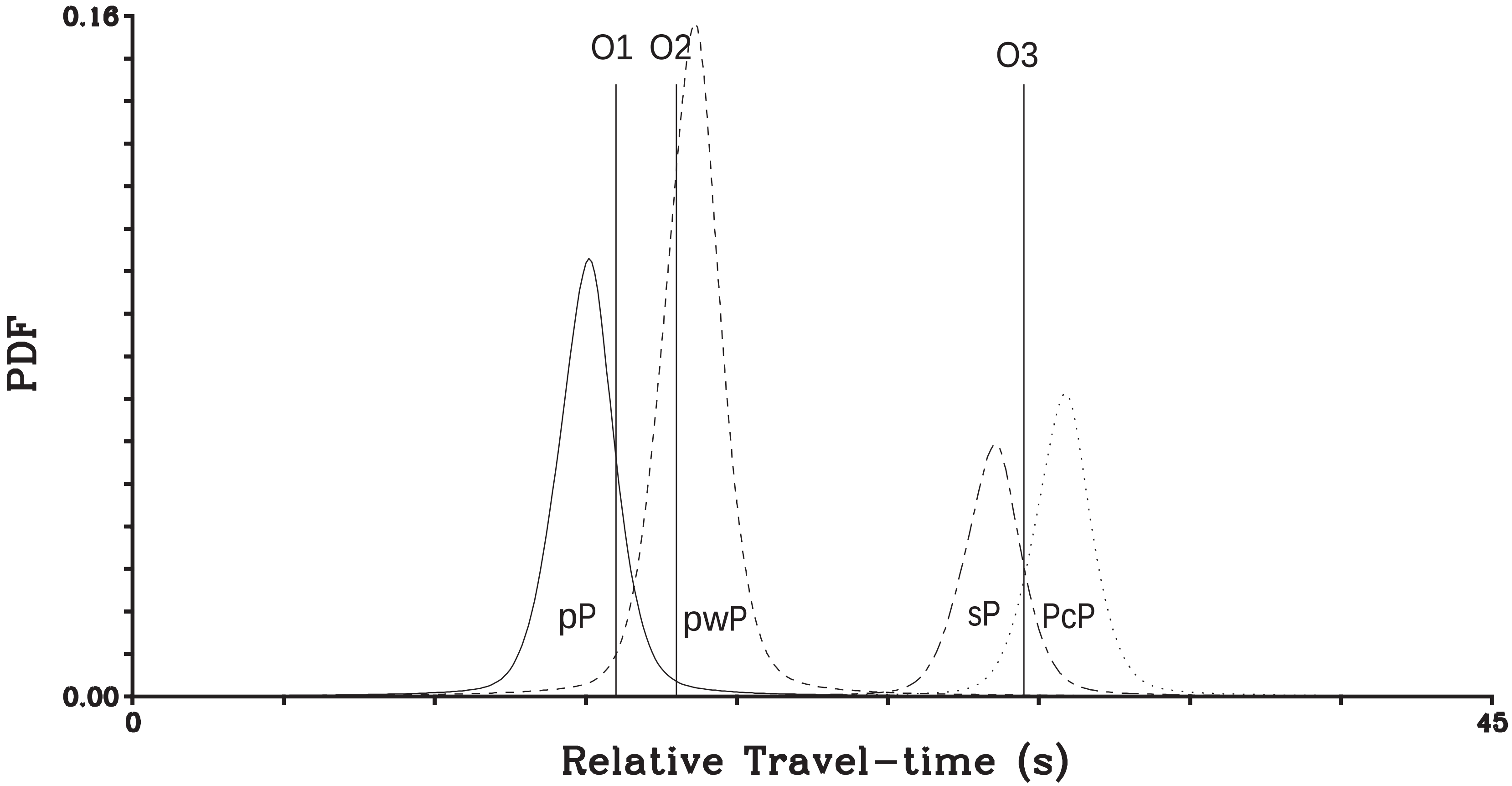
Depth to origin trade-off is avoided by the inclusion of depth phases (pP, pwP, sP) because their travel time derivatives with respect to depth are opposite in sign to those of direct P.


pwP
OBN Broadband
Displacement
pwwP
P
pP
sP
0
40
80
120
160
200
240
Broadband Velocity
pwwP
0
40
80
120
160
200
240

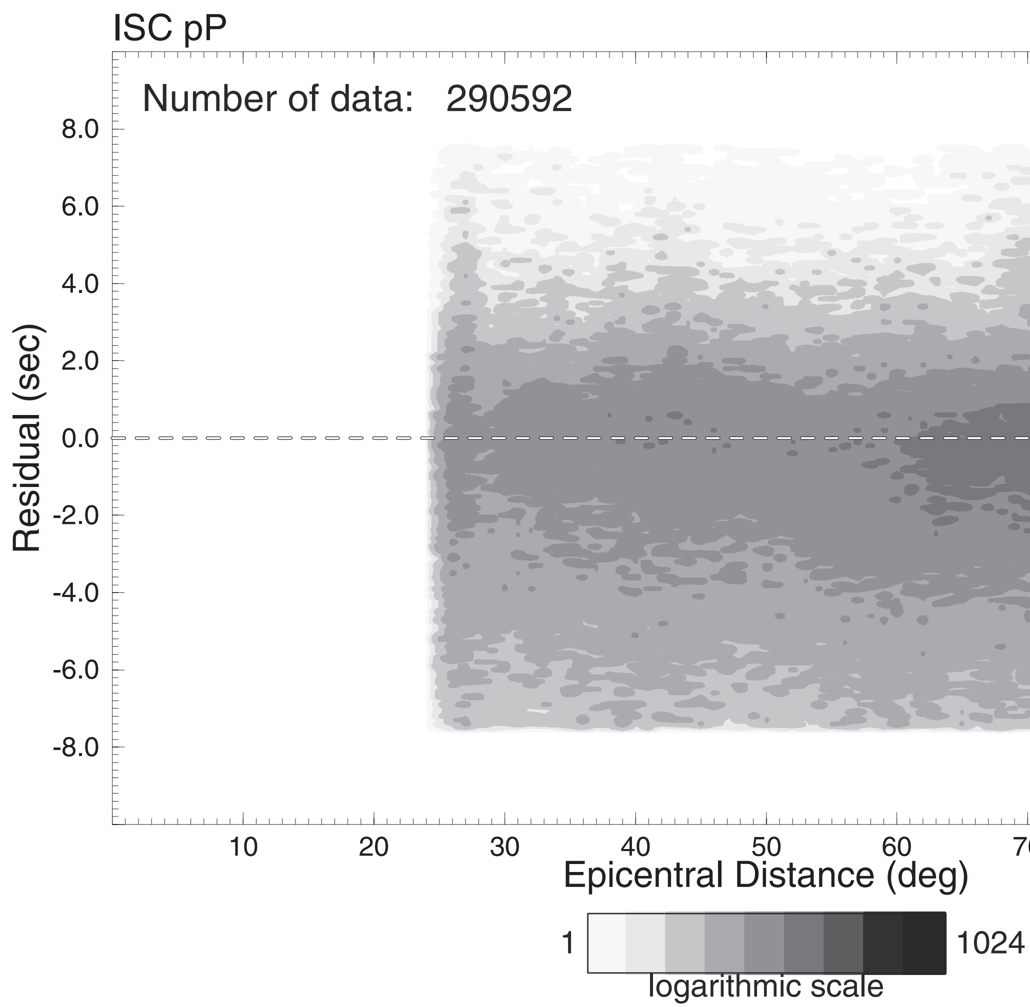


pP Residuals

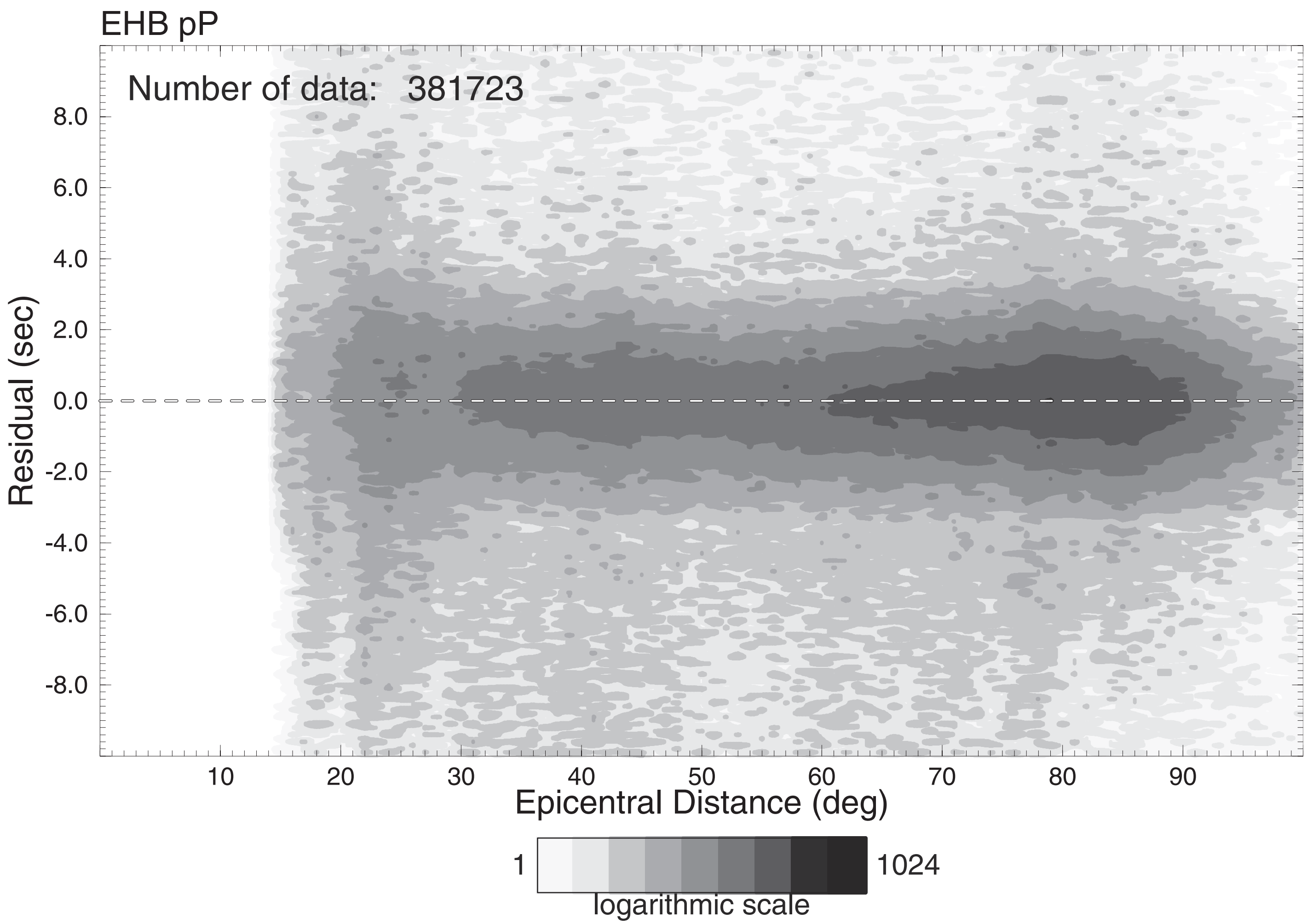
- A problem with the use of depth phases is that their correct identification often requires knowledge of the event depth and distance. Hence, depth phase arrivals are re-identified after each iteration using a statistically based association algorithm.
- Probability density functions (PDFs) for depth phases, centered on their theoretical relative travel times for a given hypocenter, are compared to the observed phase arrivals.
- When PDF’s overlap for a particular depth phase, a phase identification is assigned in a probabilistic manner based on the relevant PDF values, making sure not to assign the same phase to two different arrivals.

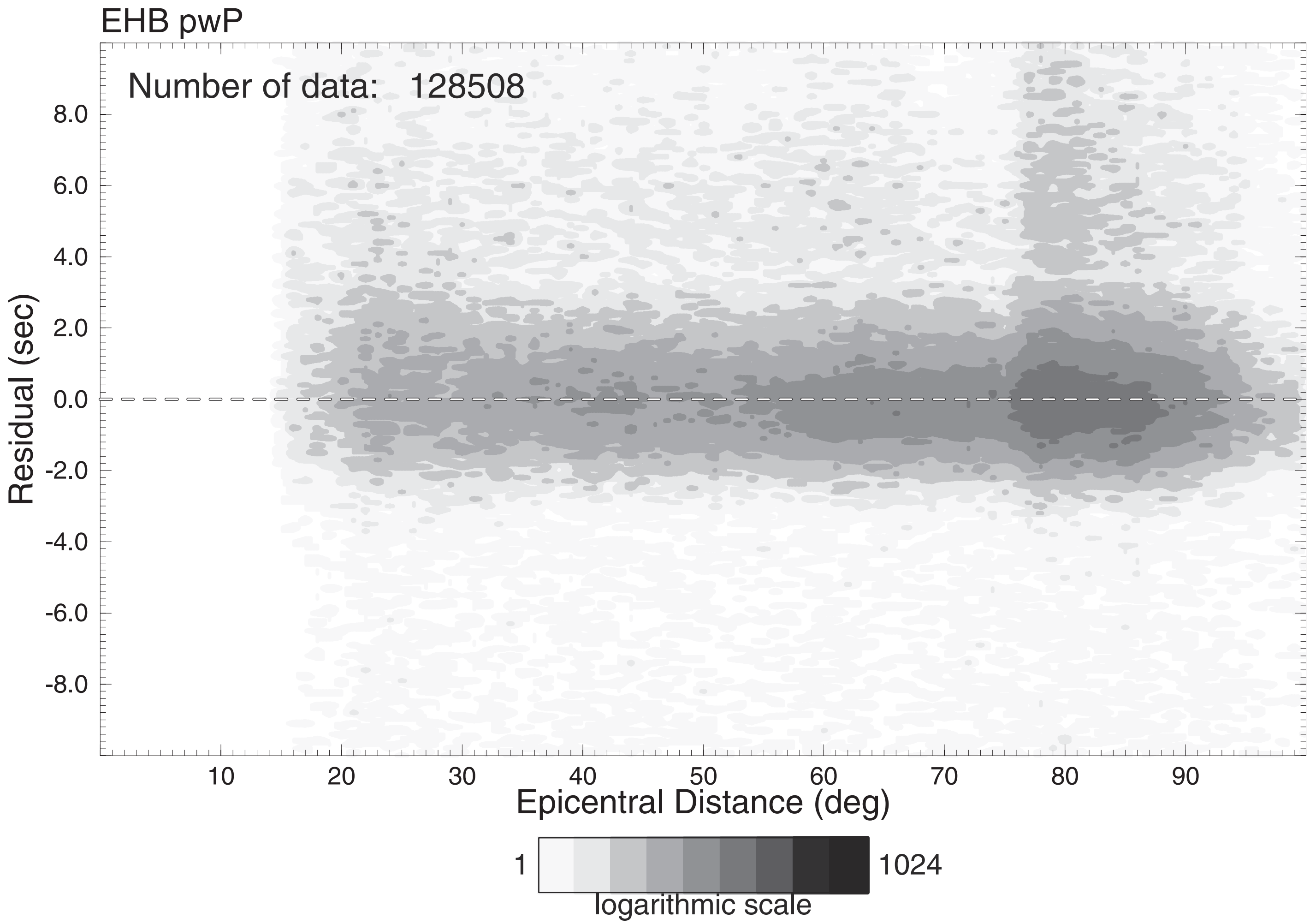


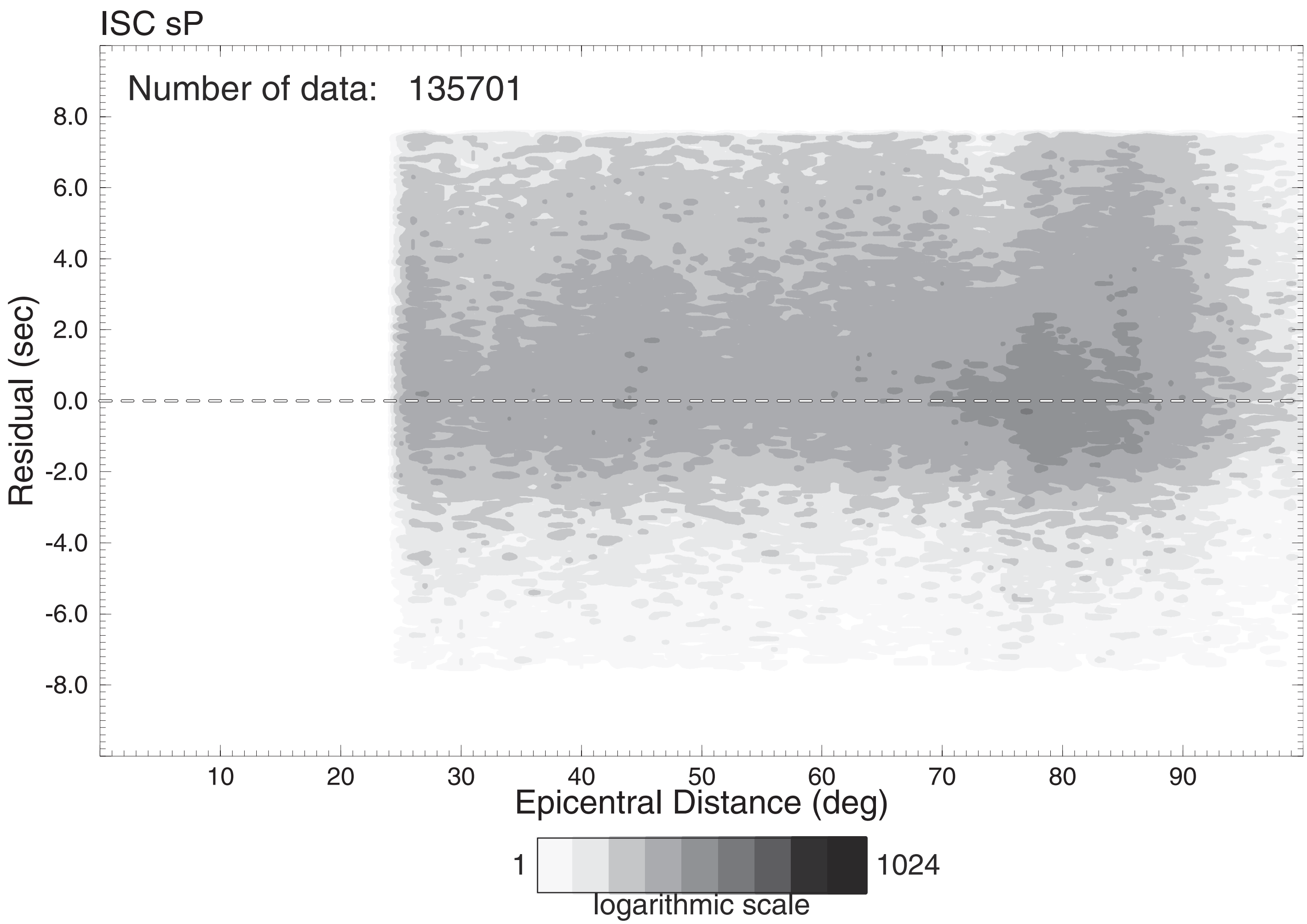
0.16
0.00
PDF
O1
O2
O3
pP
pwP
sP
PcP
0
45
Relative Travel-time (s)

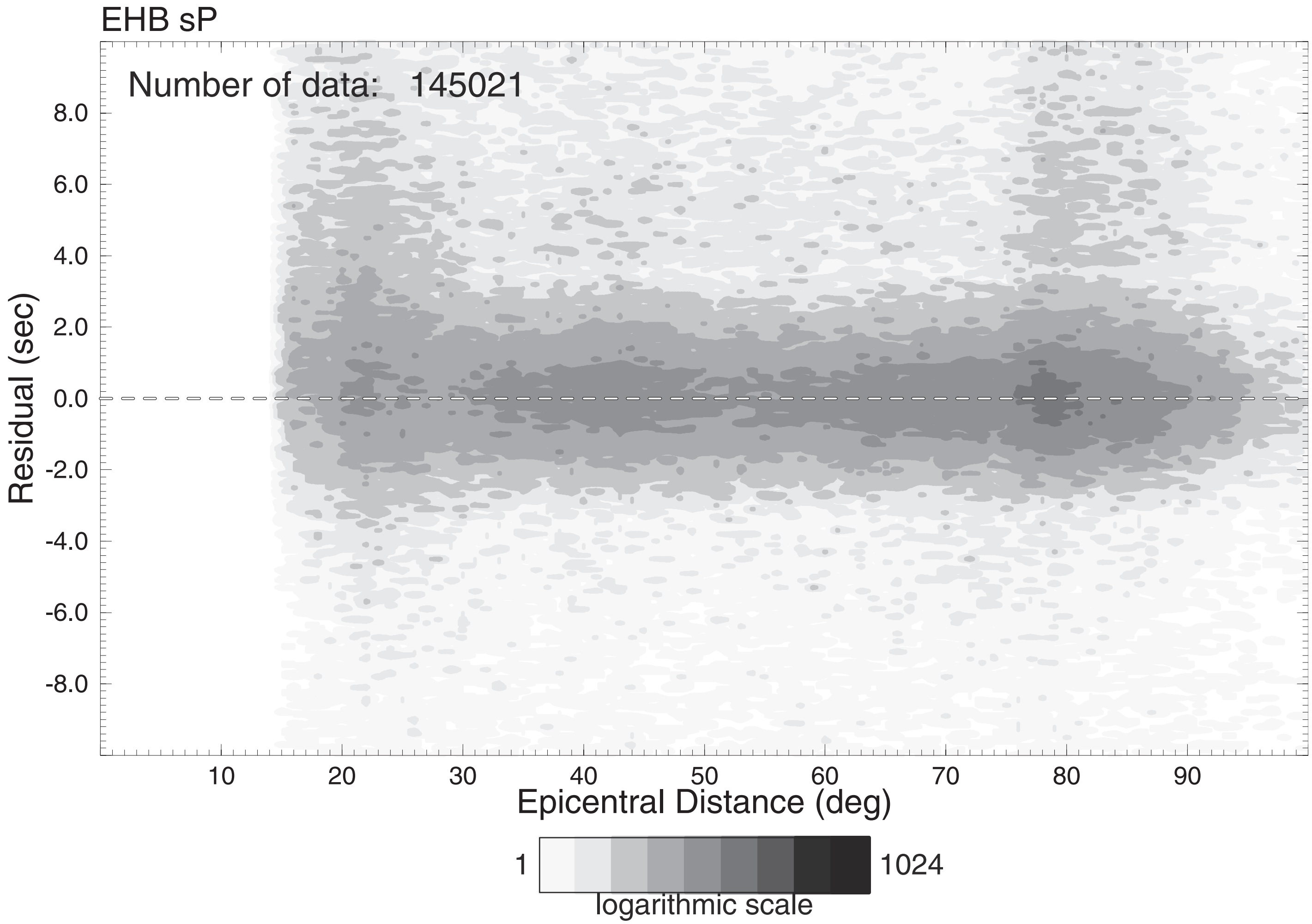


ISC pP
Number of data: 290592
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
Residual (sec)
10
20
30
40
50
60
70
80
90
Epicentral Distance (deg)
1
1024
logarithmic scale


EHB pP
Number of data: 381723
Residual (sec)
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
10
20
30
40
50
60
70
80
90
Epicentral Distance (deg)
1
1024
logarithmic scale


EHB pwP
Number of data: 128508
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
Residual (sec)
10
20
30
40
50
60
70
80
90
Epicentral Distance (deg)
1
1024
logarithmic scale


ISC sP
Number of data: 135701
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
Residual (sec)
10
20
30
40
50
60
70
80
90
Epicentral Distance (deg)
1
1024
logarithmic scale


EHB sP
Number of data: 145021
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
Residual (sec)
10
20
30
40
50
60
70
80
90
Epicentral Distance (deg)
1
1024
logarithmic scale

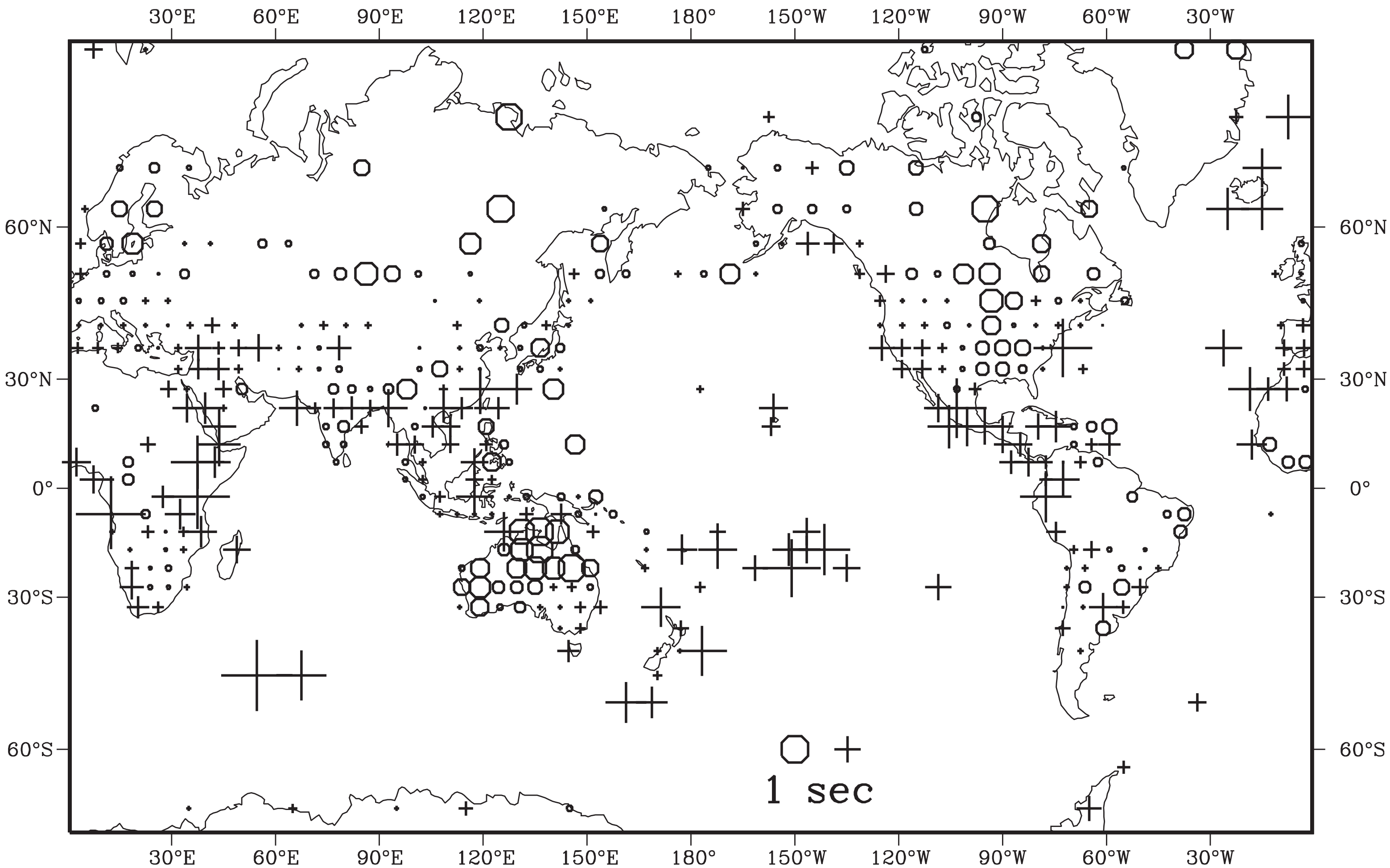
Effects of Later Phase Arrival Times on Location and Depth

Phase Arrival Times	Number of Events	Location Error (km)	Depth Error (km)
P Phase Arrival Times (at least 3 P phases < 28 deg)	92	11.6	16.1
P, PcP, ScP & ScS Phase Arrival Times (at least 3 PcP, ScP and/or ScS phases)	48	10.5	14.1
P & PKPdf Phase Arrival Times (at least 3 PKiKP and/or PKPdf phases in the distance ranges 110-140 & 150-180 deg)	50	11.3	13.3
P & S Phase Arrival Times (at least 3 S phases < 28 deg)	72	10.0	12.1
P & Depth Phase Arrival Times (at least 3 pP, pwP and/or sP phases > 28 deg)	68	10.8	7.0
P, PKP, S & Depth Phase Arrival Times (EHB Methodology)	101	9.1	9.0

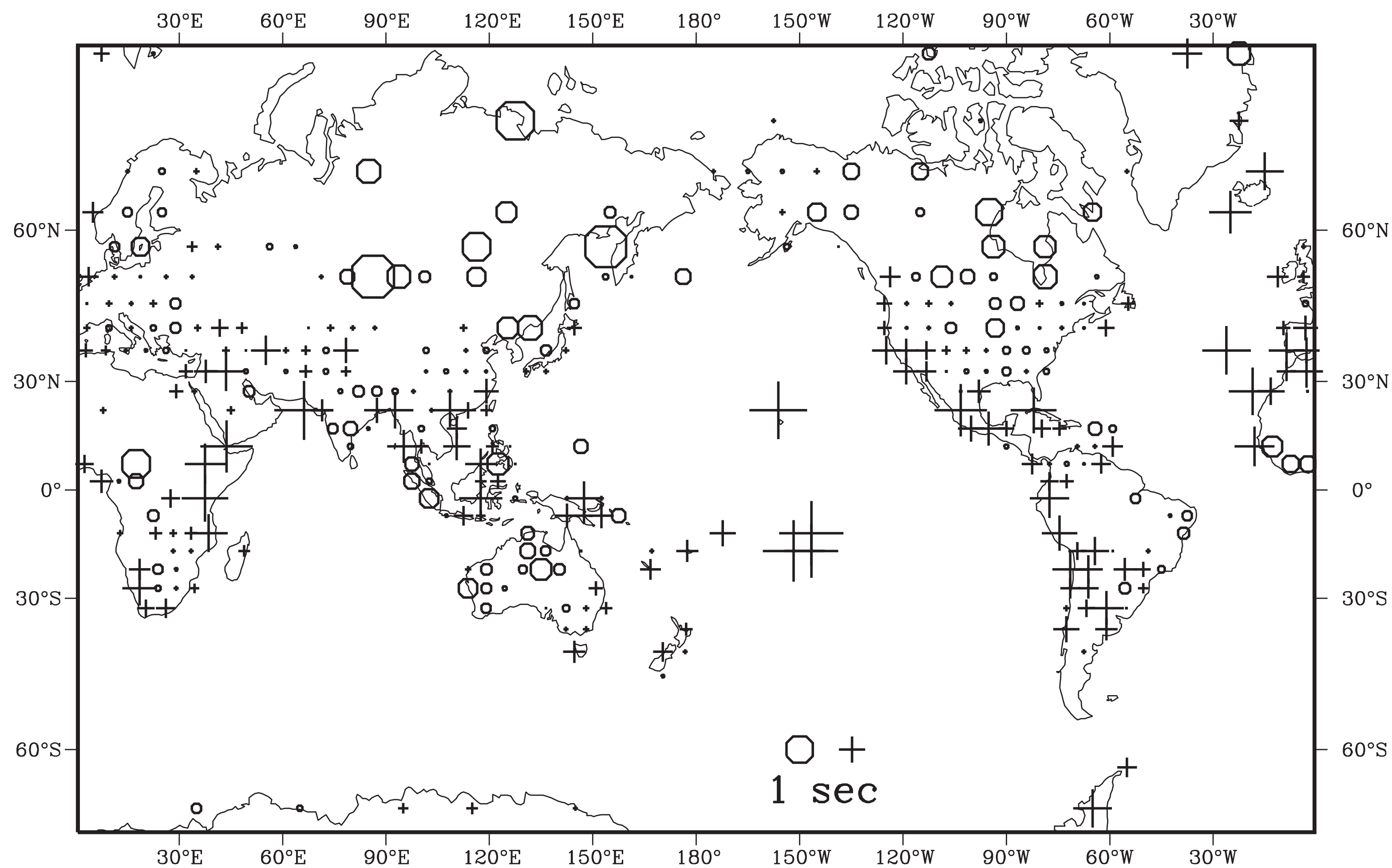
Station Corrections

- Station corrections are a long-recognized mechanism for trying to compensate for upper mantle velocity heterogeneity beneath stations when 1-D velocity models are assumed.
- In the EHB method a teleseismic “patch correction” approach has been adopted, determining from P teleseismic residuals a single median correction for all stations within 5 x 5 degree regions.
- Patch medians derived separately from teleseismic P and PKP residual data agree well with each other.

PLM PATCH MEDIANS (5 X 5 DEG PATCHES)
LOWER MANTLE BOTTOMING DEPTHS (760-2740 KM)



PKP PATCH MEDIANS (5 X 5 DEG PATCHES)
INNER CORE BOTTOMING DEPTHS (5153.5-6371 KM)

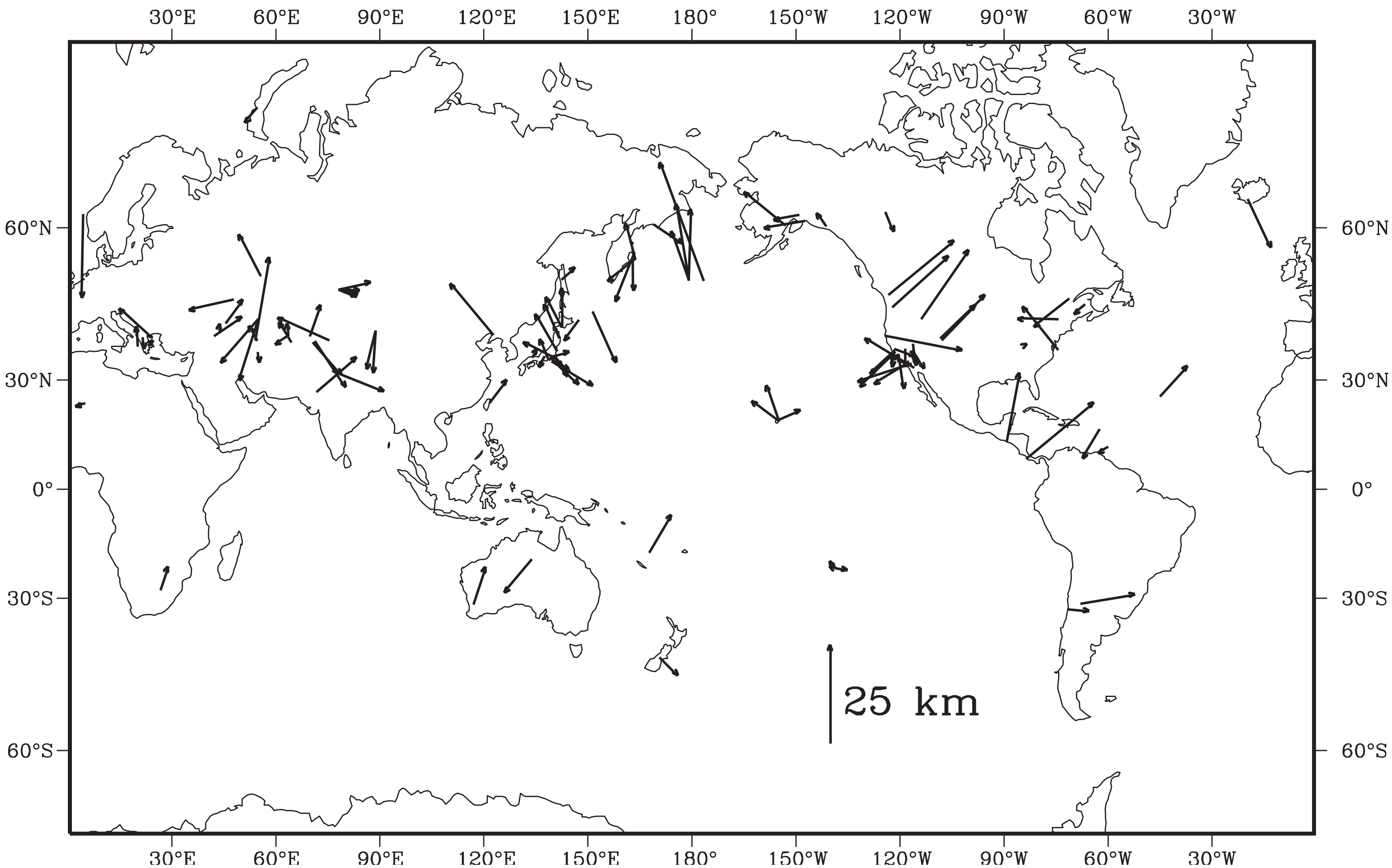


Aspherical Earth Structure

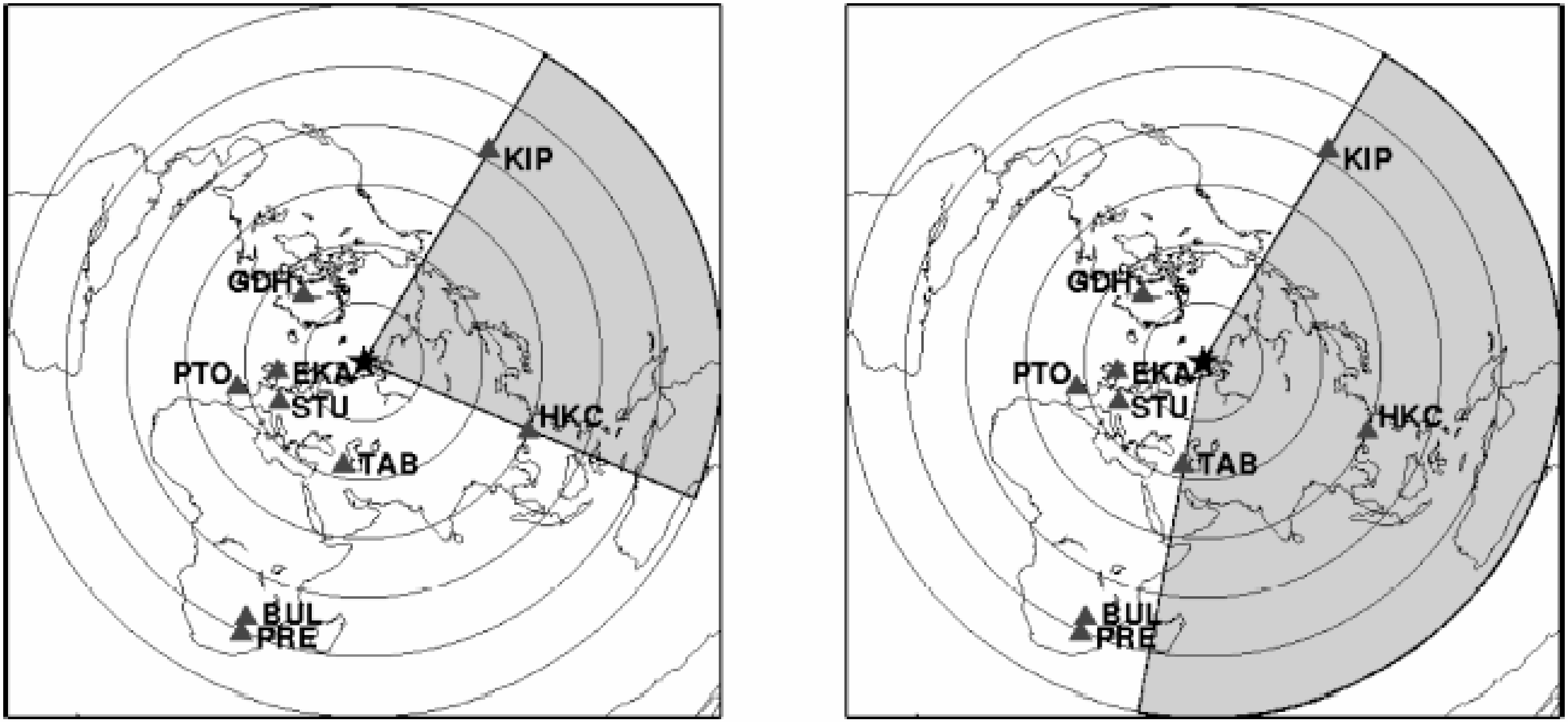
- The travel times predicted by recently developed, radially symmetric, Earth models (such as ak135) are extremely valuable for earthquake location and phase identification.
- Nevertheless, most earthquakes occur in or near subducted lithosphere where aspherical variations in upper mantle seismic wave velocities are large (i.e., on the order of 5 - 10%)
- Such lateral variations in seismic velocity, the uneven spatial distribution of seismological stations, and the specific choice of seismic data used to determine the earthquake hypocenter can still easily combine to produce bias in earthquake locations of several tens of kilometers

- Kennett and Engdahl (1991) have shown that a set of reference events (events for which we have well-constrained hypocenters, such as nuclear explosions or earthquakes located within a local network) are on average mislocated by about 14 km using standard procedures.

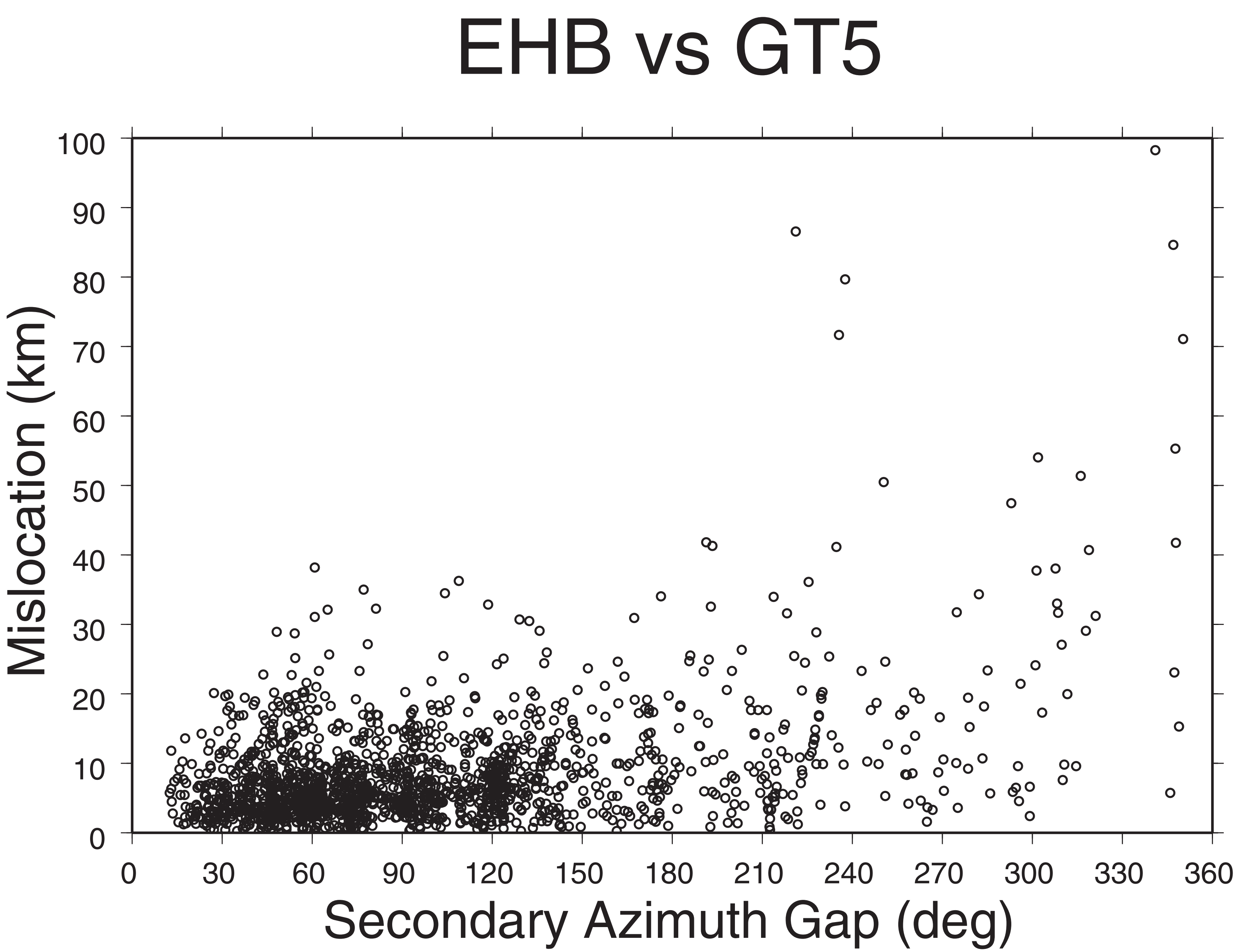
EPICENTER MISLOCATIONS (EHB VS TEST EVENTS)



- Tests of location bias globally using a new archive of reference event information and the EHB location algorithm show that most explosions and earthquakes are mislocated by less than 20 km if the secondary azimuth gap to observing stations at all distances is less than 180 degrees.



- Although the 82^{o} primary azimuthal gap (left panel) is quite good for this event, any reading error at HKC that provides the 160^{o} secondary azimuthal gap (right panel) may bias the location.


EHB vs GT5
Mislocation (km)
0
10
20
30
40
50
60
70
80
90
100
0
30
60
90
120
150
180
210
240
270
300
330
360
Secondary Azimuth Gap (deg)

Location Conclusions

- At least in the case of events well constrained azimuthally by reporting stations, mislocation errors introduced by lateral heterogeneity can be minimized.
- For smaller and/or poorly recorded events, however, there is not much hope of significantly reducing the resulting mislocation error until we can somehow better account for aspherical Earth structure in 1-D earthquake location procedures.

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