Evaluating Effectiveness of DART® Buoy Networks

Don Percival

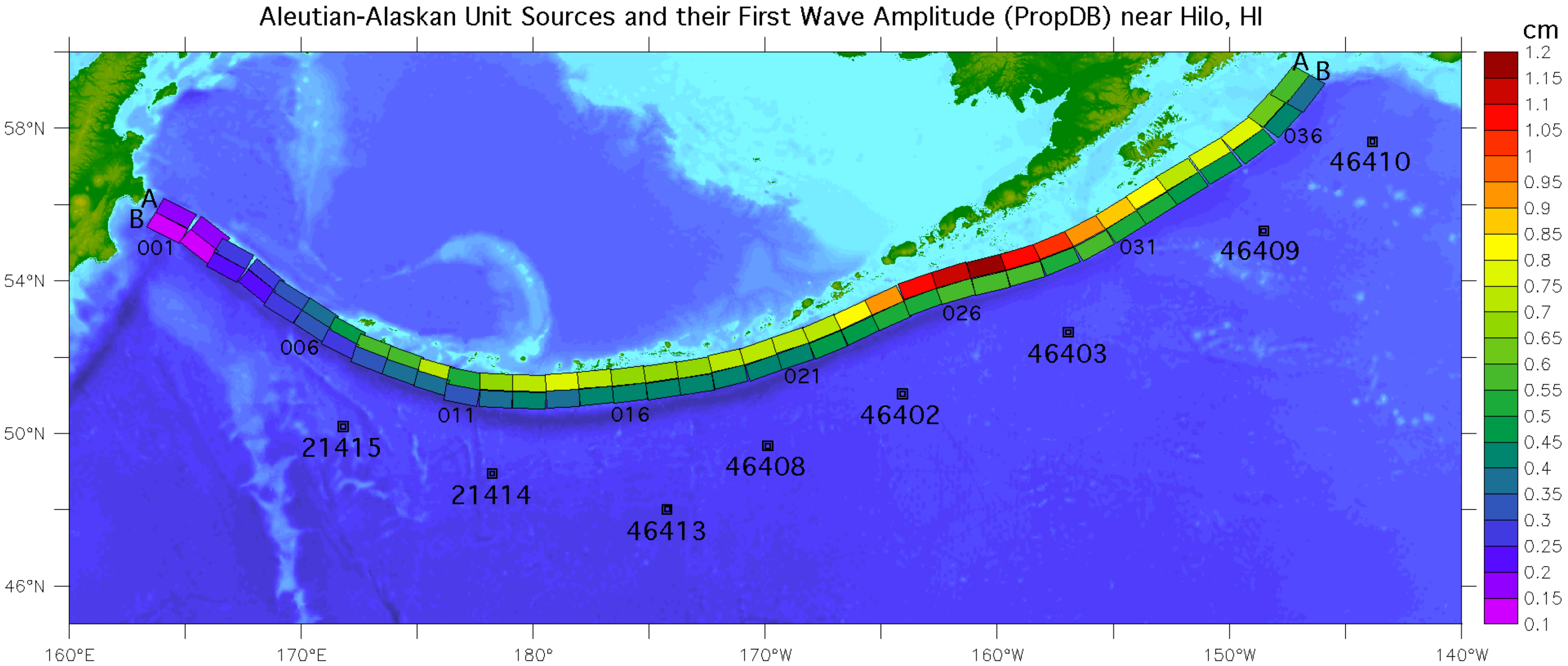
Applied Physics Laboratory
Department of Statistics
University of Washington, Seattle

Ongoing joint work with Don Denbo, Edison Gica, Paul Huang,
Hal Mofjeld, Mick Spillane and Vasily Titov

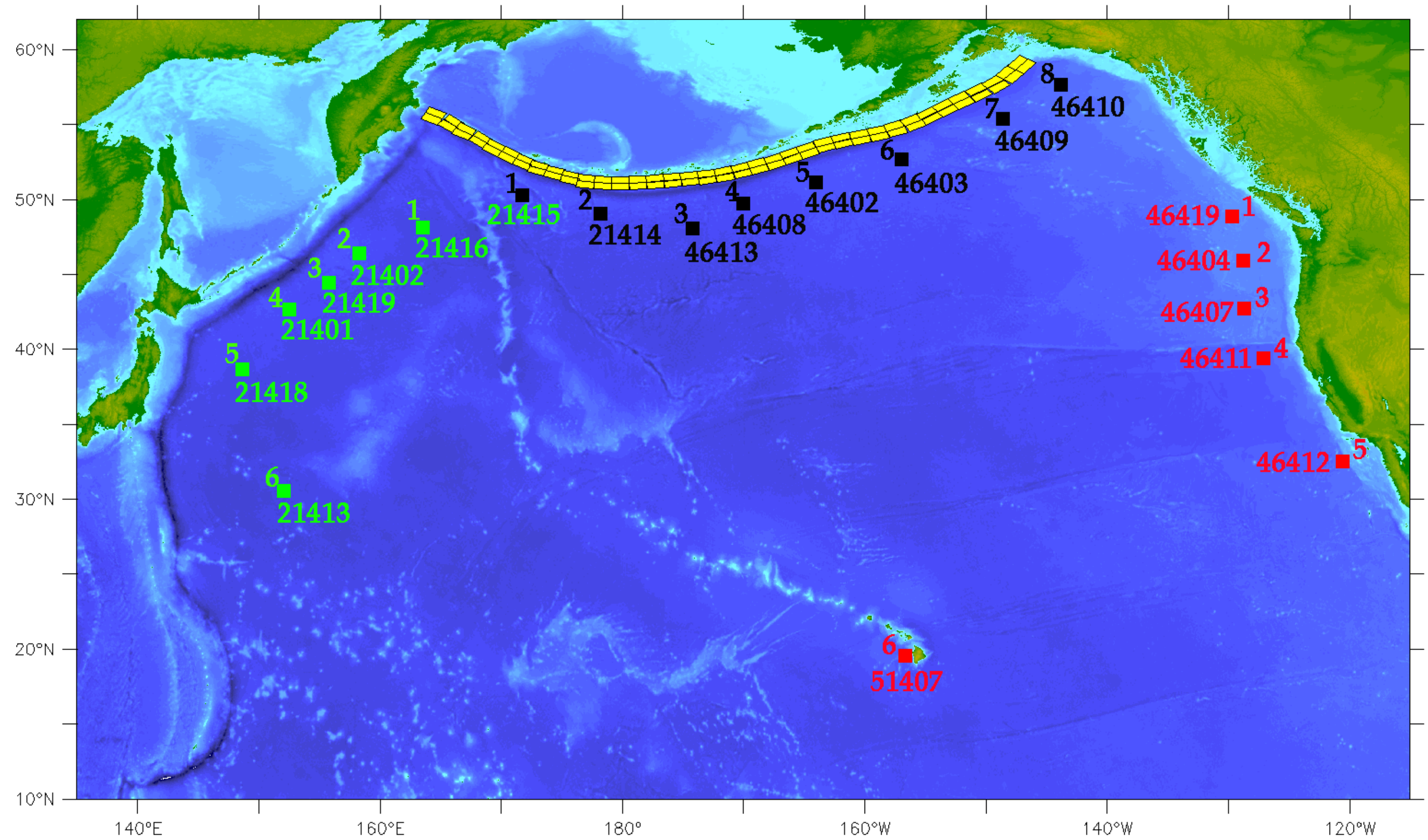
Overview

- task: evaluate effectiveness of DART® buoy network in providing accurate and timely predictions of wave heights at locations near coasts of interest
- desideratum: simple measure of effectiveness that can be monitored over time and used to raise alarm if network deteriorates
- challenge: devise useful measure that does not oversimplify
  - chosen simplifications admittedly ignore (possibly important) aspects of multifaceted system for predicting wave heights
- approach: layered summaries from simulated predictions with focus on parts of system that limit efficacy of predictions
  - not enough actual data for realistic evaluation of network

Aleutian DART® Buoys/Unit Source



DART® Buoys East/West of Aleutian and Hilo



Location, Locations, Location

- basic simplified elements:
  - tsunami-generating event from within a single unit source
  - data from event collected at multiple DART®'s
  - data from single buoy used to predict wave heights at Hilo – one prediction for each buoy
- assumptions behind simplifications
  - small events from within a single unit source useful for assessing effectiveness of network; i.e., scaling to larger events from multiple unit sources would yield similar evaluation
  - predictions based on each buoy separately can assess effectiveness of overall network – using two or more buoys simultaneously won't lead to a significantly different evaluation
  - Hilo useful site to focus on to start with – can consider others

Sources of Errors in Wave Height Predictions: I

- given data from single buoy, fit joint linear model for tides and tsunami signal using unconstrained/constrained least squares
  - tidal model consists of constant and sine & cosine terms at M2 frequency (regression coefficients are unconstrained)
  - signal model consists of precomputed unit sources (regression coefficients – called α's – are constrained to be nonnegative)
- perfect signal model & α's $\Longrightarrow$ perfect wave height predictions
- estimated α's are imperfect because of, inter alia,
  1. imperfect tidal model
  2. background noise
  3. mismatch between assumed model and true tsunami signal
  4. limited amount of data

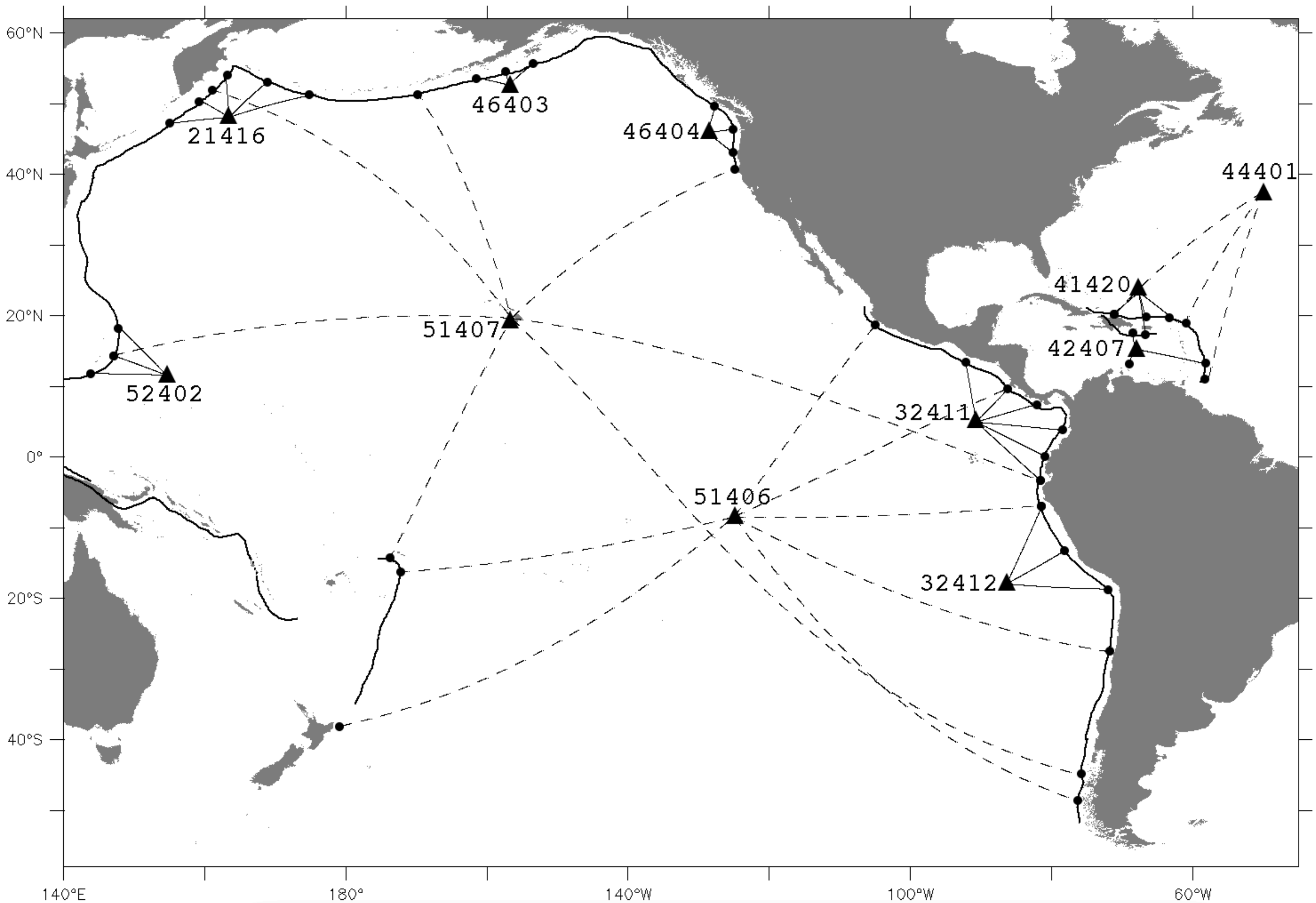
Sources of Errors in Wave Height Predictions: II

- note: seismic noise also affects α estimates, but, for simplicity, have chosen to ignore this potentially important contributor
- simulation study accounts for contributors 1, 2, 3 and 4 to imperfections in estimated α's in the following ways
- can handle 1 (imperfect tidal model) and 2 (background noise) by using DART® data recorded under ambient conditions and retrieved during routine servicing of buoy
  - archived 15-sec data not available for all DART® buoys – have to resort to surrogates for these
- easy to handle 4 (limited amount of data)
- to handle 3 (mismatch between assumed model and true tsunami signal), used following procedure to create tsunami signals

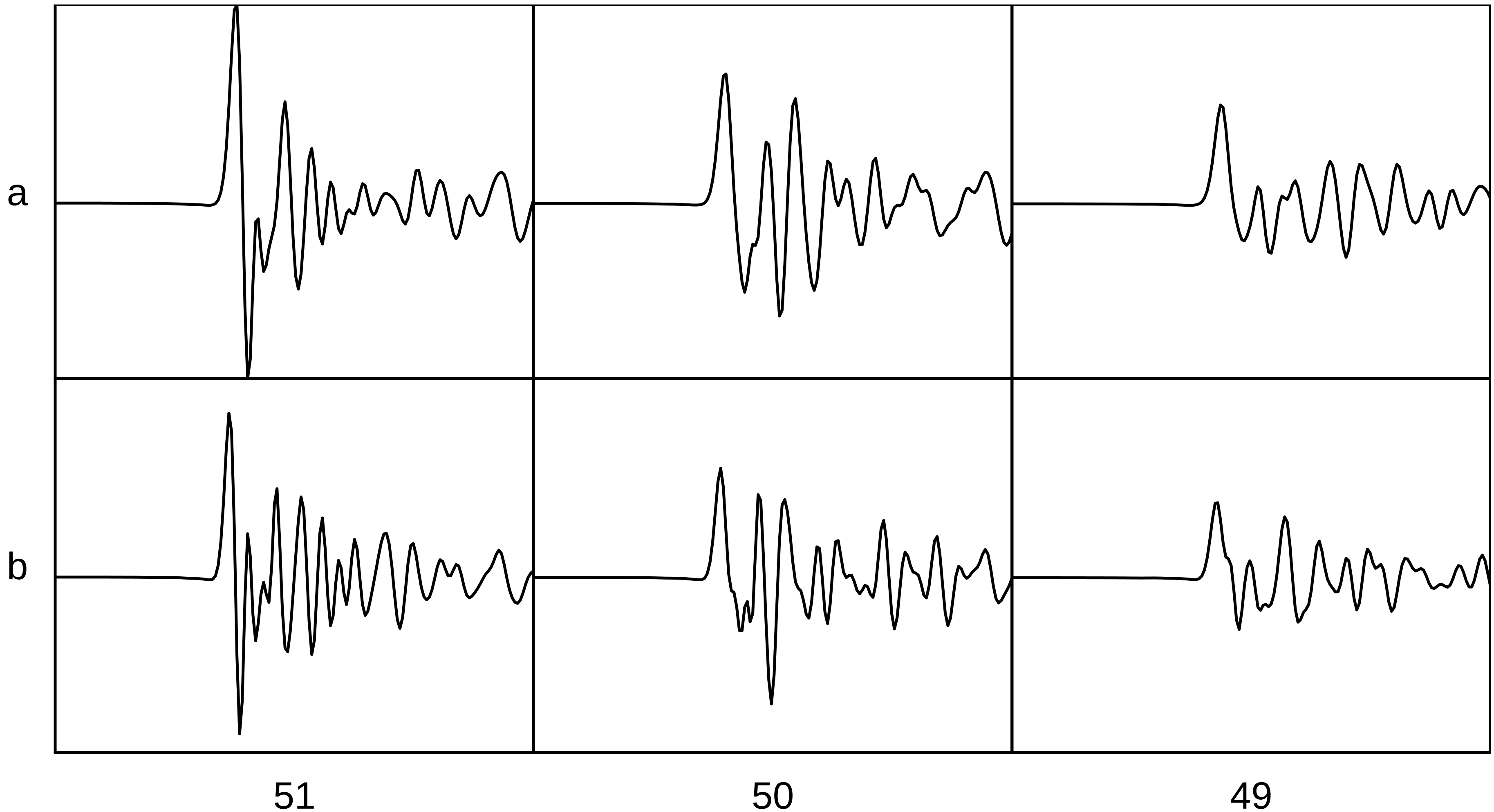
Creation of Tsunamis and Wave Heights: I

- unit source series describe what a particular buoy would see from tsunami-generating event located within a particular 50 by 100 km rectangle
- can predict wave heights in open ocean near Hilo that correspond to each event from
  - SIM runs (time consuming)
  - propagation data base (easy to extract and gives results differing little from SIMs)
- in what follows, will standardize to $\alpha = 4$ (appropriate for event contained within a single 50 by 100 km rectangle)
- here are examples for DART® buoy 52402 with unit source ki050b and five unit sources adjacent to it

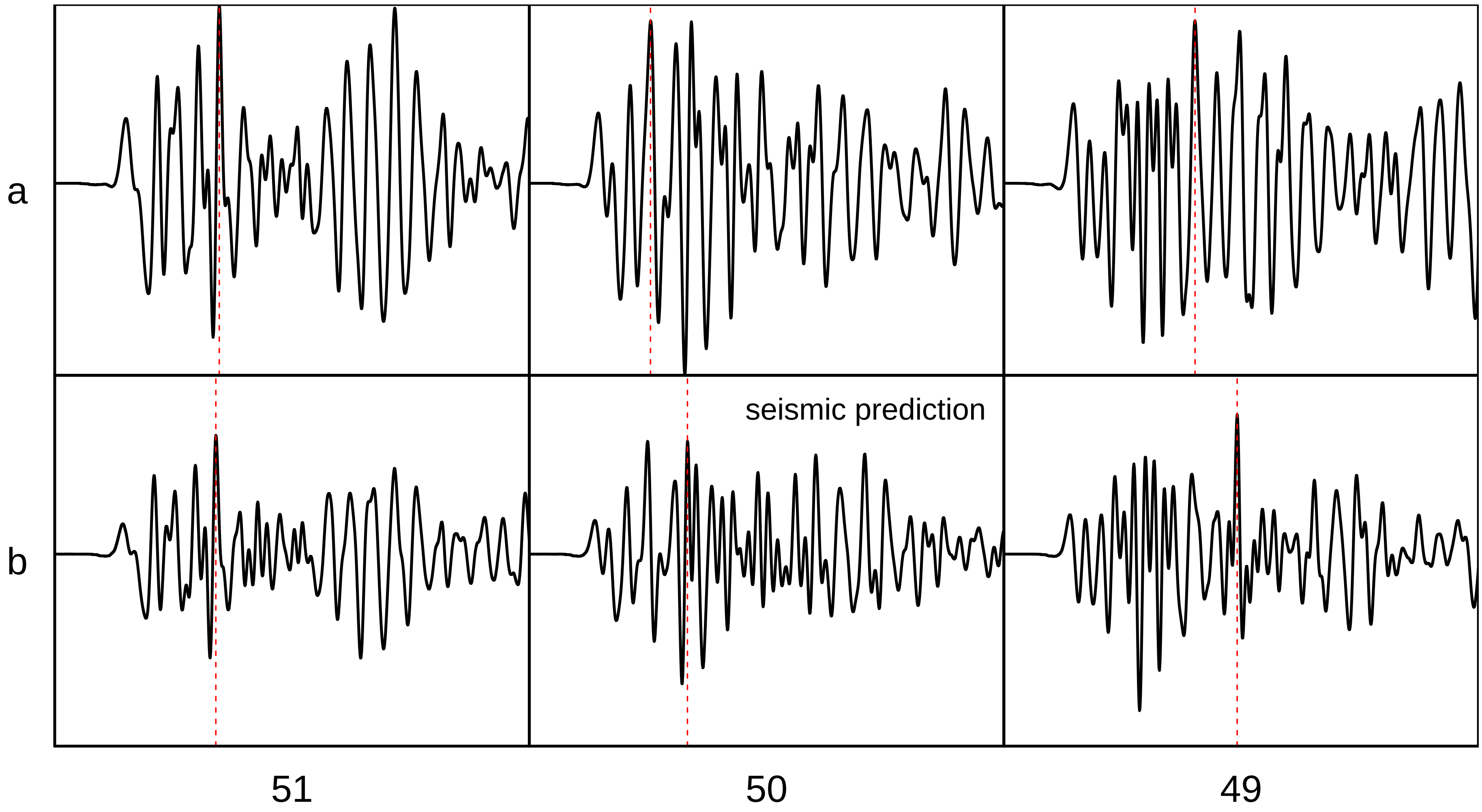
Location of DART® Buoy 52402, Unit Source ki050b



Unit Source Series for Buoy 52402 (0 to 3 hours)



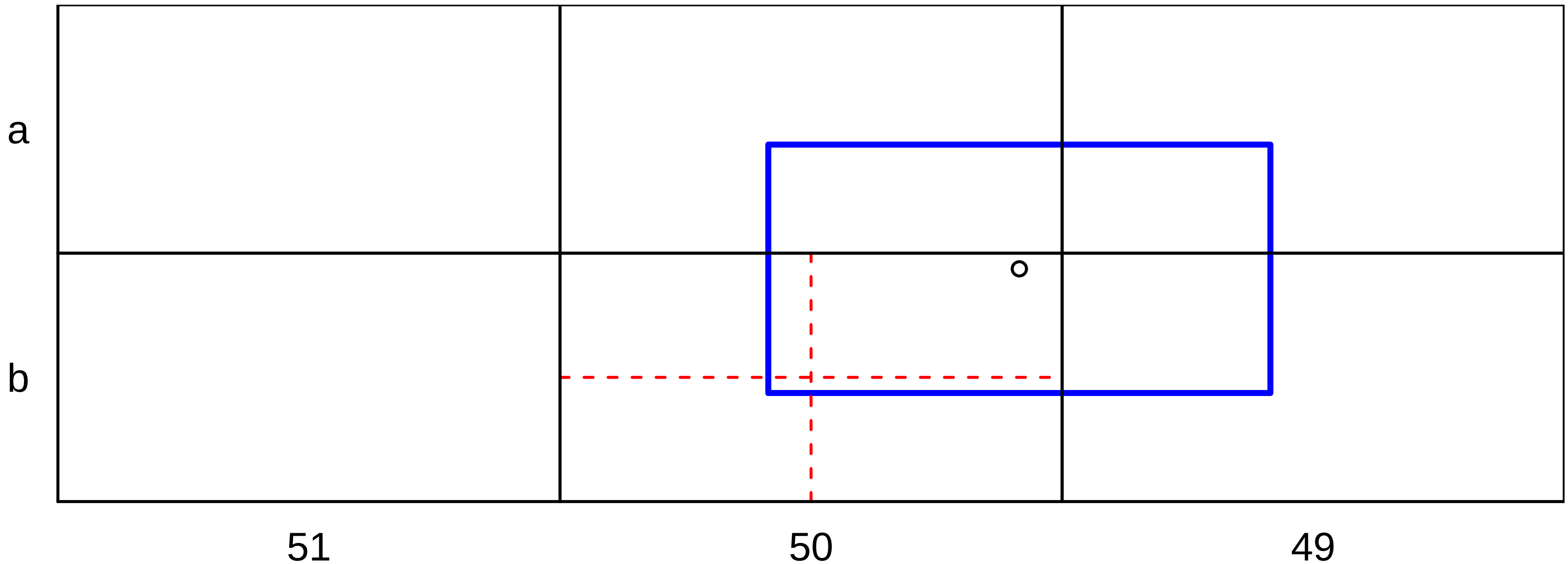
Hilo Wave Height Predictions (6.7 to 14.9 hours)



Creation of Tsunamis and Wave Heights: II

- to create a tsunami signal based on ki050b,
  - pick random location within its 50 by 100 km rectangle
  - center a 50 by 100 km rectangle (divided into four quadrants) on random location
    * rectangle will cover part of ki050b rectangle (25% to 100%) and typically one or three adjacent rectangles, depending on which quadrant random location falls into
  - spread $\alpha = 4$ amongst six possible unit sources commensurate with area covered by randomly placed rectangle
  - use spread to create linear combination of unit source series
- use same α spread to create wave heights using an analogous linear combination (note: critical assumption of linearity!)

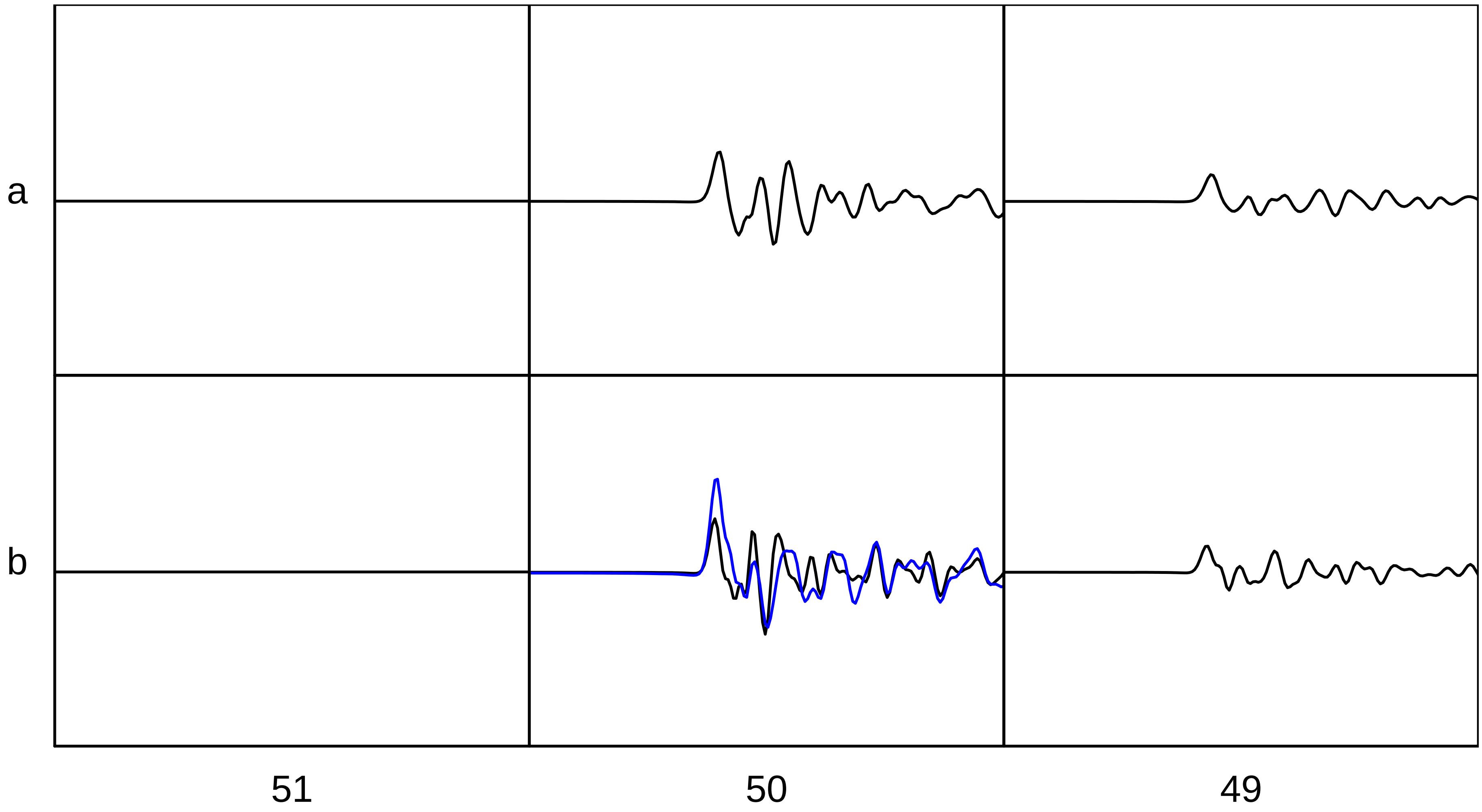
First Random Pick within ki050a (Quadrant #1)



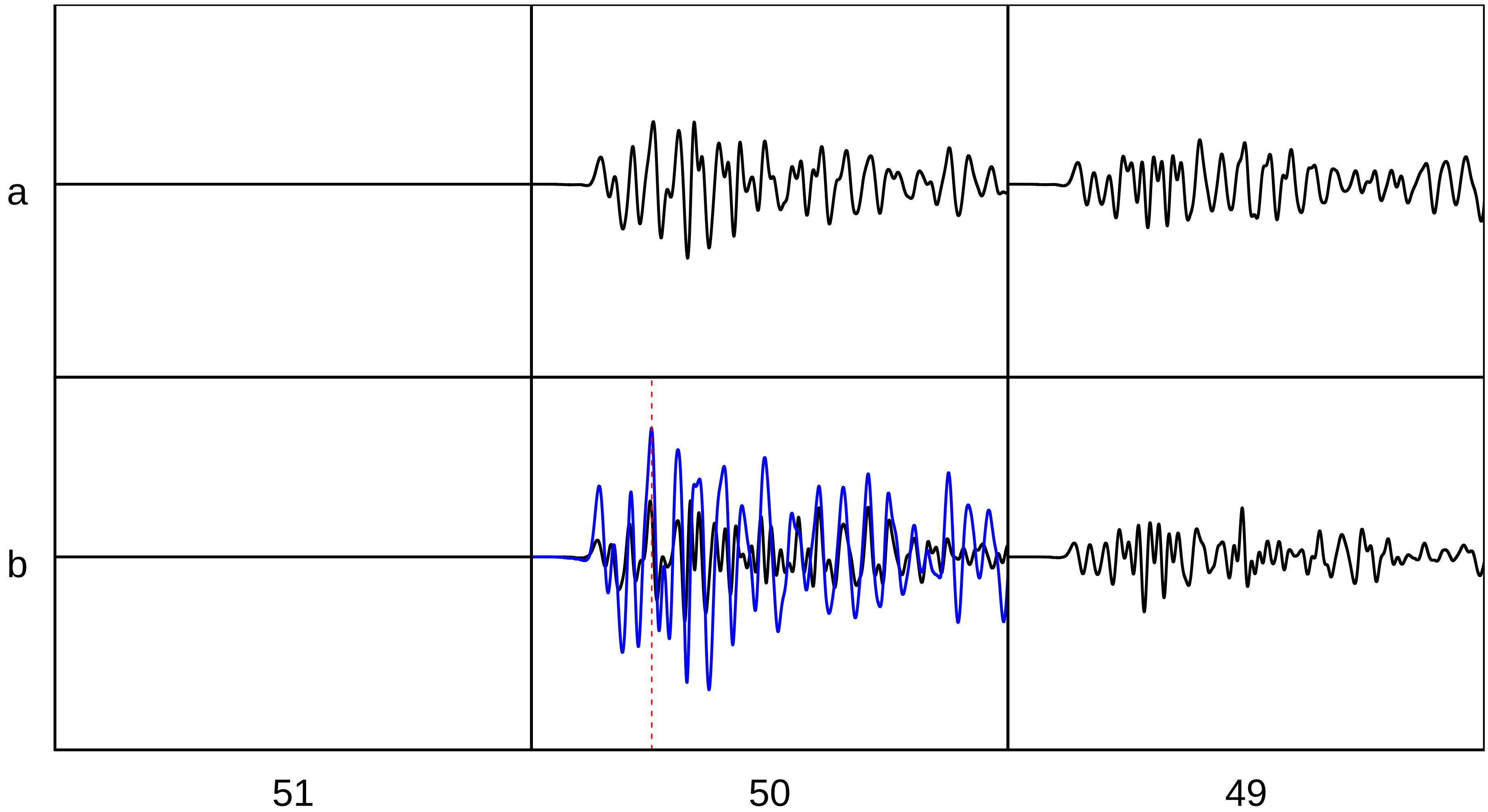
Spreading of $\alpha = 4$ Amongst Unit Sources

a	0	1.02	0.73
b	0	1.32	0.93
	51	50	49

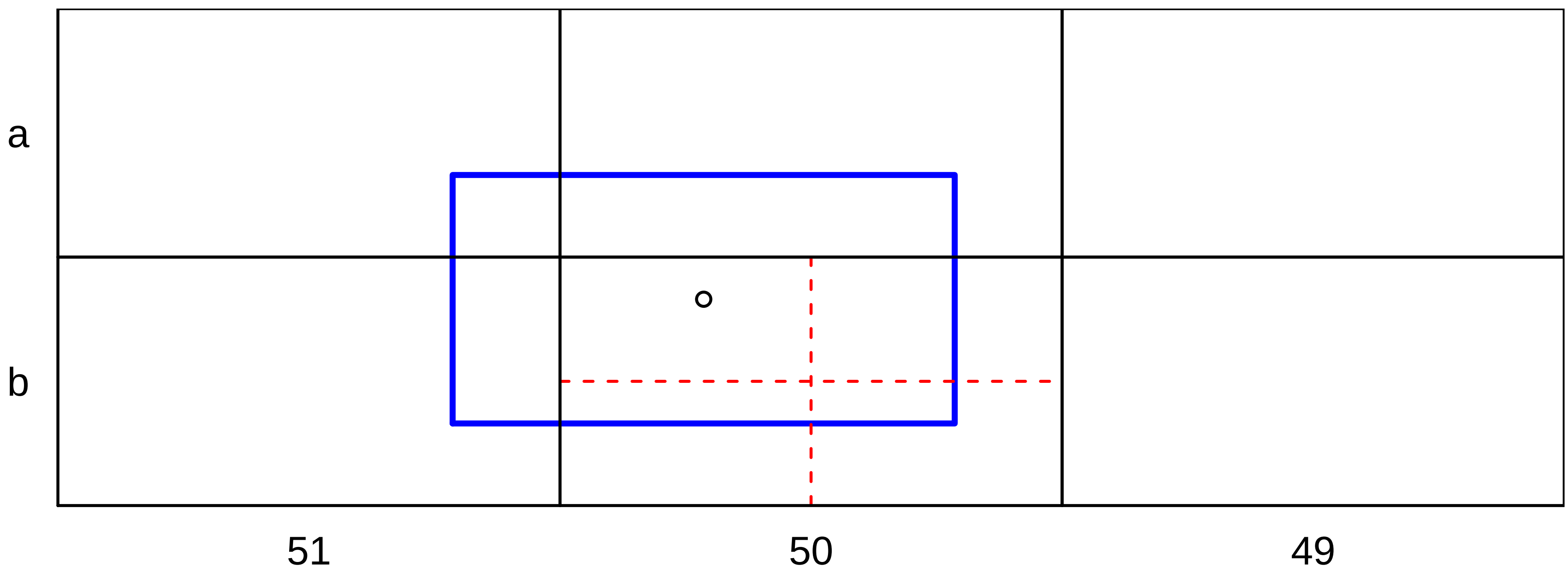
Unit Sources × α's (Black) and Composite (Blue)



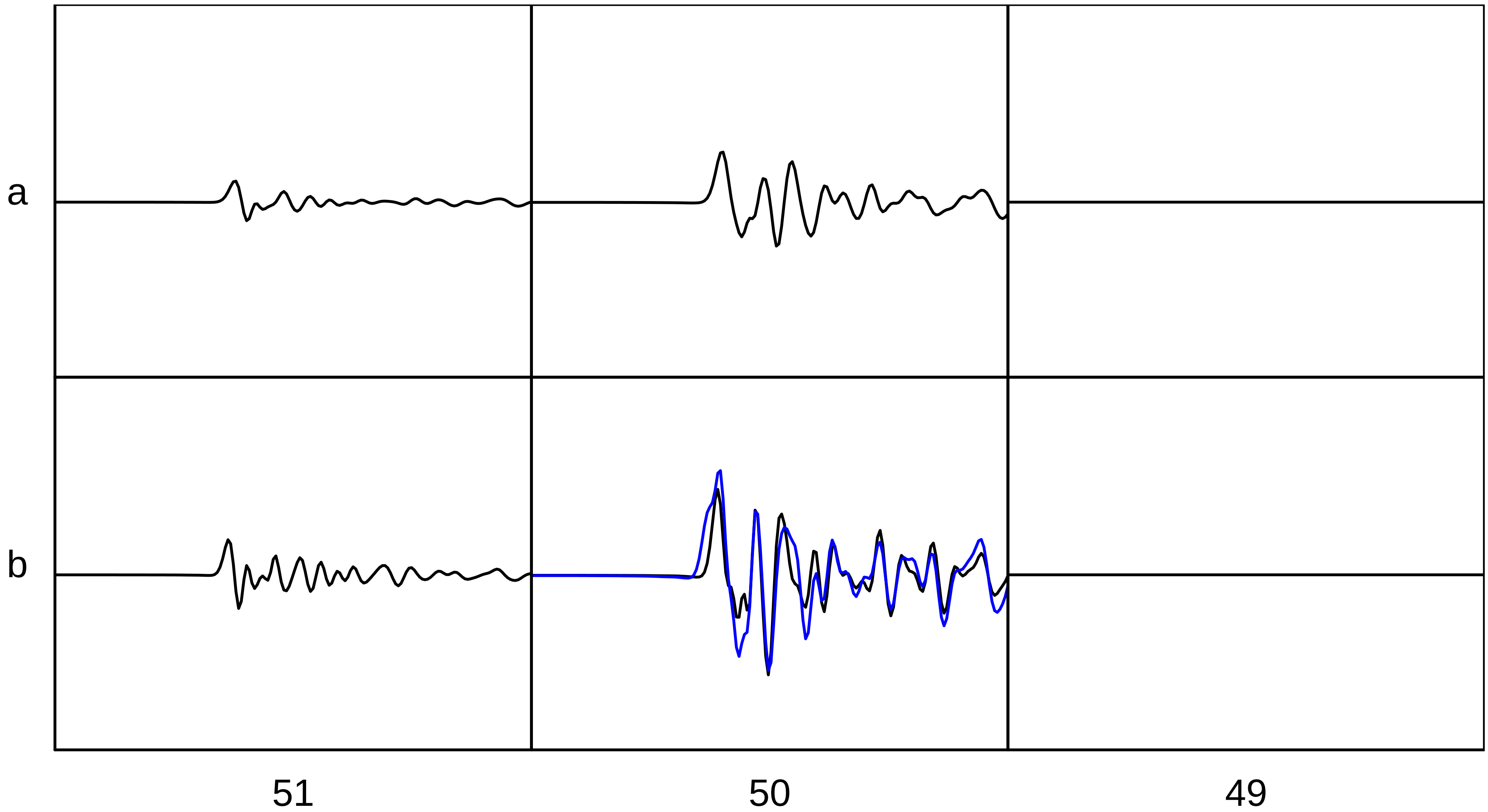
Wave Heights × α's (Black) and Composite (Blue)



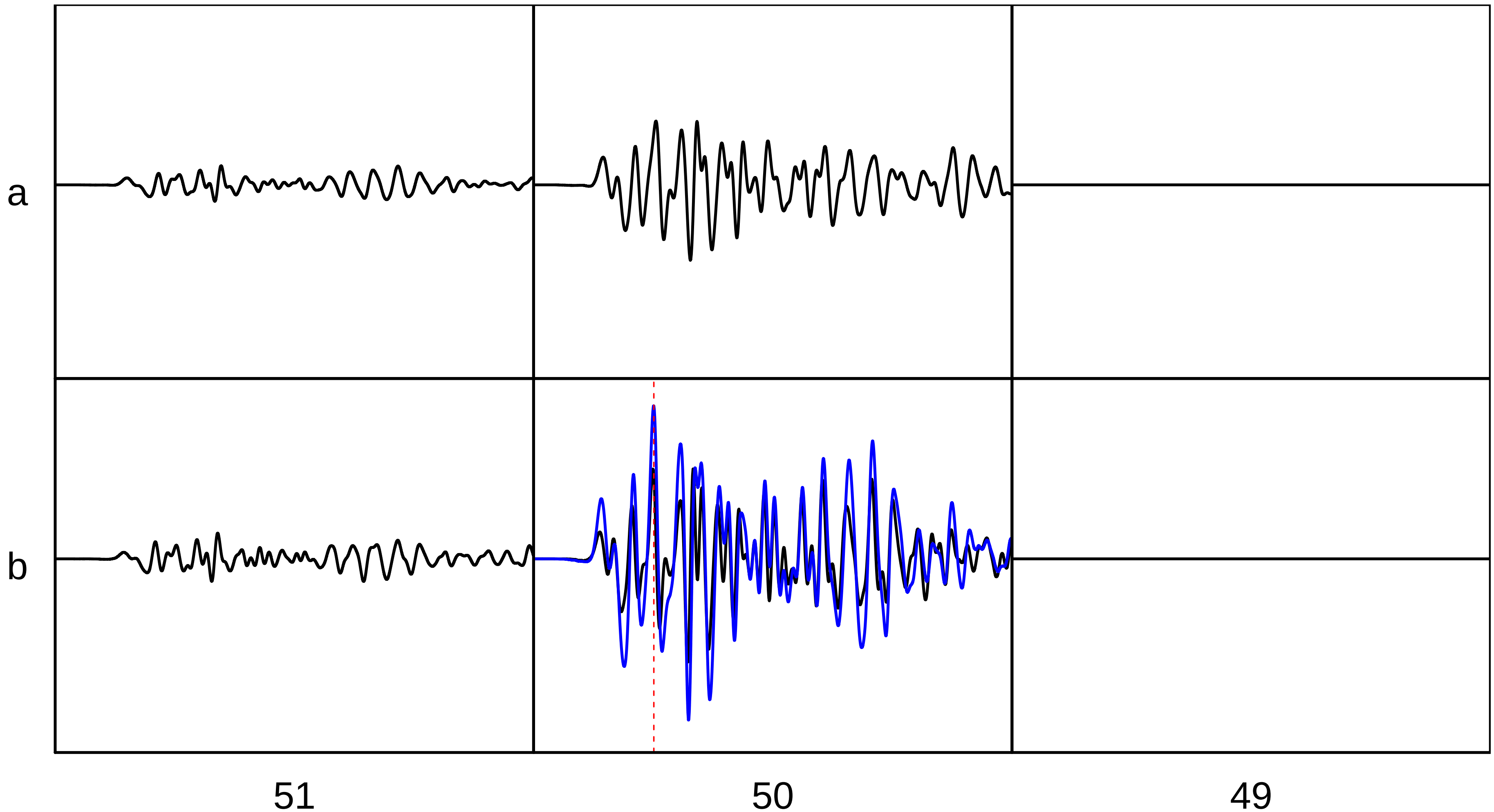
Second Random Pick within ki050a (Quadrant #2)



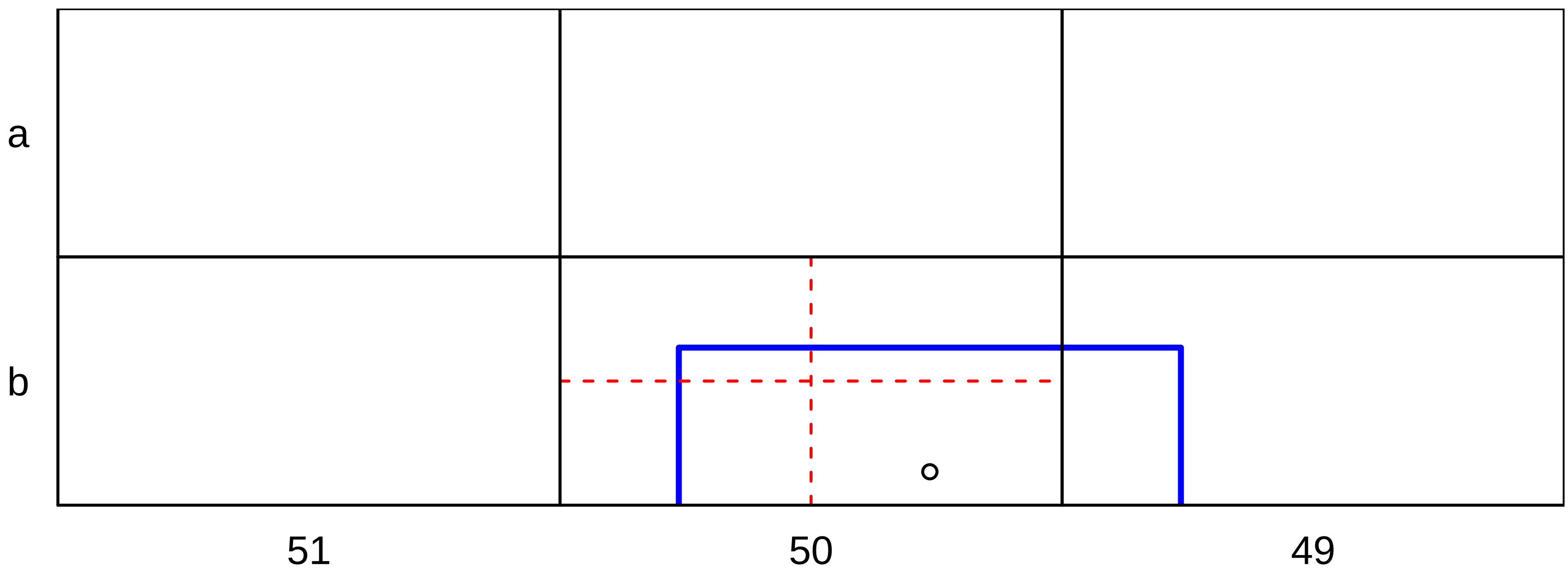
Unit Sources × α's (Black) and Composite (Blue)



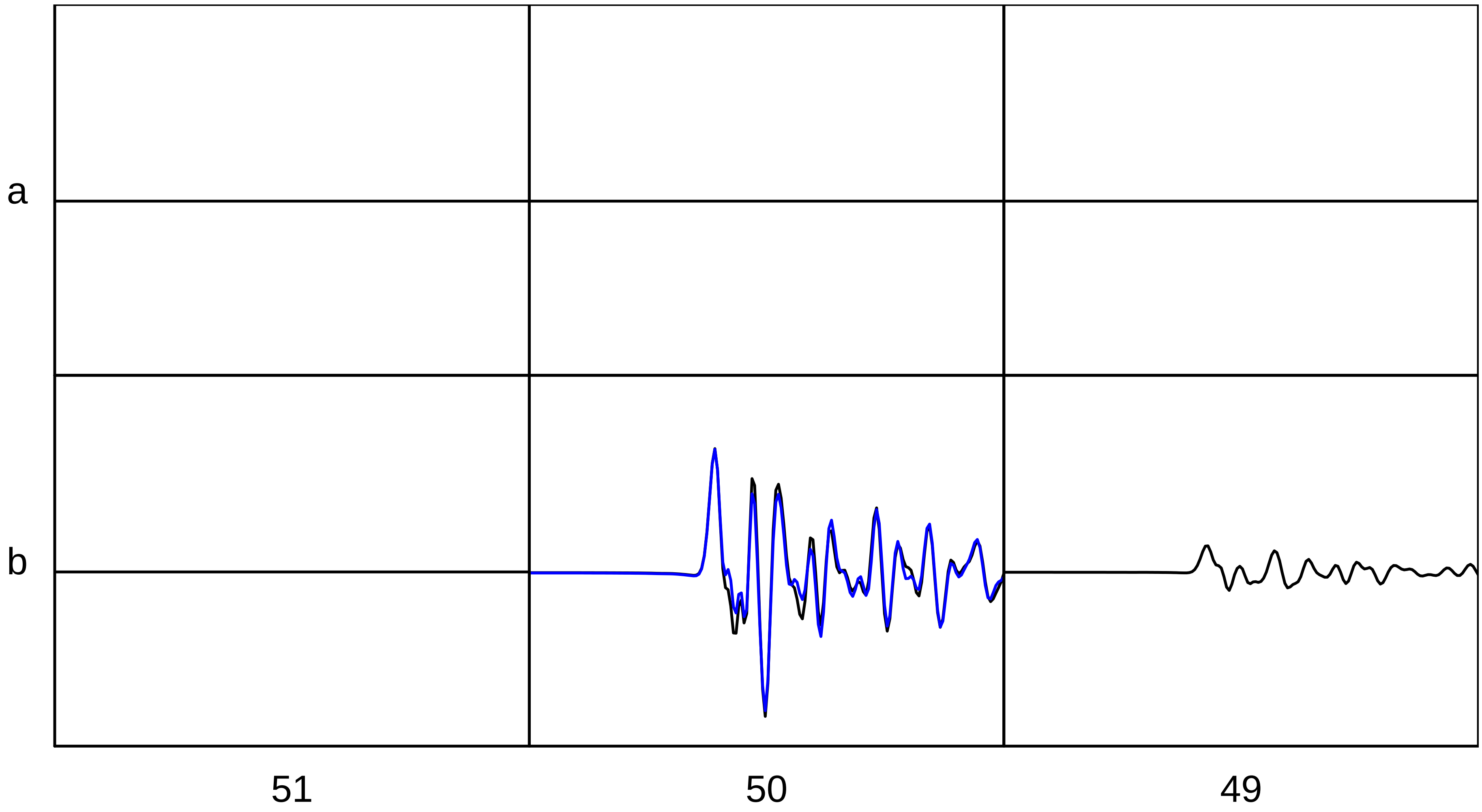
Wave Heights × α's (Black) and Composite (Blue)



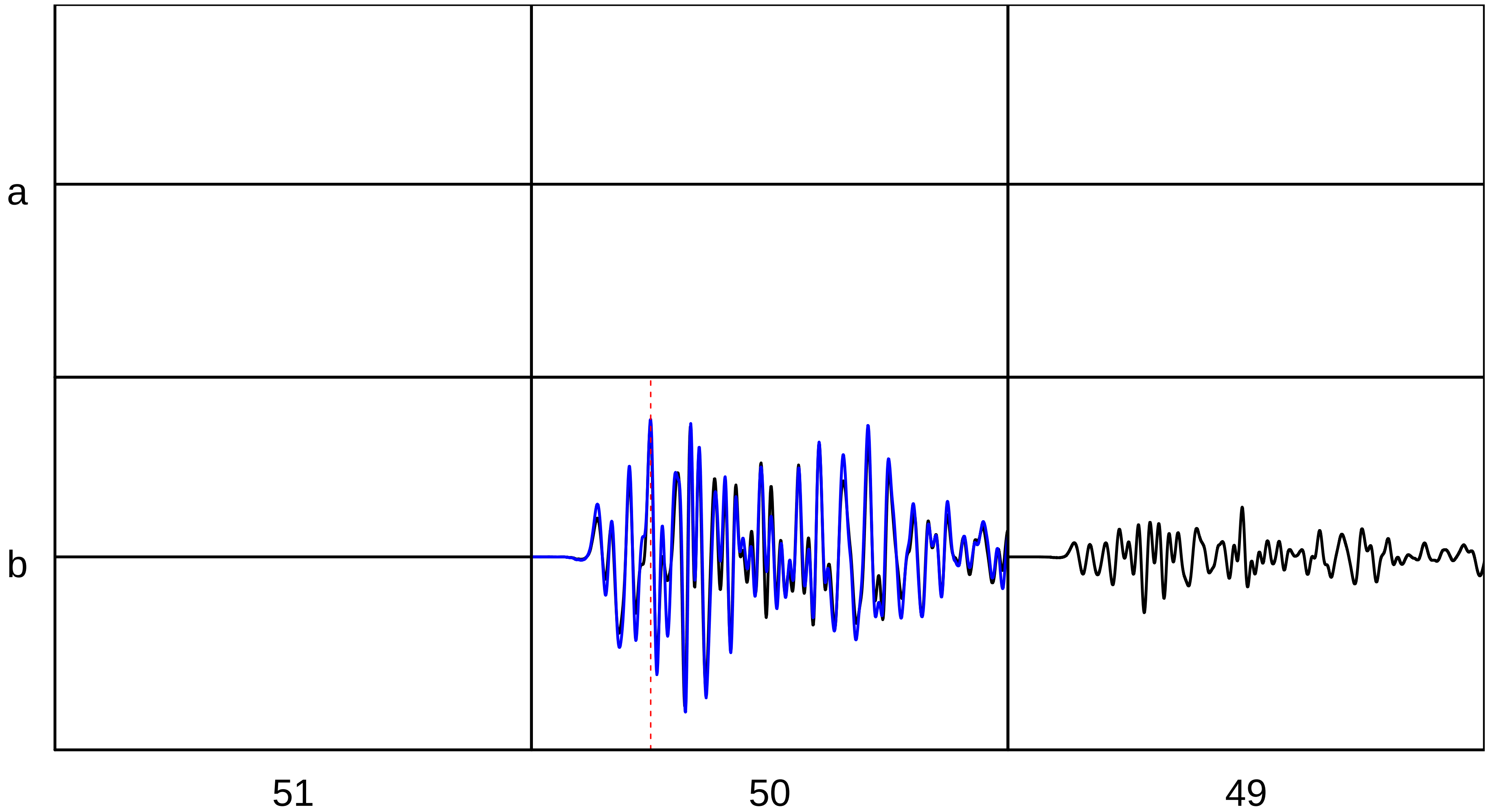
Third Random Pick within ki050a (Quadrant #4)



Unit Sources × α's (Black) and Composite (Blue)



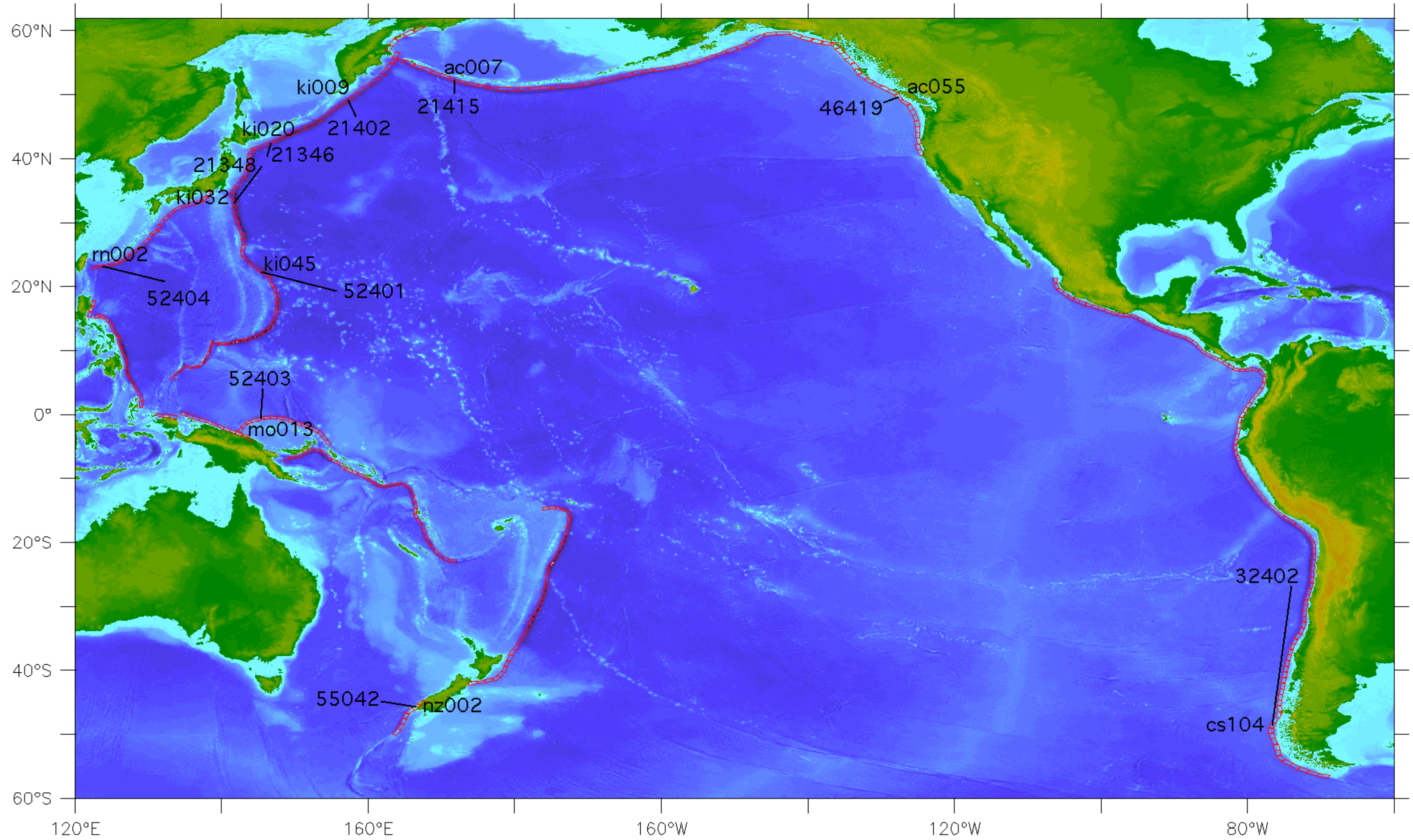
Wave Heights $\times$ α's (Black) and Composite (Blue)



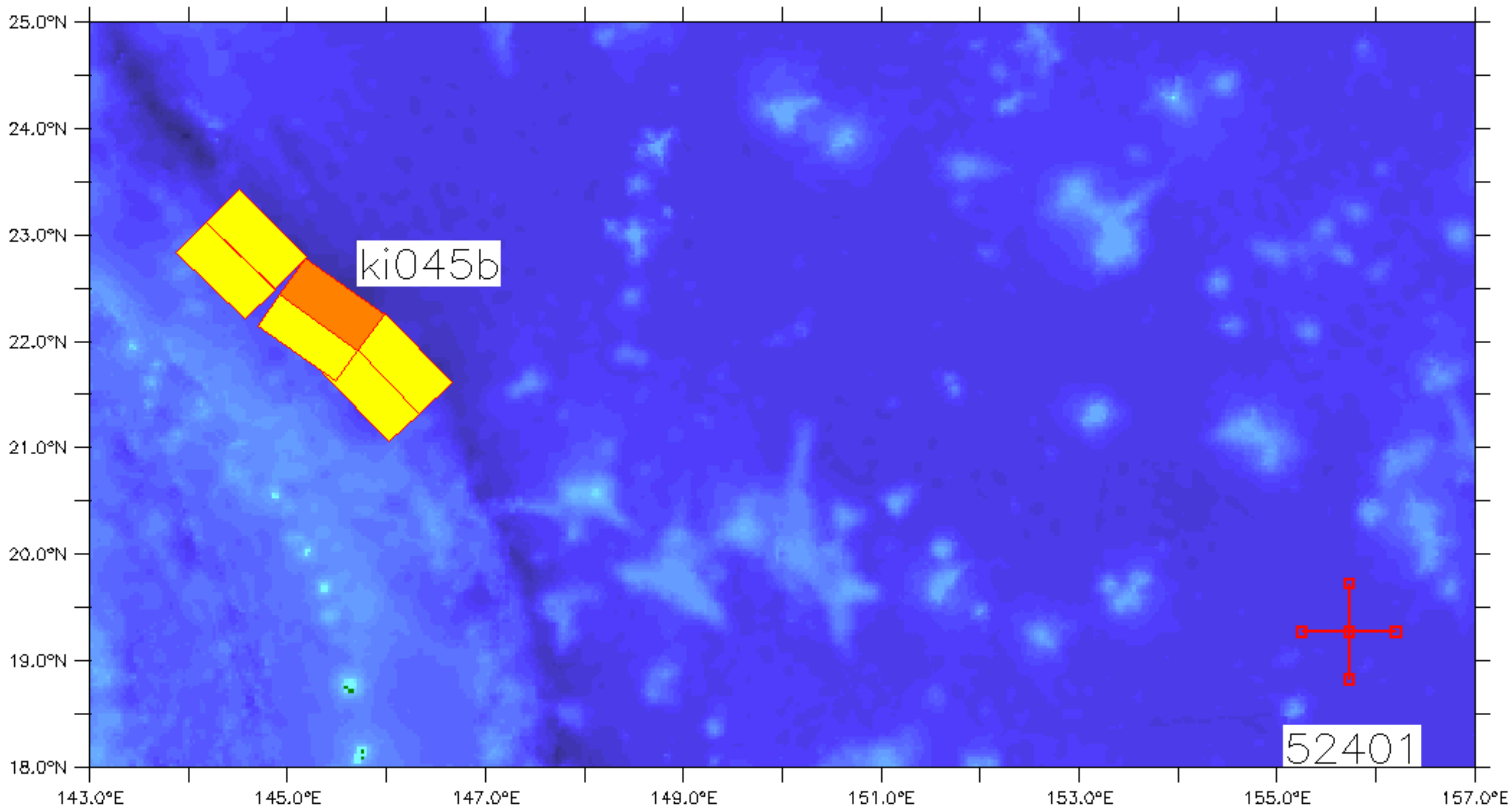
Simulation & Assessment of Hilo Wave Heights: II

- for each unit source/buoy combination, repeat basic simulation scheme 1000 times using
  - 1000 different tsunami signals
  - 1000 random selections from data recorded by DART® buoy or – if need be – by surrogate
- for each repetition, estimate α's by fitting joint linear model for tides and tsunami signal using
  - amounts of data varying from up to 60 minutes prior to first 1/4 wave in tsunami signal to either 1, 11 or 21 minute(s) beyond first 1/4 wave
  - either 1, 2 or 4 unit sources in regression model
- use α estimates to predict maximum Hilo wave height and compare with truth (4 hour maximum power yields similar results)

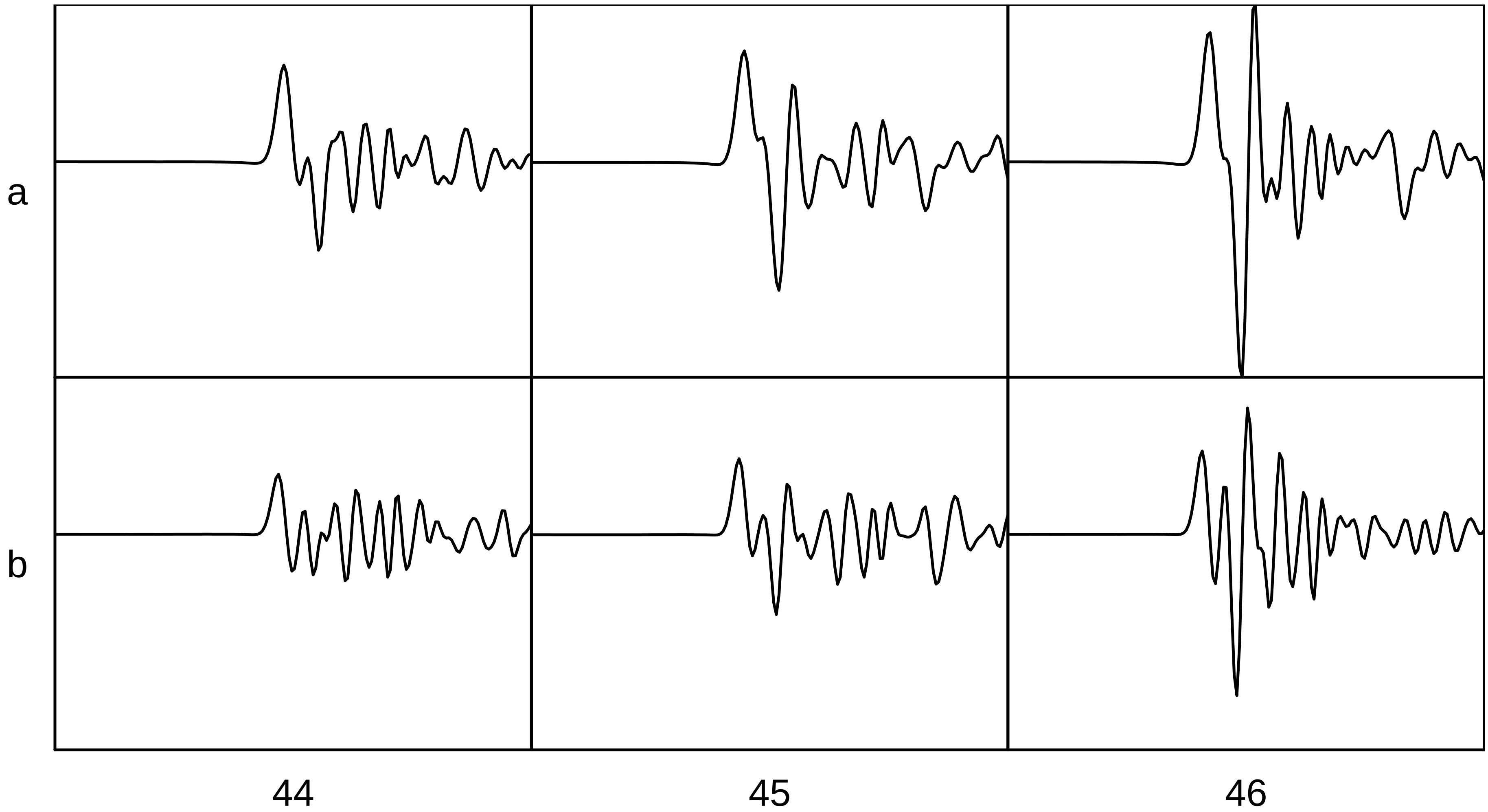
Locations of Ten Randomly Selected Unit Sources



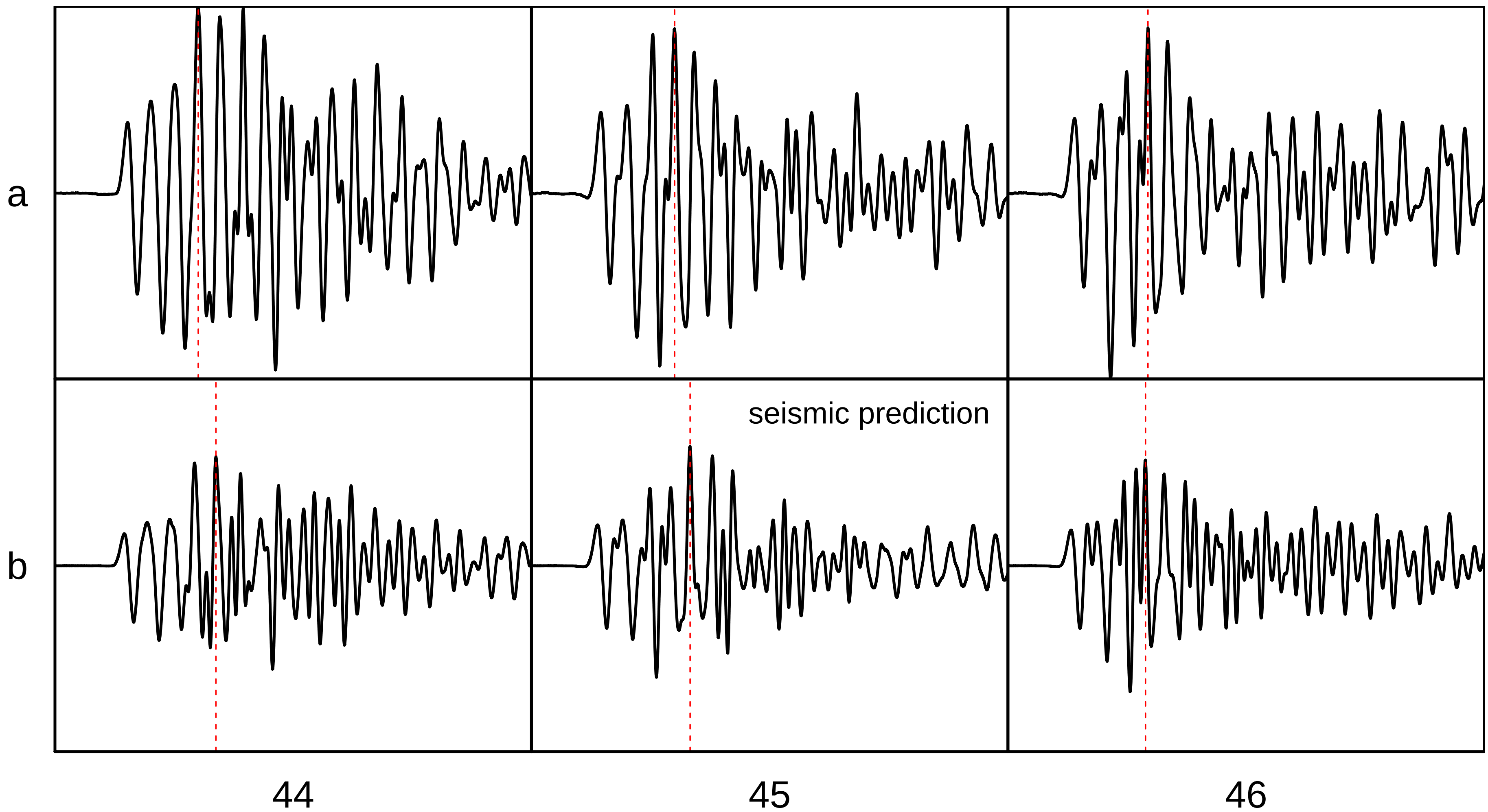
Unit Source ki045b et al. and DART® Buoy 52401

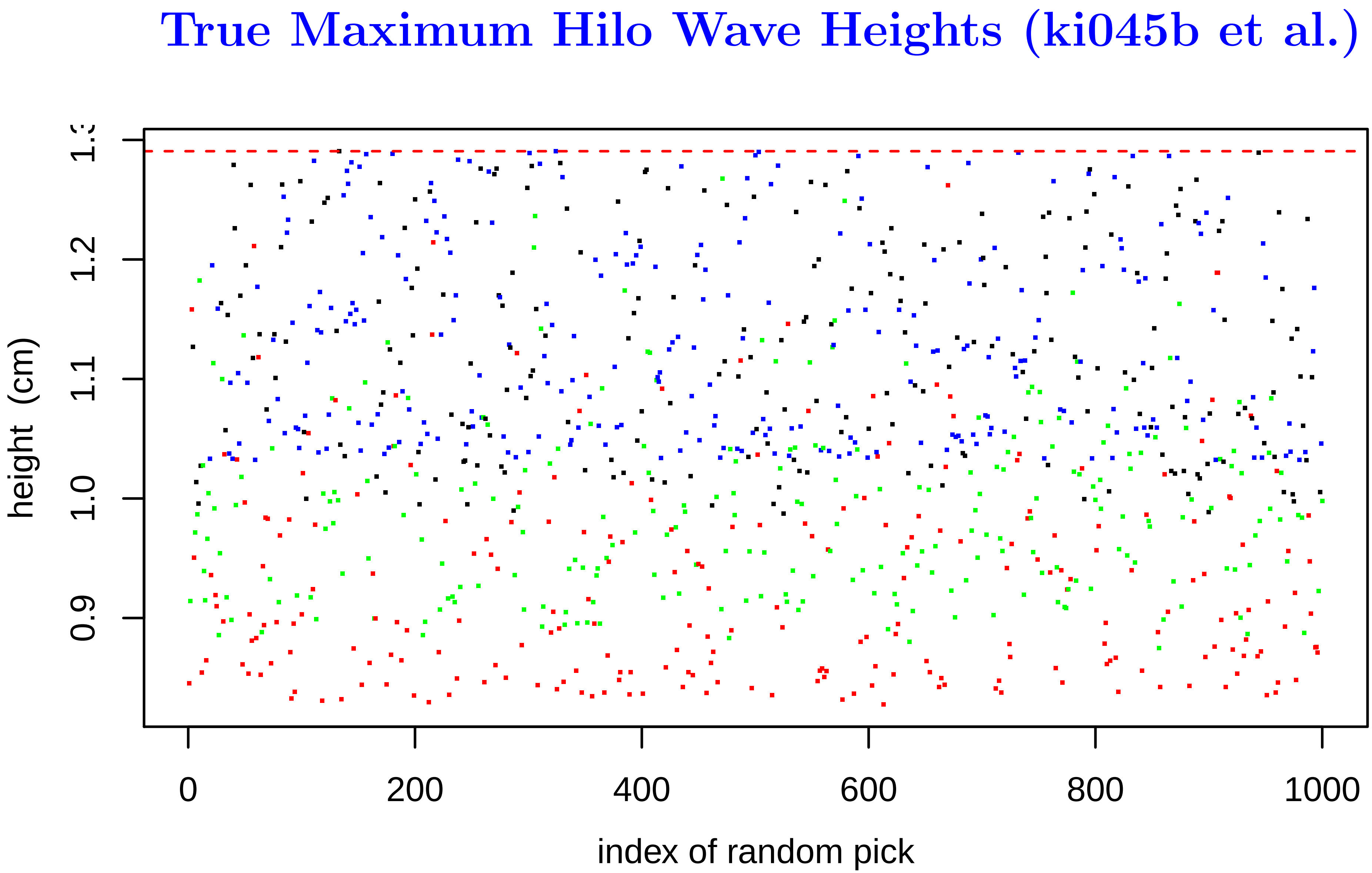


Unit Sources for Buoy 52401 (0 to 3 hours)

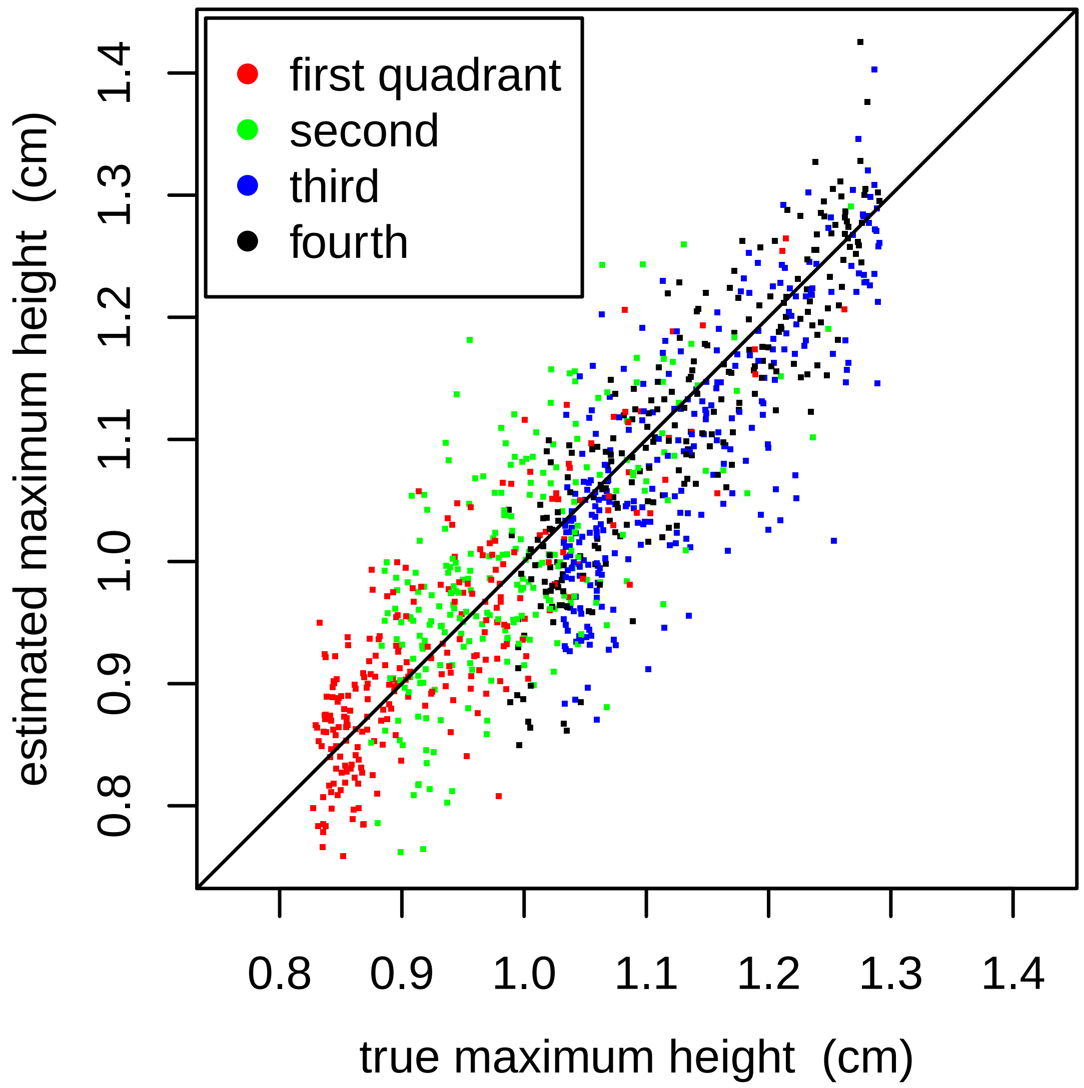


Hilo Wave Height Predictions

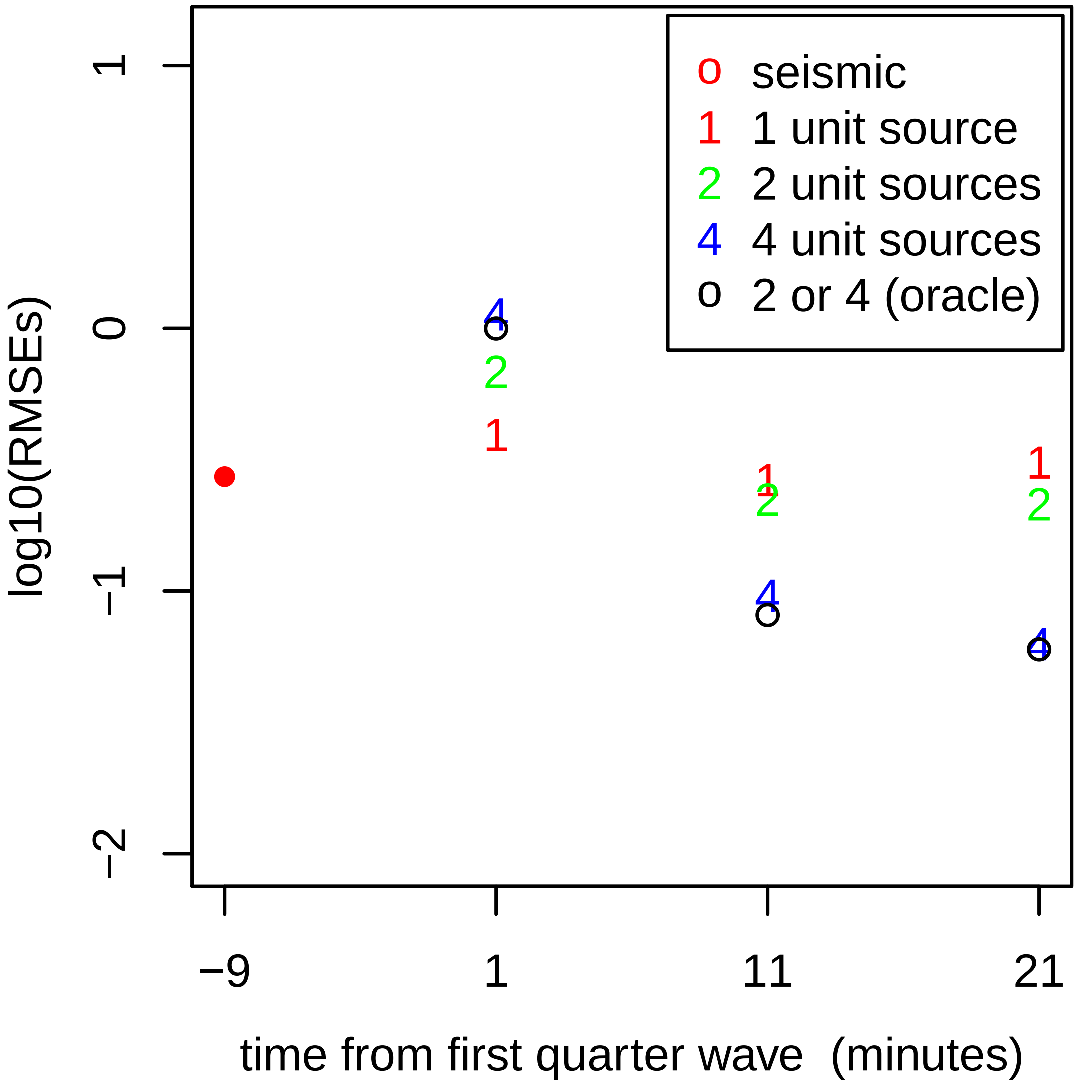



True Maximum Hilo Wave Heights (ki045b et al.)
height (cm)
0.9
1.0
1.1
1.2
1.3
0
200
400
600
800
1000
index of random pick

21 Min, 4 USs, ki045b, 52401 (52401 for noise)



RMSEs for Maximum Wave Heights



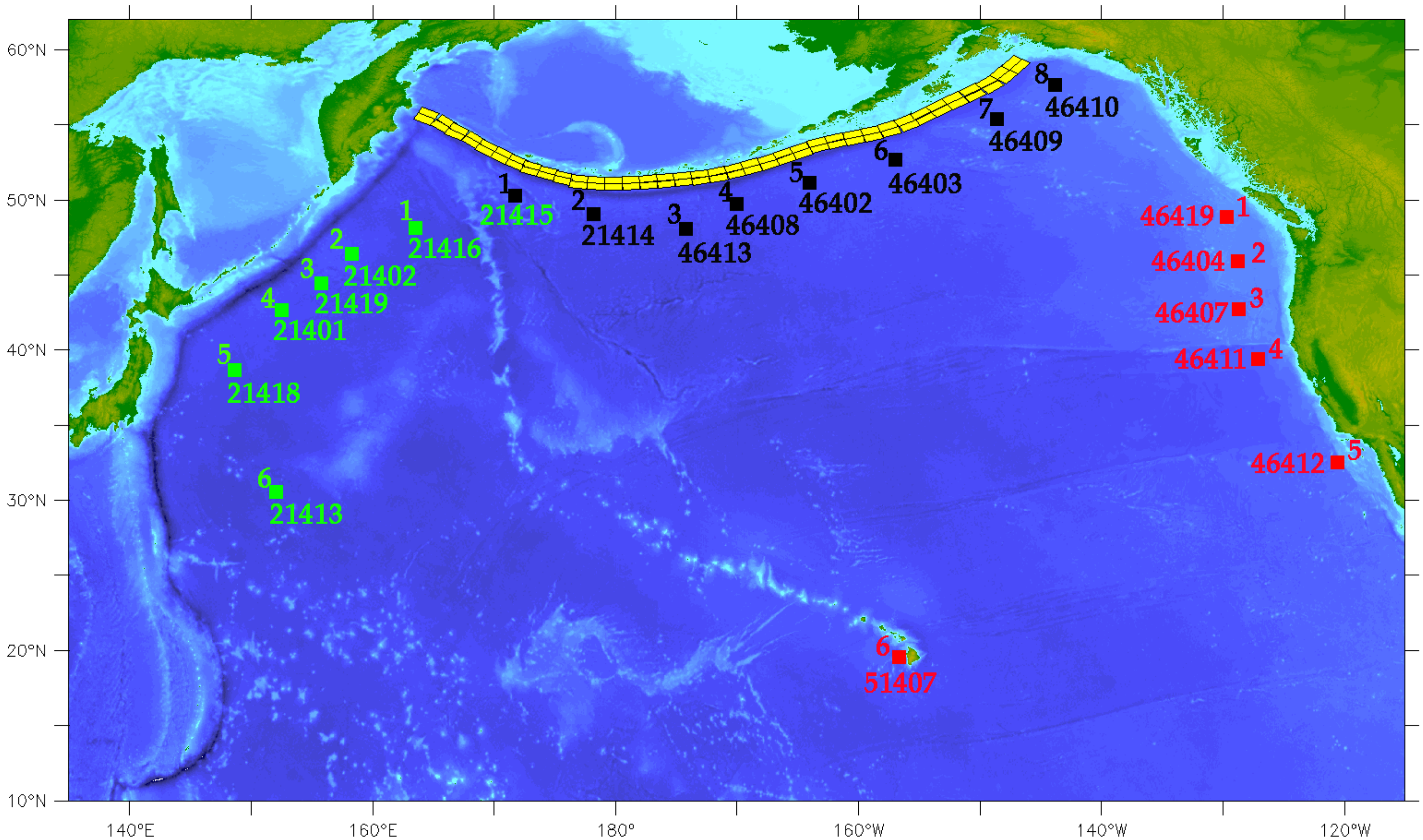
Simulation & Assessment of Hilo Wave Heights: III

- to summarize further, will now concentrate on RMSEs for 21 minutes after first 1/4 wave using regression model with 4 unit sources
  - close to best RMSE in most – but not all – cases
  - model includes correct unit sources in about 50% of cases, but two extraneous unit sources in remaining cases

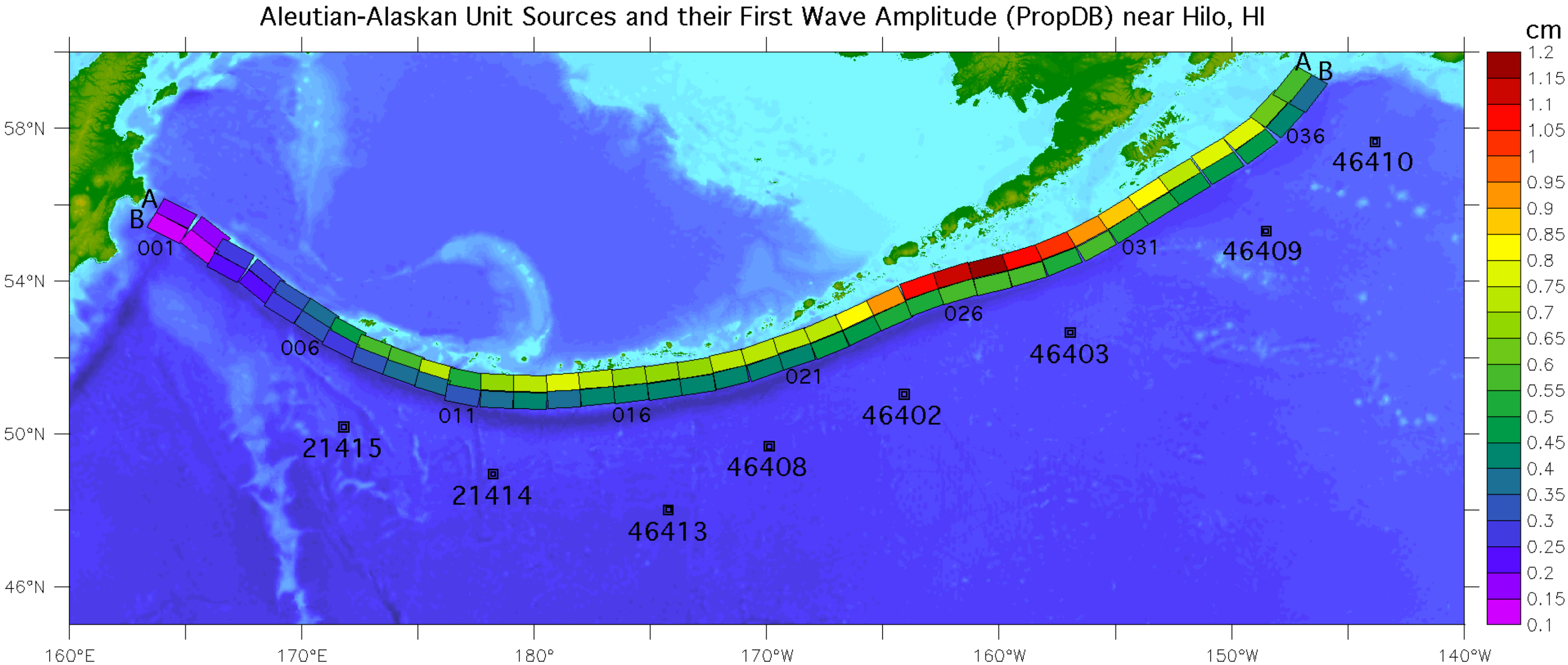
Evaluation of Aleutian Chain Unit Sources: I

- as an example, consider Aleutian chain unit sources as monitored by
  - 6 buoys to west of chain labeled by U (furtherest from chain) to Z (closest)
  - 8 along chain labeled by 1 (western-most) to 8 (eastern-most)
    - buoy 5 is 46402 – closest unit sources are ac023b & ac024b
  - 5 to east labeled by A (closest to chain) to E (furtherest)

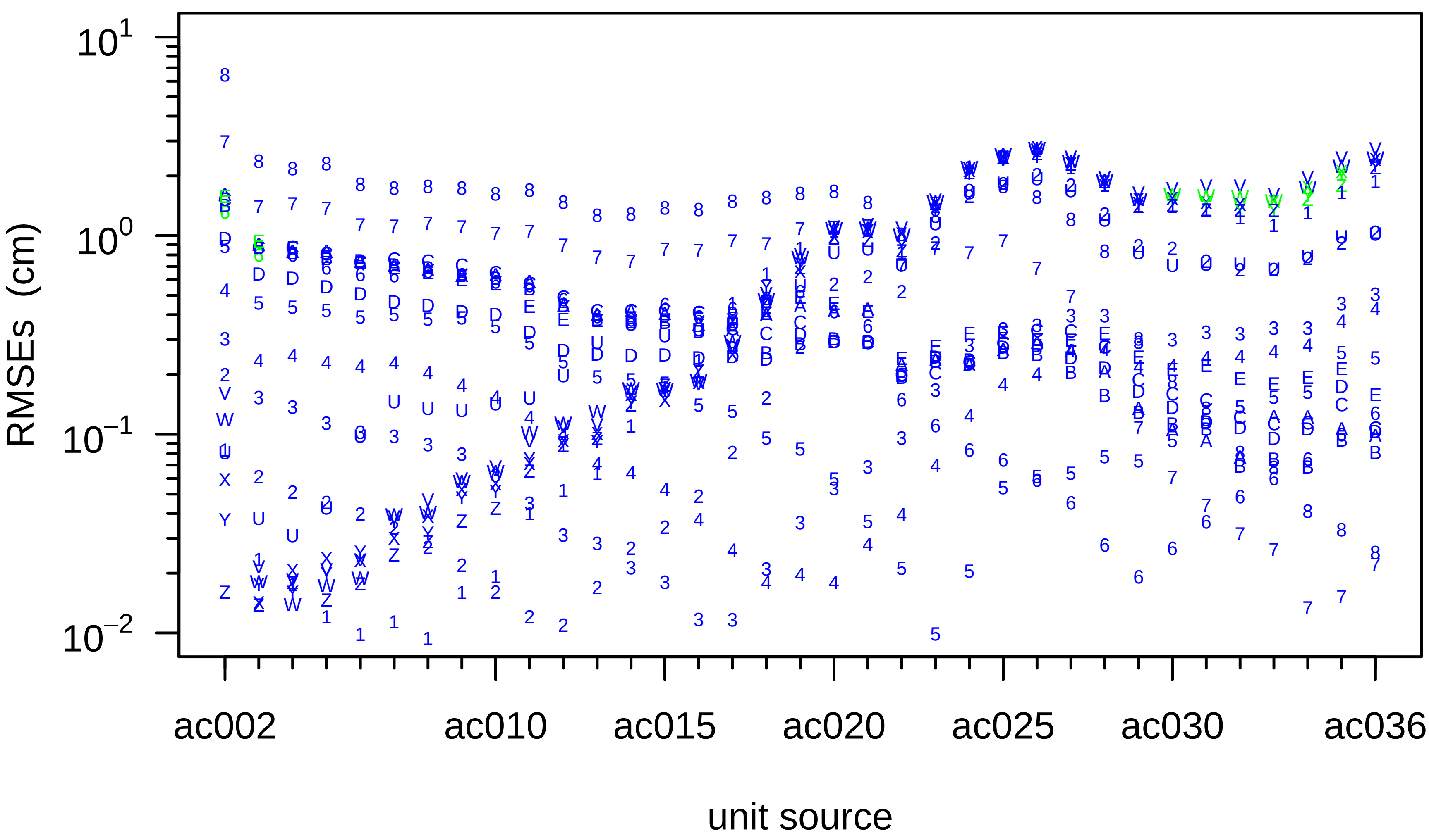
DART® Buoys East/West of Aleutian and Hilo



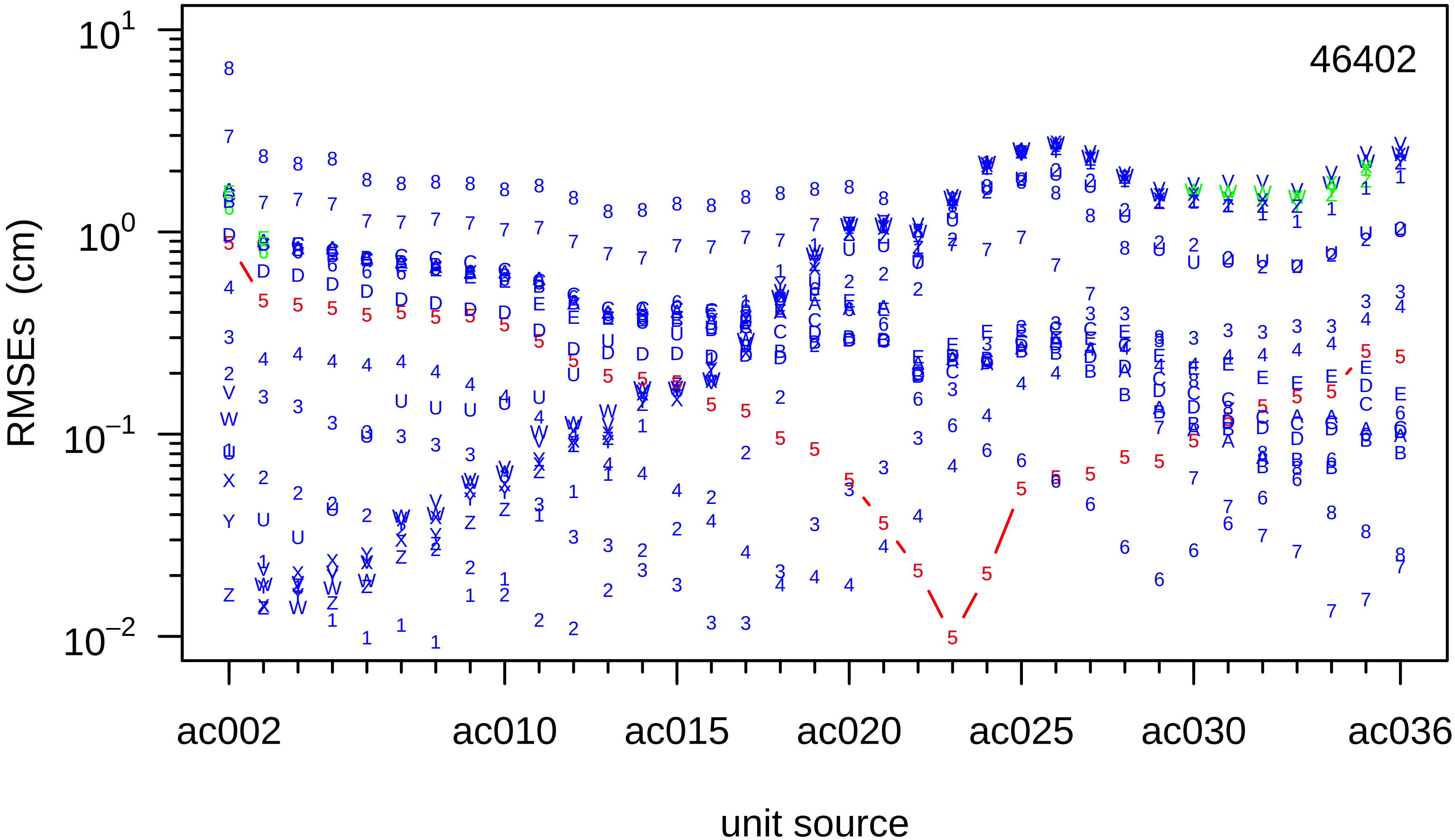
Aleutian DART® Buoys/Unit Source



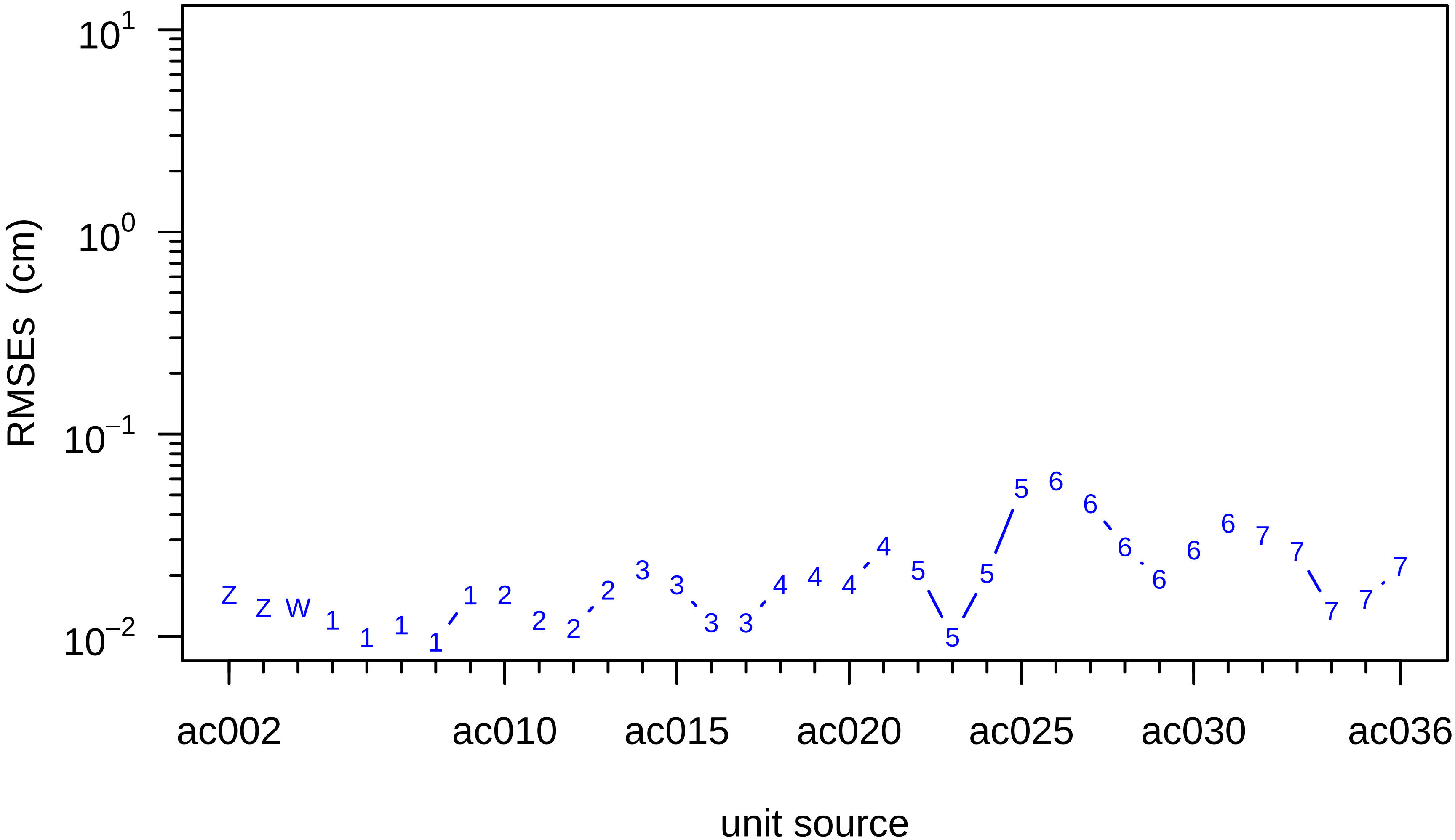
RMSEs for 35 Unit Sources

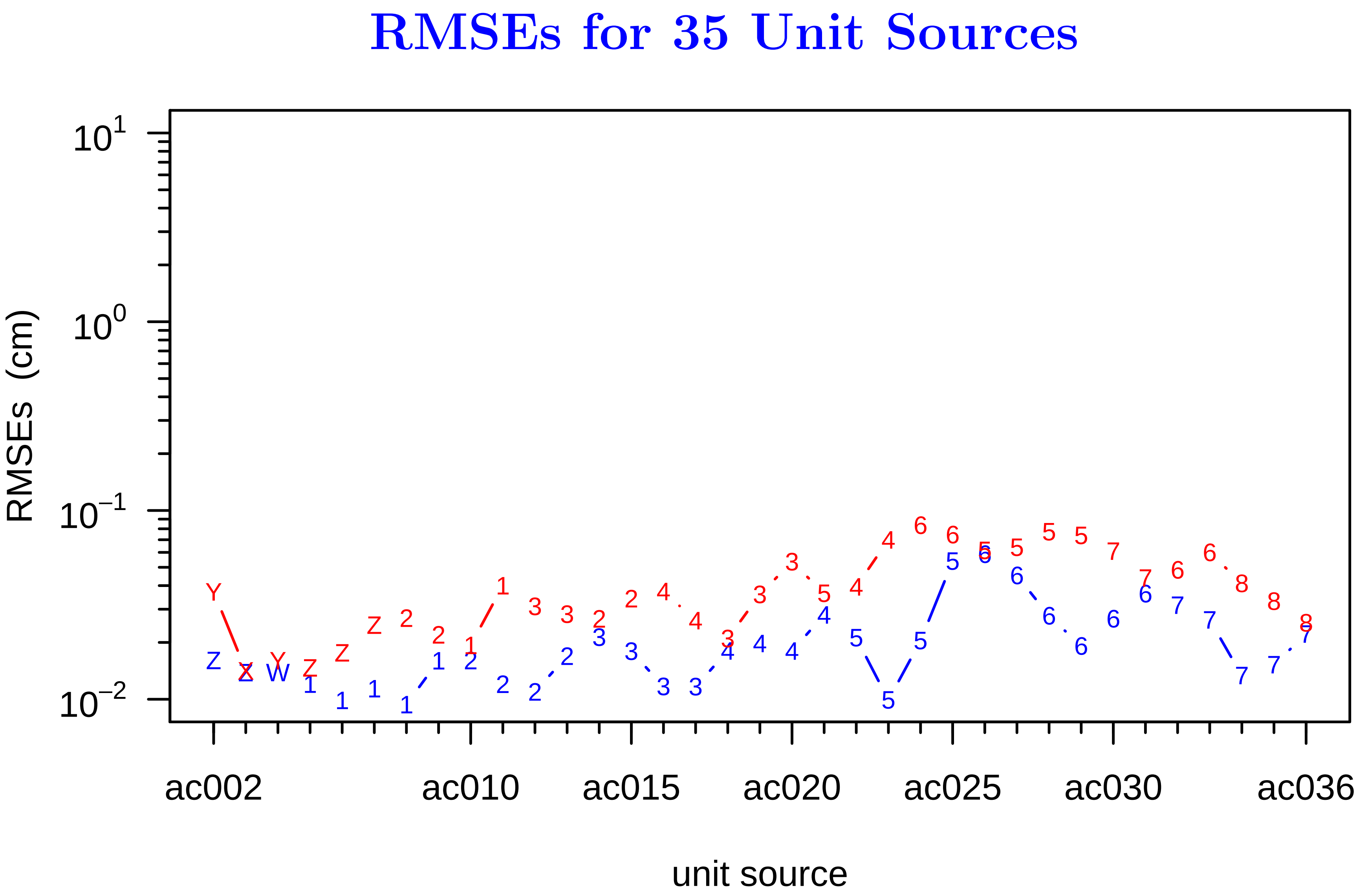


RMSEs for 35 Unit Sources



RMSEs for 35 Unit Sources

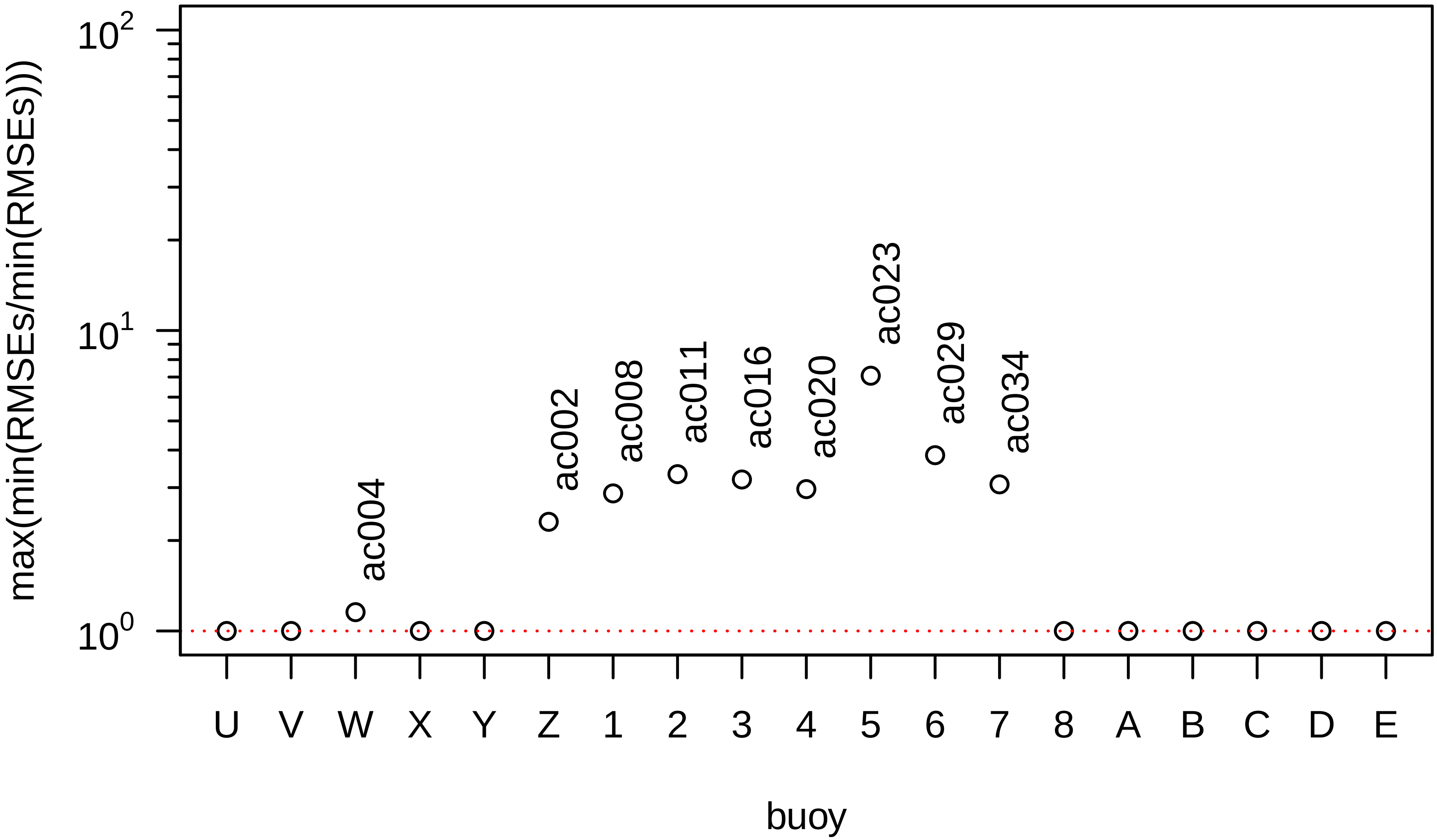



RMSEs for 35 Unit Sources
RMSEs (cm)
10^1
10^0
10^{-1}
10^{-2}
ac002
ac010
ac015
ac020
ac025
ac030
ac036
unit source

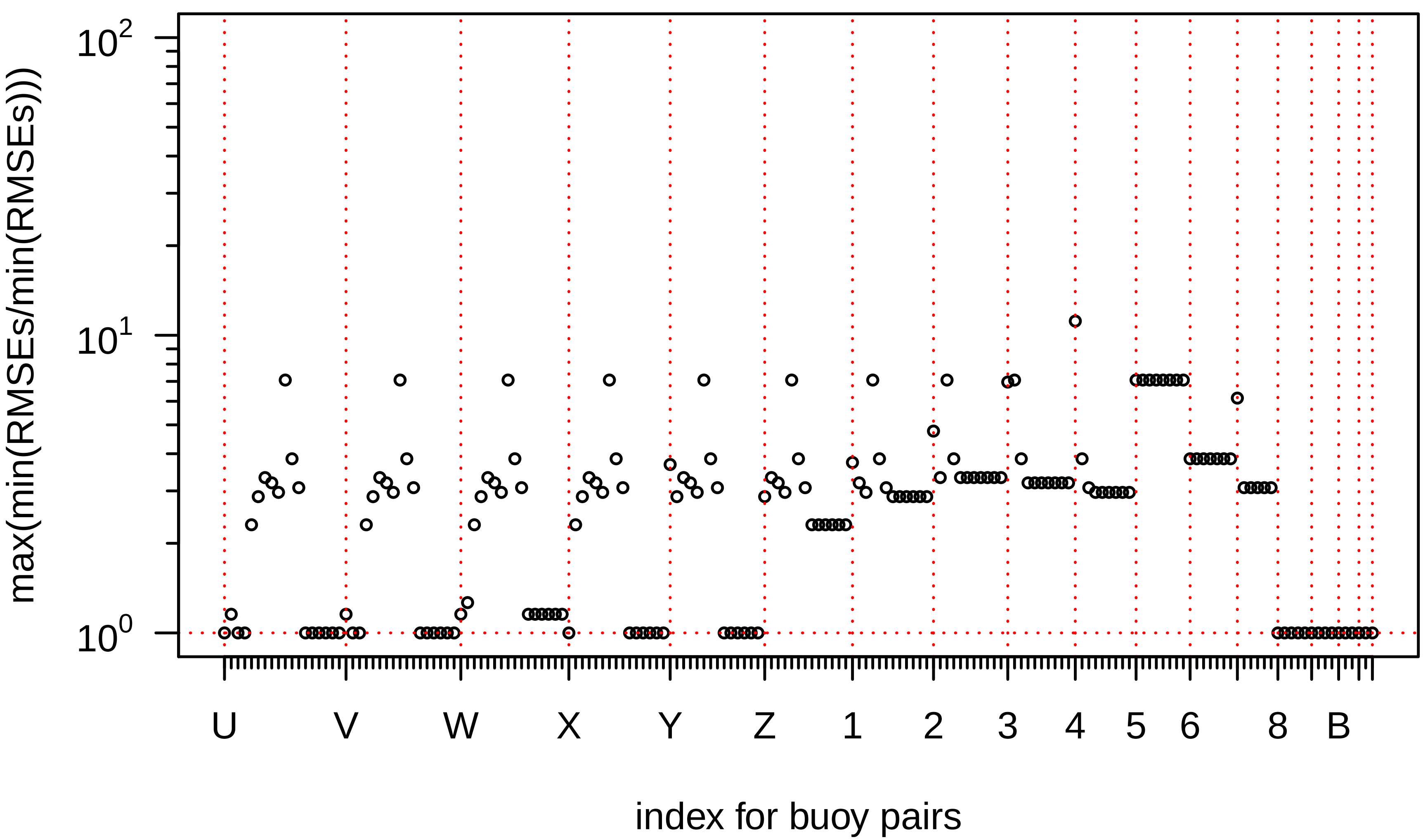
Evaluation of Aleutian Chain Unit Sources: II

- suppose now that all 19 DART® buoys are operational
- want to assess effect on prediction of wave heights if one or more buoys drops out
- can do so by considering maximum increase in RMSE over all unit sources as compare to best RMSE when all 19 DART® buoys are functional

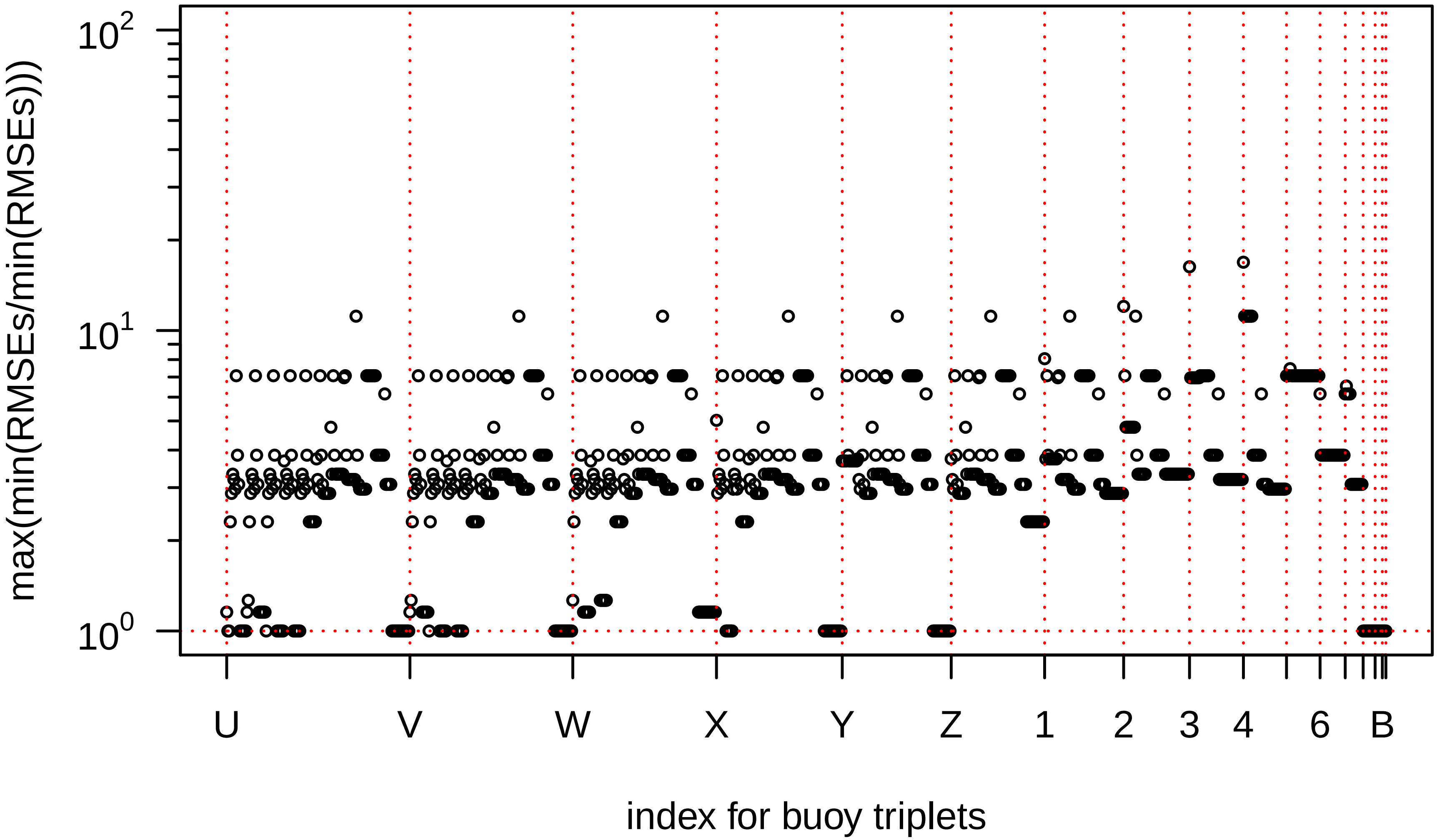
Effect of Dropout of One Buoy (19 Cases)



Effect of Dropout of Two Buoys (171 Cases)



Effect of Dropout of Three Buoys (969 Cases)



Evaluation of Aleutian Chain Unit Sources: III

- increases in RMSE *roughly* cluster around three levels:
  - close to unity: defines a green level (array is healthy)
  - 4-fold increase: defines a yellow level (array deteriorated)
  - 8-fold increase: defines a red level (serious deterioration)
- can have three buoys drop out and still have green rating for Aleutian chain (but presumably not elsewhere)
- dropout of single buoy (46402) would raise red alarm
- once a particular buoy has dropped out, can assess effect of loss of another buoy
  - addresses question: how close is array now to a red alarm?

On the 'To be Done' Plate

- look at locations other than Hilo (have looked cursorily at Port San Luis)
- evaluate unit sources besides ones along Aleutian chain (have looked at ones along southern part of South America, but eventually want to analyze all unit sources around Pacific Ocean)
- reconsider graphical presentation of results
- factor in past performance of bouys (how often has each buoy been inoperative?)

Reference

- ‘Detiding DART® Buoy Data for Real-Time Extraction of Source Coefficients for Operational Tsunami Forecasting’, by D.B. Percival, D.W. Denbo, M.C. Eblé, E. Gica, P.Y. Huang, H.O. Mofjeld, M.C. Spillane, V.V. Titov and E.I. Tolkova, *Pure and Applied Geophysics*, 2015