Comparing Higher-dimensional Velocity Models for Seismic Location Accuracy using a Consistent Travel Time Framework

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Abstract

Historically, location algorithms have relied on simple, one-dimensional (1D, with depth) velocity models for fast, seismic event locations. The speed of these 1D models made them the preferred type of velocity model for operational needs, mainly due to computational requirements. Higher-dimensional (2D-3D) seismic velocity models are becoming more readily available from the scientific community and can provide significantly more accurate event locations over 1D models. The computational requirements of these higher-dimensional models tend to make their operational use prohibitive. The benefit of a 1D model is that it is generally used as travel-time lookup tables, one for each seismic phase, with travel-time predictions pre-calculated for event distance and depth. This simple, lookup structure makes the travel-time computation extremely fast. Comparing location accuracy for 2D and 3D seismic velocity models tends to be problematic because each model is usually determined using different inversion parameters and ray-tracing algorithms. Attempting to use a different ray-tracing algorithm than used to develop a model almost always results in poor travel-time prediction compared to the algorithm used when developing the model. We will demonstrate that using an open-source framework (GeoTess, www.sandia.gov/geotess) that can easily store 3D travel-time data can overcome the ray-tracing algorithm hurdle because the lookup tables (one for each station and phase) can be generated using the exact ray-tracing algorithm that is preferred for a specified model. The lookup surfaces are generally applied as corrections to a simple 1D model and also include variations in event depth, as opposed to legacy source-specific station corrections (SSSCs), as well as estimates of path-specific travel-time uncertainty. Having a common travel-time framework used for a location algorithm allows individual 2D and 3D velocity models to be compared in a fair, consistent manner.

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Outline

- **Introduction**
- **Software used for this study**
- **Source-specific Station Corrections (SSSCs)**
- **Travel time framework**
  - 3D lookup surfaces (GeoTess)
- **Considerations for using 3D lookup surfaces for location testing**
- **Testing 3D lookup surfaces for location accuracy with the International Monitoring System (IMS) network**
  - Accuracy of tessellated grid (i.e., lookup surfaces) for travel times
  - Location comparison
- **What is needed from 3D model developers to enable comparisons**
- **Conclusions**

Introduction (1 of 2)

- **Historically, location algorithms have relied on simple, one-dimensional (1D, with depth) velocity models for fast, seismic event locations.**
  - The speed of using these 1D models made them the preferred type of velocity model for operational needs, mainly due to computational requirements.
- **Higher-dimensional (2D-3D) seismic velocity models are becoming more readily available from the scientific community and can provide significantly more accurate event locations over 1D models.**
  - The computational requirements of these higher-dimensional models tend to make their operational use prohibitive.
- **The benefit of a 1D model is that it is generally used as travel-time lookup tables, one for each seismic phase, with travel-time predictions pre-calculated for event distance and depth. This simple, lookup structure makes the travel-time computation extremely fast.**

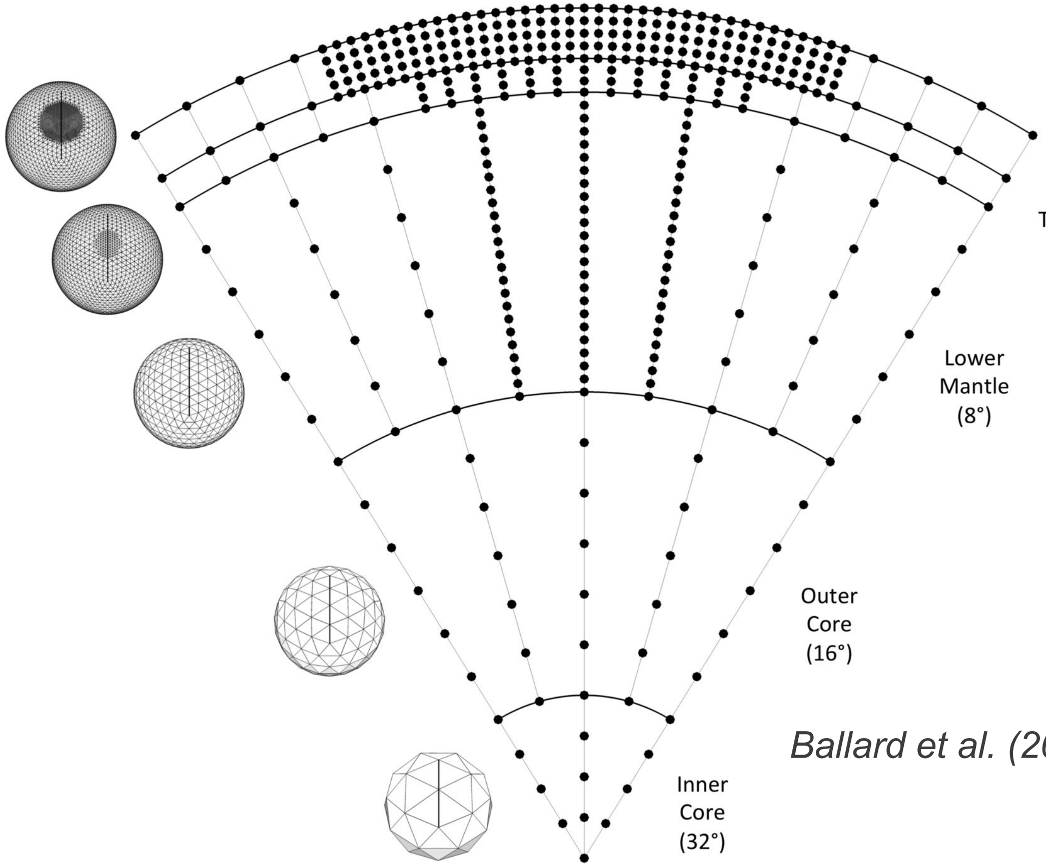
Introduction (2 of 2)

- **Comparing location accuracy for 2D and 3D seismic velocity models tends to be problematic because each model is usually determined using different inversion parameters and ray-tracing algorithms.**
  - Attempting to use a different ray-tracing algorithm than used to develop a model almost always results in poor travel-time prediction compared to the algorithm used when developing the model (Rowe et al., 2009)
  - Populating consistent station/phase-specific lookup surfaces with the **actual predictions** from a relevant ray-tracing algorithm associated with an earth model removes an inconsistency that can lead to problems comparing 3D models used for travel-time prediction
- **Using a 3D, travel-time framework would enable fair and consistent comparisons of seismic location accuracy for various higher-dimensional velocity models.**

Rowe, C., S. Ballard, M. Begnaud, C. Young, L. Steck, and J. Hipp (2009). Validating 3D geophysical models for use in global travel-time calculation for improved event locations, in Proc. of the 2009 Monitoring Research Review, Tucson, Arizona, 408-415.

Open-source Gridding Software: *GeoTess*

- **GeoTess (www.sandia.gov/geotess)**
  - A GeoTess model (Ballard et al., 2016a) is comprised of 2D triangular tessellations of a unit sphere with 1D radial arrays of nodes associated with each vertex of the 2D tessellations. Variable spatial resolution in both geographic and radial dimensions is supported.
  - Can store any spatially-defined values
    - *Earth models*
      - 2.5D: Regional Seismic Travel Time (RSTT) (Myers et al., 2010; Begnaud et al., 2020)
      - 3D: SALSA3D (**SA**ndia **L**o**S** **A**lamos) (Ballard et al., 2016b), other reformatted models (no loss of info)
    - *Station/Phase-Specific Travel times*
      - 3D travel-time/uncertainty lookup surfaces
      - Empirical corrections
    - *Other models/predictions*
      - Amplitude



An example of using triangular tessellations of differing resolutions to achieve variable resolution in the radial direction. Points along the radial profiles depict the positions where model parameter values are represented.

Myers, S. C., M. L. Begnaud, S. Ballard, M. E. Pasyanos, W. S. Phillips, A. L. Ramirez, M. S. Antolik, K. D. Hutchenson, G. S. Wagner, J. J. Dwyer, C. A. Rowe, and D. R. Russell (2010). A crust and upper mantle model of Eurasia and North Africa for Pn travel time calculation, *Bull. Seism. Soc. Am.* **100**, 2, 640-656.

Ballard, S., J. Hipp, B. Kraus, A. Encarnacao, and C. Young (2016a). GeoTess: A generalized earth model software utility, Seis. Res. Lett. 87, 3, 719-725, doi:10.1785/0220150222.

Ballard, S., J. Hipp, M. Begnaud, C. Young, A. Encarnacao, E. Chael, and W. S. Phillips (2016b). SALSA3D – A tomographic model of compressional wave slowness in the Earth's mantle for improved travel time prediction and travel time prediction uncertainty, Bull. Seism. Soc. Am. 106, 6, doi:10.1785/0120150271.

Begnaud, M. L., S. C. Myers, B. Young, J. R. Hipp, D. Dodge, and W. S. Phillips (2020). Updates to the Regional Seismic Travel Time (RSTT) Model: 1. Tomography, *PAGEOPH*, in press.

Open-source Software for Relocation/Prediction: *LocOO3D, PCalc*

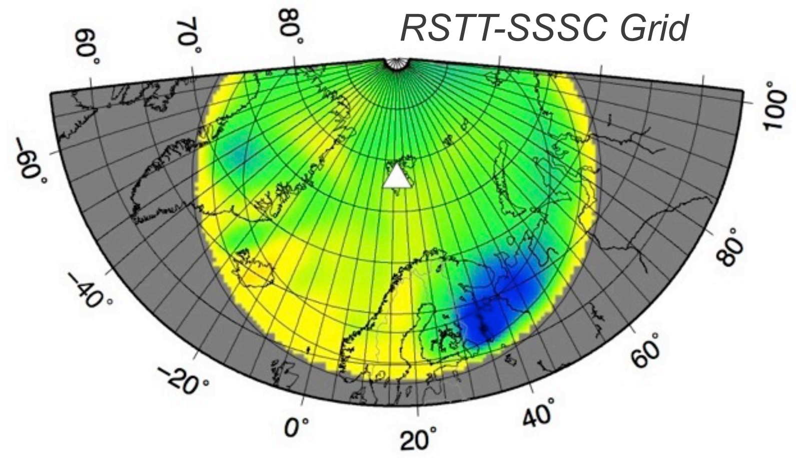
- **Relocation/Predictions (www.sandia.gov/salsa3d/Software.html)**
  - **LocOO3D (Ballard et al., 2008; 2009)**
    - *Software package used for locating single seismic events (or as master event) using a variety of seismic velocity models*
    - *Reflecting its origin in the seismic monitoring community, LocOO3D is compatible with the CSS3.0 data format style commonly used by monitoring agencies*
      - Oracle database
      - Flat files
      - Data can also be input as custom formatted text as long as appropriate column labels are included in a header file
    - *Multi-threaded*
    - *Models available:*
      - 1D travel-time tables (i.e., LocSat-formatted; Output from TauP)
      - **3D travel-time lookup tables (GeoTess files) –** (www.sandia.gov/geotess)
        - » Load all at initiation OR load as needed
      - 3D ray tracing (i.e., “bender”)
  - **PCalc**
    - *Prediction Calculator*
      - Compute predictions of travel time, azimuth, slowness and other values at user specified source-receiver positions
      - Extract model values from user-specified positions
      - Compute ray path geometries using ray bending through formatted 3D GeoTess earth model (e.g, SALSA3D)
    - *Multi-threaded*
    - *Same available model types as LocOO3D*

Ballard, S., J. Hipp, C. Young, G. T. Barker, and M. Chang (2008). Implementation of a pseudo-bending seismic travel time calculator in a distributed parallel computing environment, in *Proc. of the 30th Monitoring Research Review*, Portsmouth, VA, 338-346, paper 2-02.
Ballard, S., Hipp, J. R., & Young, C. J. (2009). Efficient and accurate calculation of ray theory seismic travel time through variable resolution 3D earth models. *Seismological Research Letters, 80*(6), 989-998, doi:10.1785/gssrl.80.6.989.

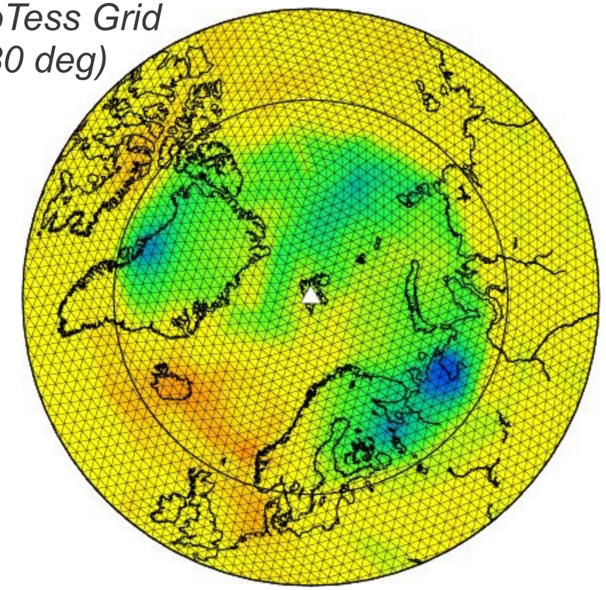
Source-specific Station Corrections (SSSCs)

- **Simple way to do fast travel time predictions**
- **The International Data Centre (IDC) uses SSSCs (Firbas et al., 1998) to do fast travel time predictions for regional phases**
  - Regular lat/lon grid of corrections to the iasp91 model, plus uncertainty
  - IMS is a relatively static network
  - This is the current framework in which the Regional Seismic Travel Time (RSTT) model predictions will be used at the IDC.
- **Only a correction at a single depth (e.g., 10 km)**
- **Rectangular grid**
  - Problem at poles, grid spacing not equal
  - Correction surfaces not equidistant from station

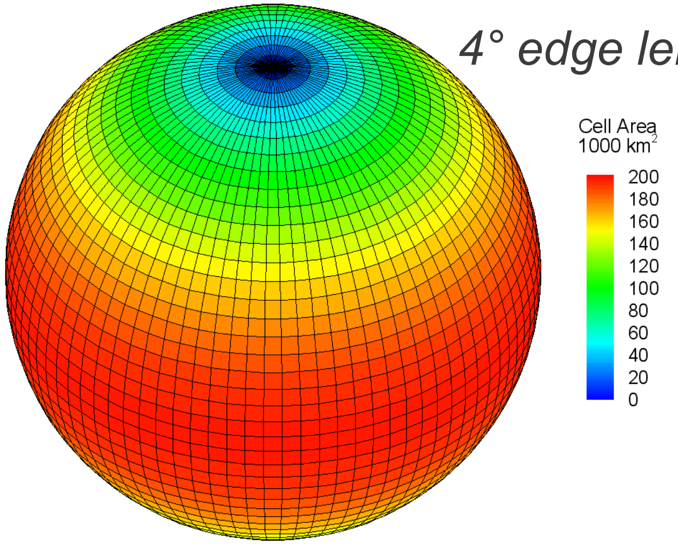
RSTT-SSSC Grid



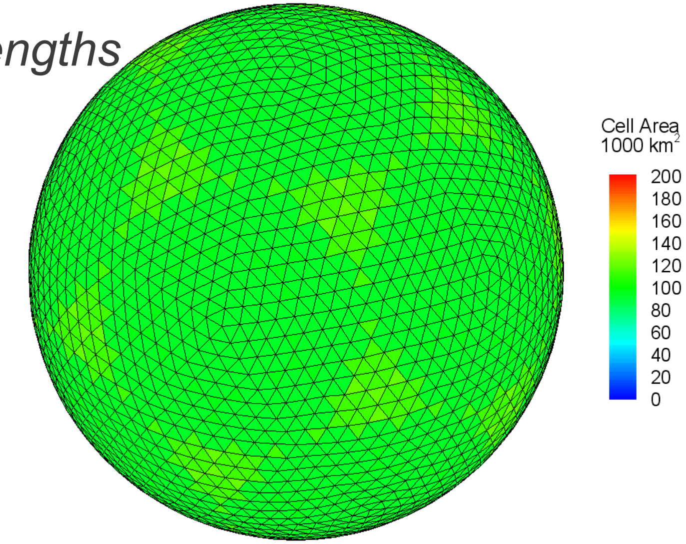
3D GeoTess Grid (to 30 deg)



4° edge lengths



Regular Lat/Lon Grid

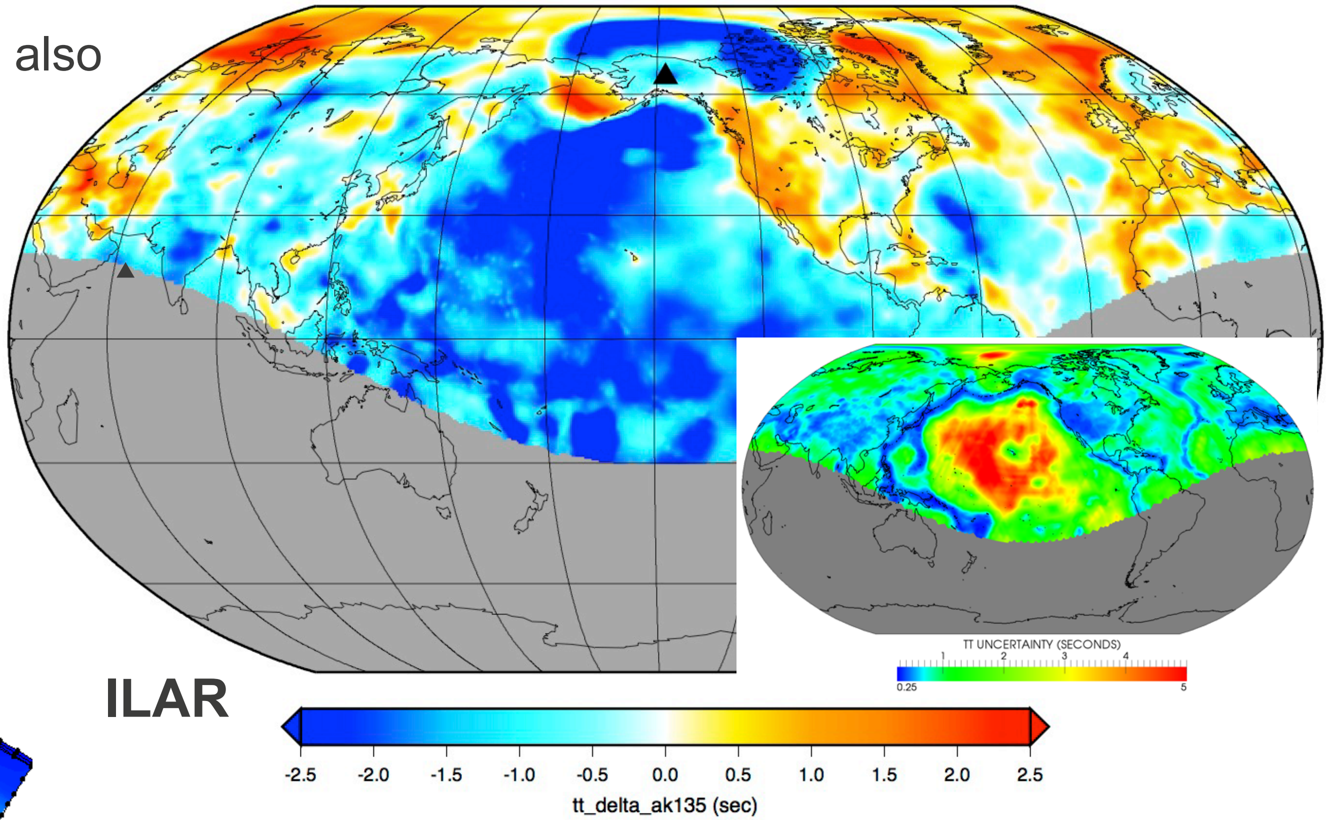


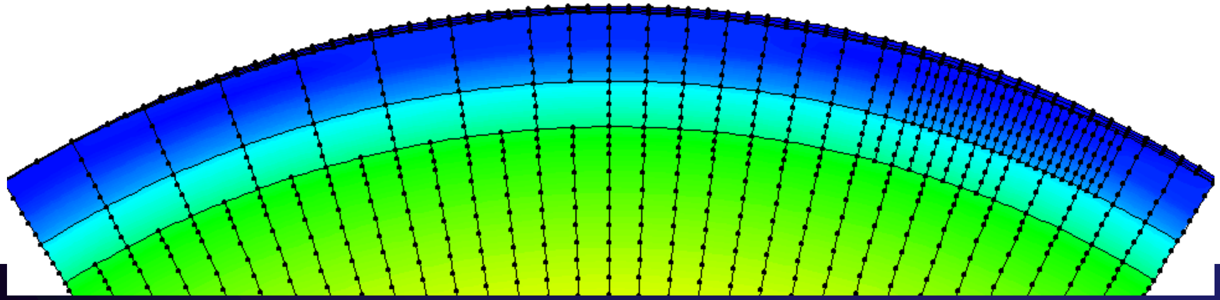
GeoTess Grid

Firbas, P., Fuchs, K., & Mooney, W. D. (1998). Calibration of seismograph network may meet Test Ban Treaty's monitoring needs. EOS, Transactions of the American Geophysical Union, 79, 413-421.

Travel Time Framework (GeoTess)

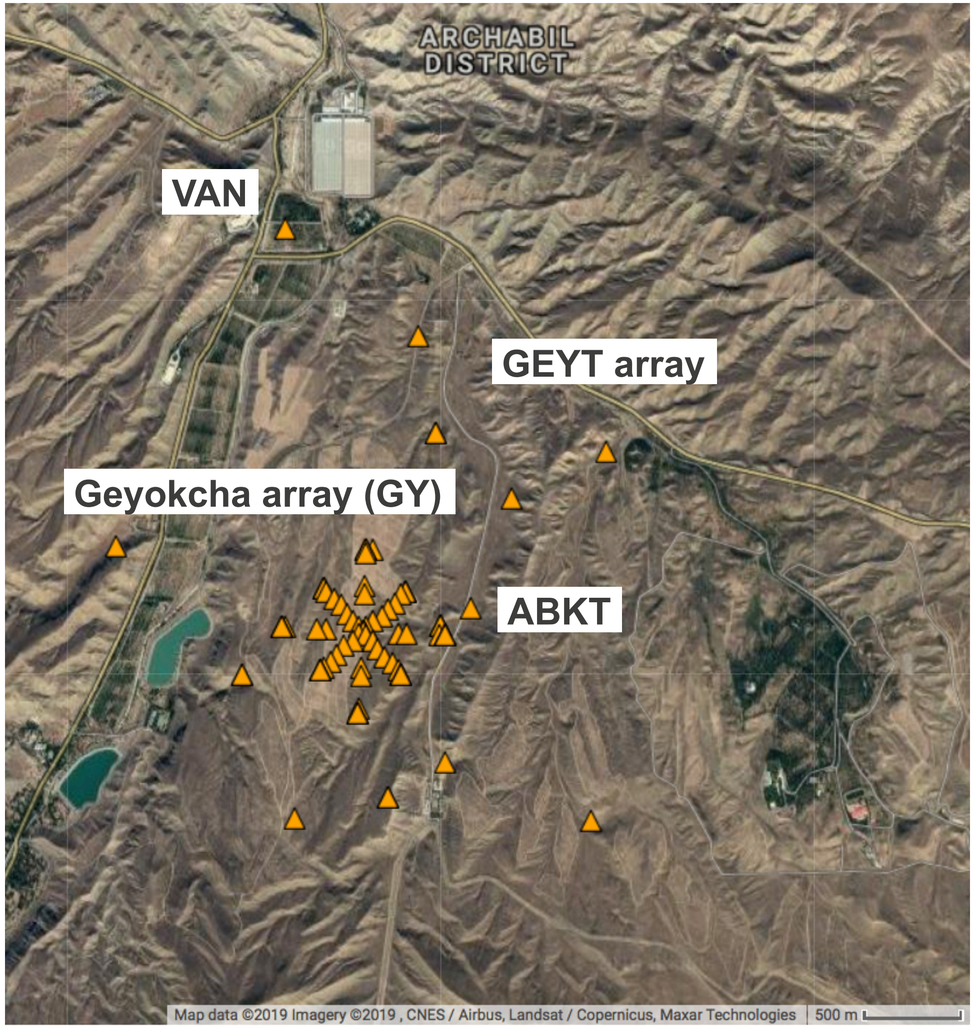
- **Using an open-source framework designed with 3D tessellated points (e.g., GeoTess, www.sandia.gov/geotess) to easily store 3D travel-time data can overcome the ray-tracing algorithm hurdle**
  - Lookup tables (one for each station and phase) **can be generated using the exact ray-tracing algorithm that is preferred for a specified model**.
  - The 3D lookup surfaces are generally applied as corrections to a simple 1D model (e.g., *iasp91*) and also
    - *Allow variations in event depth, as opposed to legacy source-specific station corrections (SSSCs)*
      - Optimized for maximum depth of seismicity (based on ISC catalog)
    - *Estimates of path-specific travel-time uncertainty*
    - *Empirical travel-time corrections (if wanted)*
  - Having a common travel-time framework used for a location algorithm allows individual 2D and 3D velocity models to be compared in a fair, consistent manner.





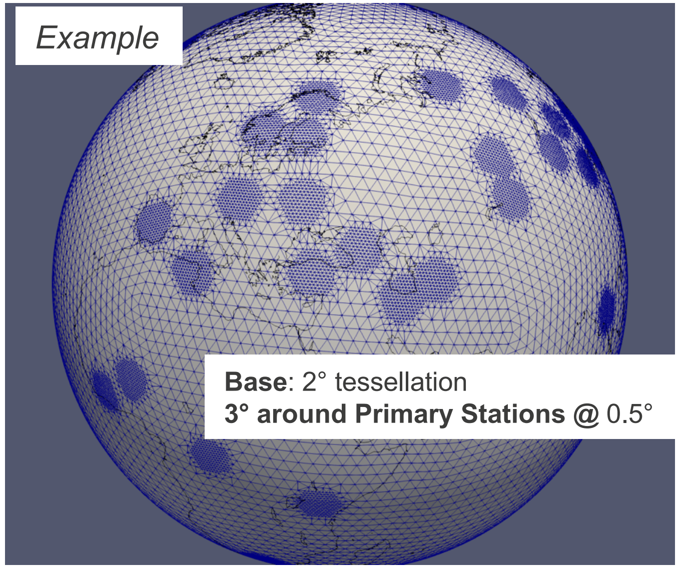
3D Travel-time Lookup Surface Information

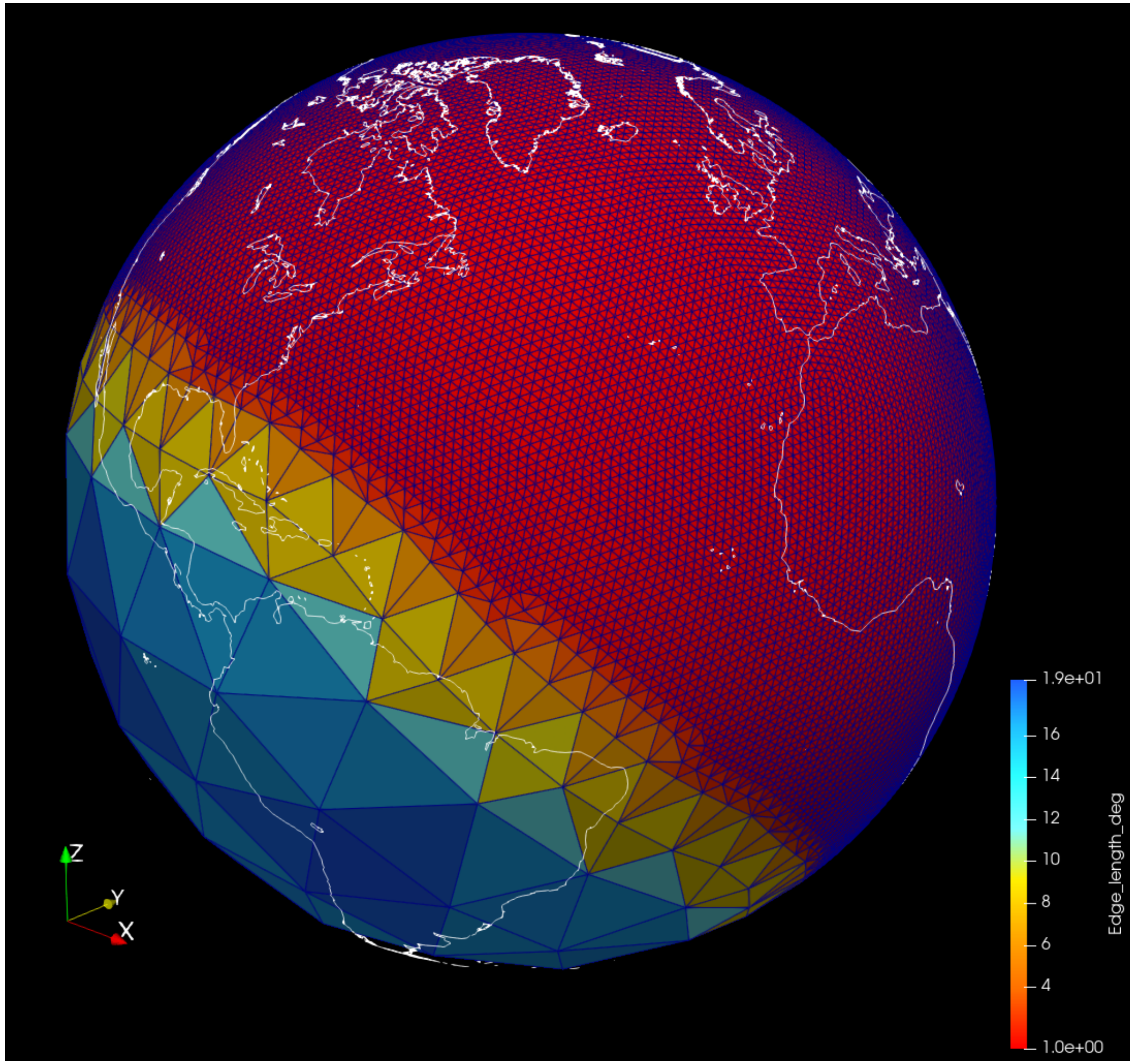
- **One surface for each station/phase combination**
  - First-P and First-S currently is combination of Pn/P and Sn/S, respectively
  - First-P (Pmantle)
    - *151 primary + auxiliary stations (at the time of creation)*
  - Other phases: PcP, PKPdf, PKPbc
- **Can use a special file called *_supportMap.txt* that defines surfaces to use with other, close stations, elements of an array, legacy stations, or stations from other networks (non-IMS)**
  - User-defined distance (10 km for this case)
    - *Because surfaces are travel-time corrections, less sensitive to small station separations*
  - For Example -- **ABKT**:
    - ABKT, GEYT (+ array elements), GY (+ array elements), VAN
  - Would minimize number of surfaces to read when using an expanded network or legacy stations



Building 3D Travel-time/Uncertainty Lookup Surfaces

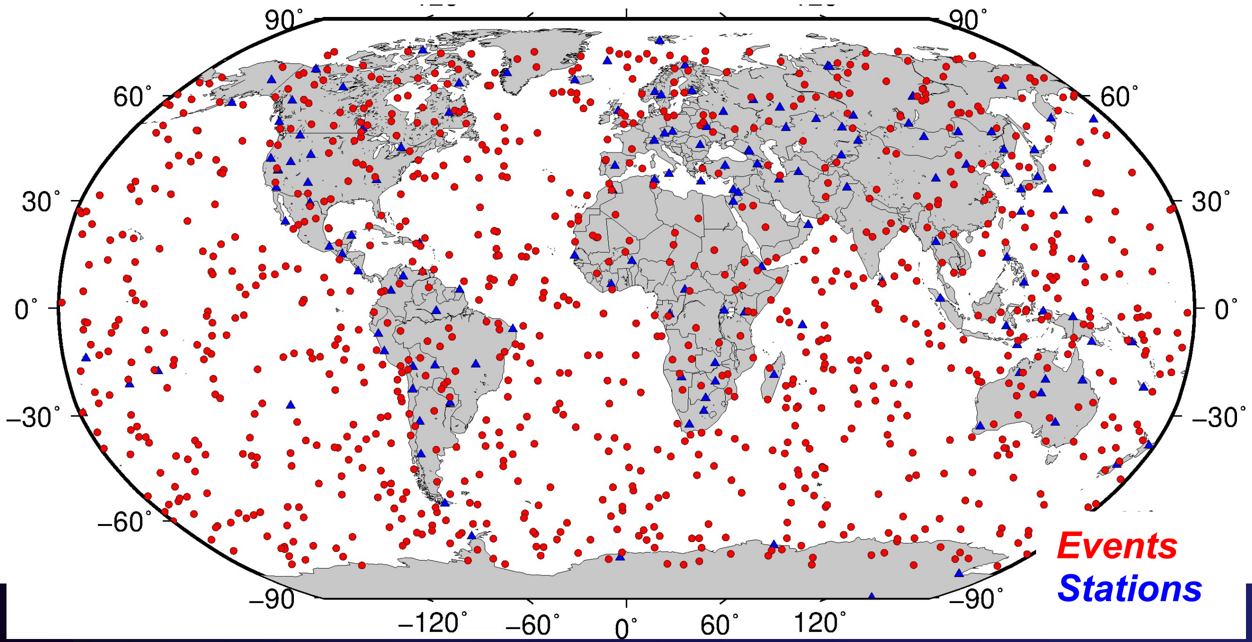
- **3D lookup surfaces are generated using GeoTess Builder software (optimized for each station/phase) – becoming part of PCalc**
- **If needed, the tessellation grid can be refined around a station or in any place specified for denser points in lookup surfaces, e.g.:**
  - Close-in distances
  - Tectonically complicated areas
- **Surfaces can use a common base grid to save memory (if all grids are the same)**

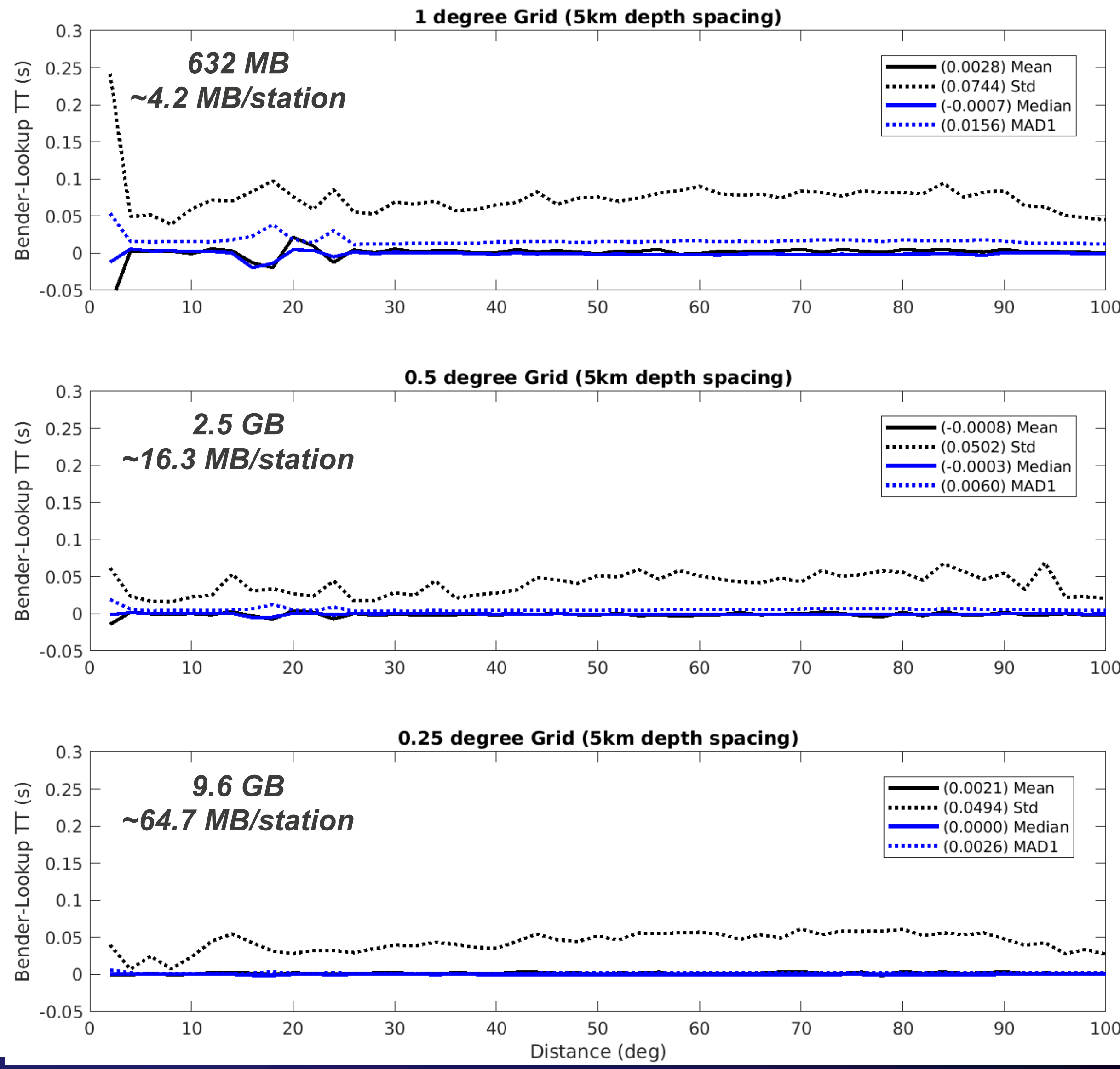




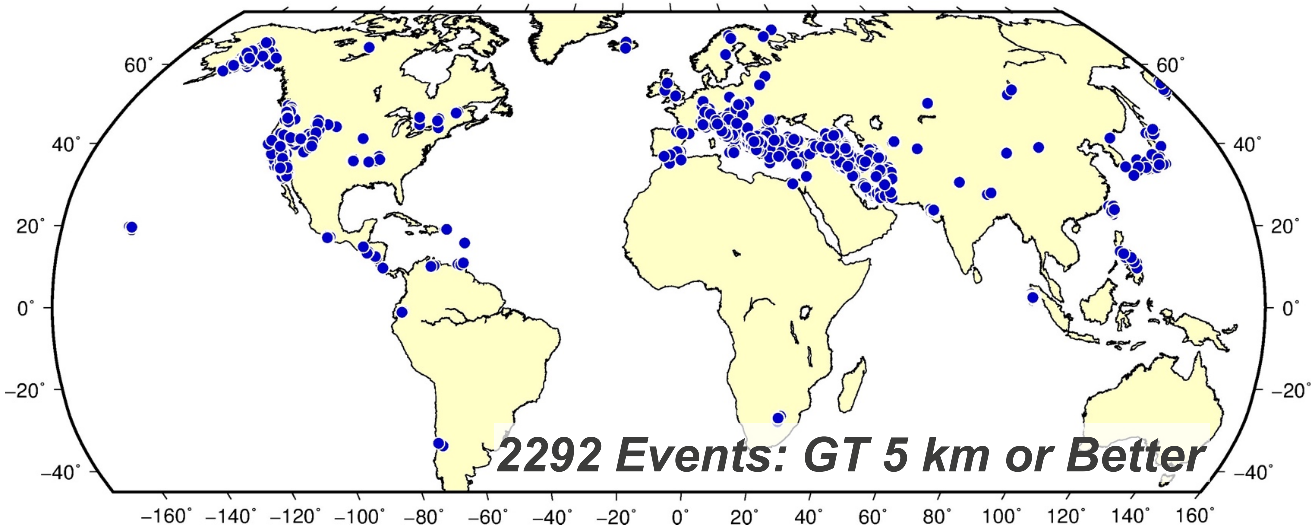
Evaluating Accuracy and Size of GeoTess Surfaces vs 3D Ray Tracing (i.e., Bending)

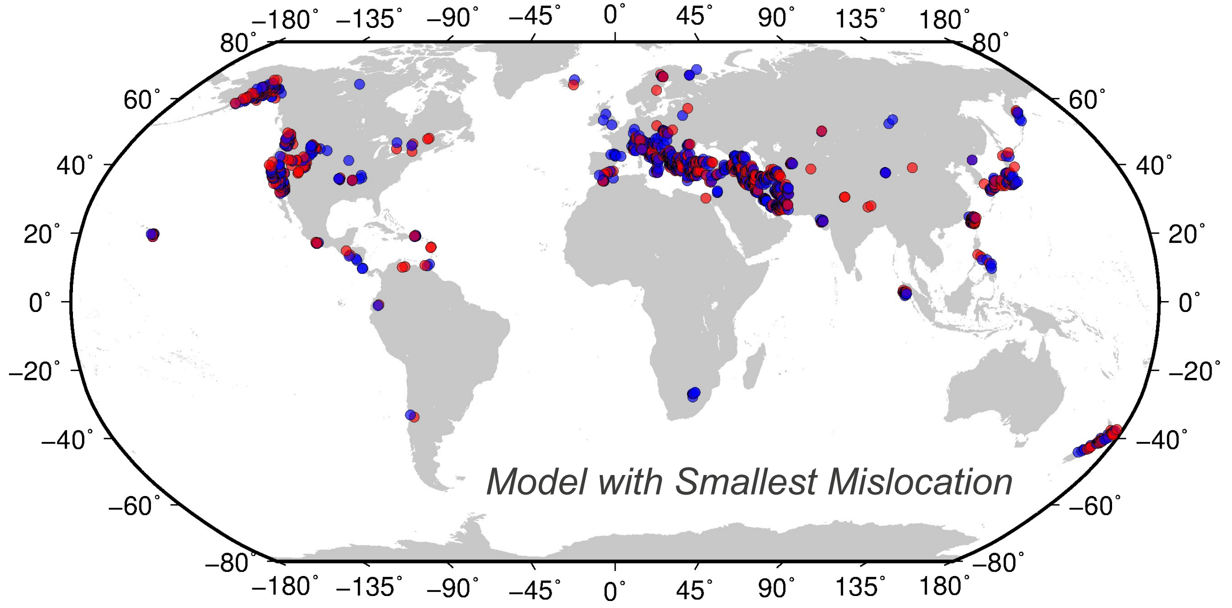
- **Sample uses the SALSA3D model**
  - Global 3D P- and S-velocity model (~1° tessellation)
  - 3D estimates of model uncertainty using full 3D covariance matrix
- **Randomly selected 1000 “events” (Latitude: -75-75°)**
- **All primary and auxiliary IMS stations (151)**
  - Pmantle (Pn, P) phases only
- **Only use event-station paths from 0-100° (91,955 paths)**
- **Testing GeoTess grid sizes: 1°, 0.5°, 0.25°**
  - Compare Bender – Lookup Surfaces at GT points

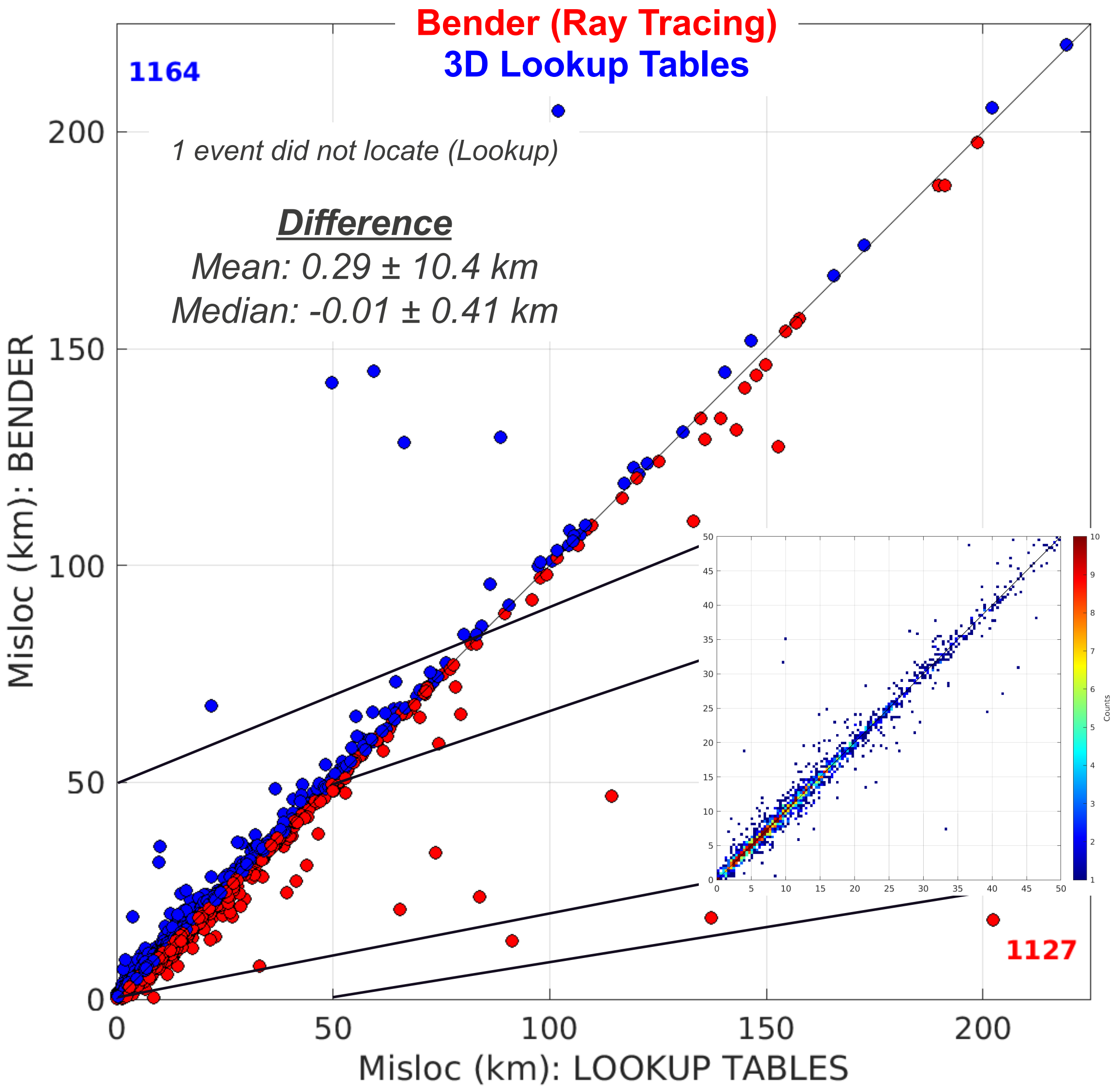




Ray Tracing vs. Lookup Tables (0.5° tessellation): Event-to-Event Relocation Comparison (IDC-REB Arrivals)







Lookup Surfaces: 0.5° tessellations, 0-100° distance from station

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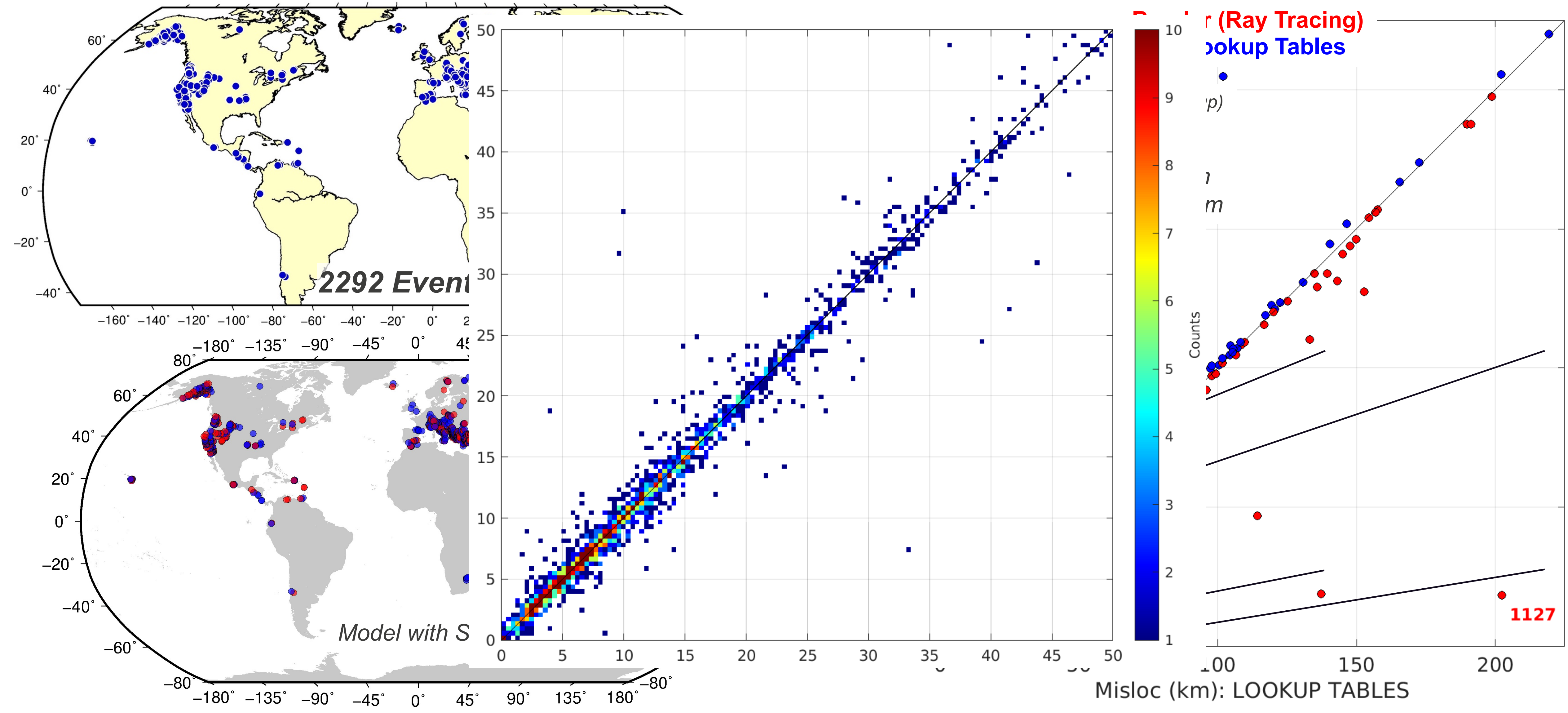

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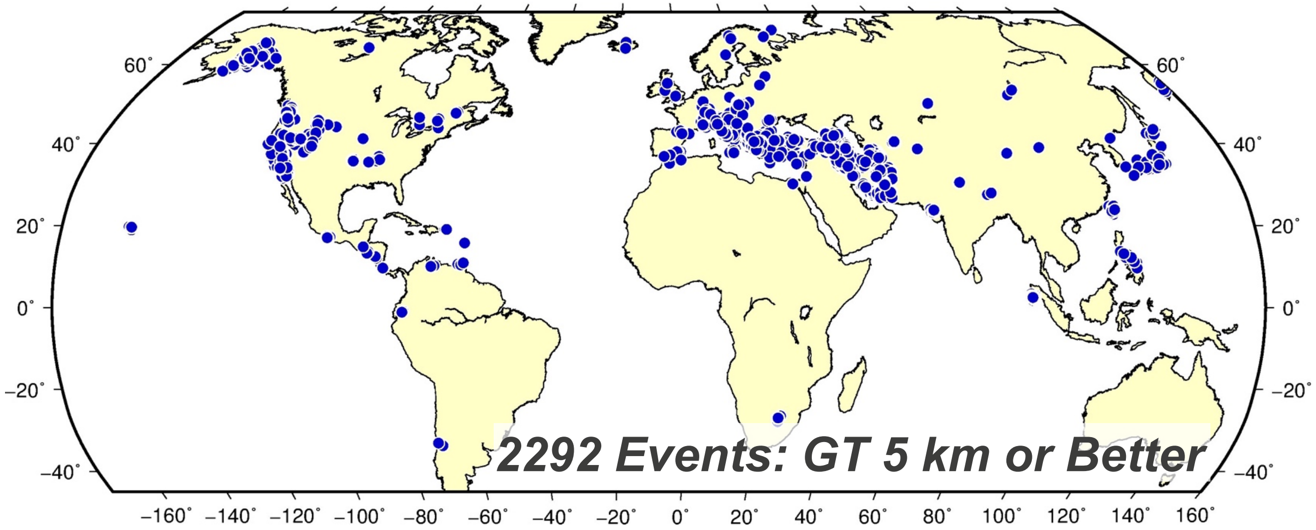

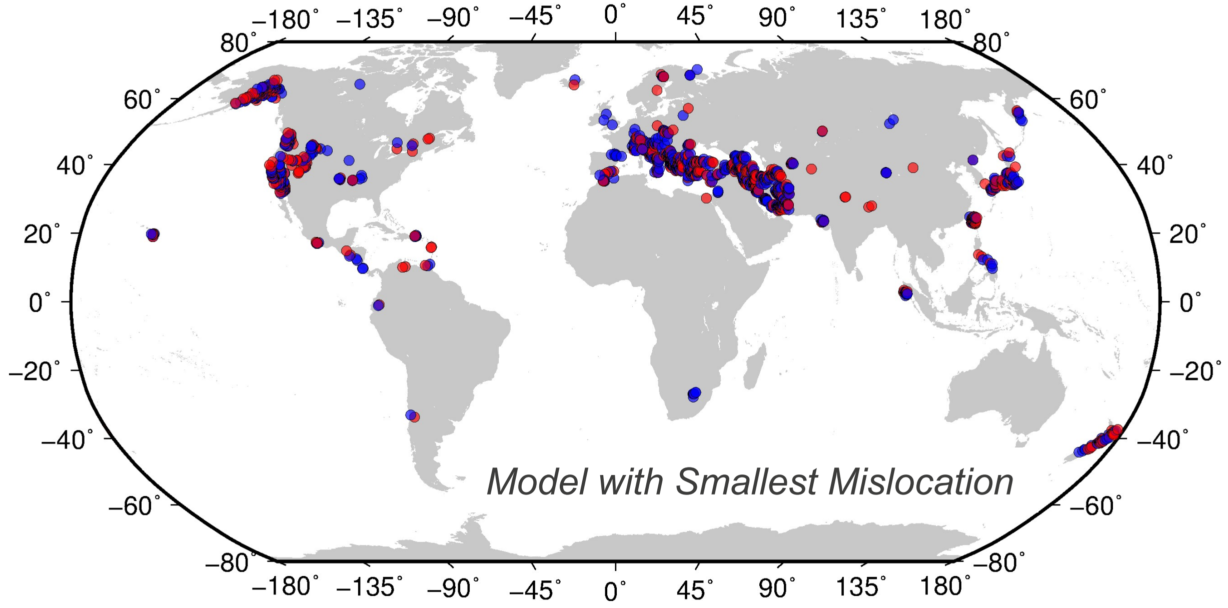

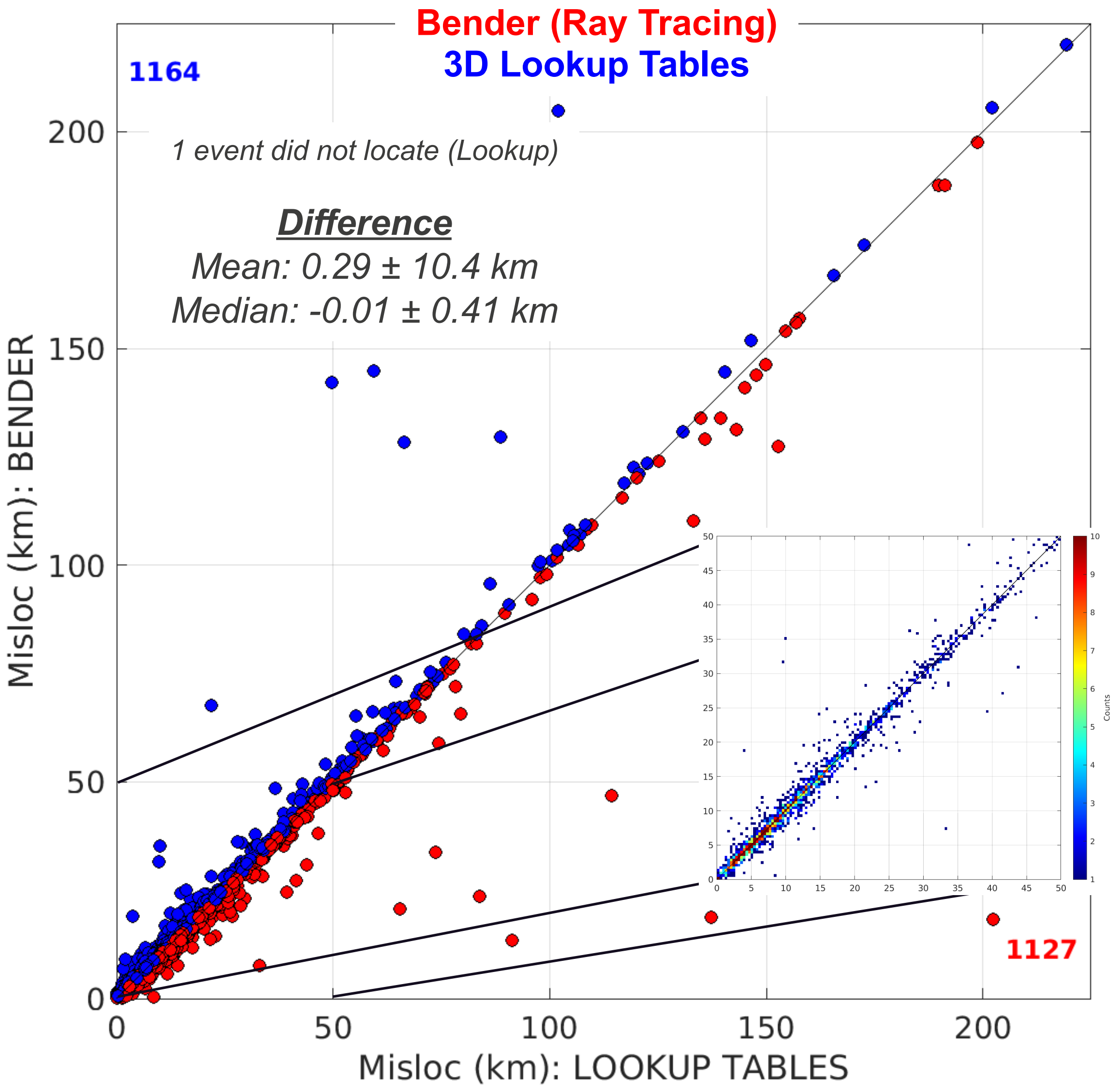

Lookup Surfaces: 0.5° tessellations, 0-100° distance from station

Memory Requirements for 3D, Global, 0.5° Travel-time + Uncertainty Grid

- **Grids developed here were specific to each station:**
  - Rotated so a tessellation point was located at the station
  - 0-100° @ 0.5°
- **To minimize file size, could generate a single global grid @ 0.5° used for every station**

Item	Memory
Grid	140 MB
1 station-phase (data only)	20 MB
Total 150 stations * 5 phases	15 GB

With **1 TB of RAM**, first P travel time tables for **50,000 stations** could be stored.

Conclusions

- **Many 2D/3D global velocity models are publicly available to use for comparison**
  - Do the developers provide the algorithms for calculating travel times and uncertainties for their models? – ***Required for next steps***
- **3D travel-time/uncertainty lookup surfaces can be built for a set of stations/phases for relocation tests**
  - Comparisons of predictions using full 3D ray tracing show comparable values and relocation tests suggest 50/50 split between methods for location accuracy
    - *Lookup surfaces could be optimized for stations to reduce interpolation issues if found*
  - Memory required for reading 3D lookup surfaces is relatively small
    - *Location algorithms (e.g., LocOO3D) could read in only those surfaces that are required OR system could hold all in memory as a "service"*
- **3D lookup surfaces can provide a way to allow consistent, fair comparisons of velocity models used for location**
  - A set of extracted grid values could be made available to model developers to populate *using the ray tracing/travel-time prediction algorithm that is appropriate for their model*
  - Predictions from developers allow production of new 3D lookup surfaces
  - All predictions would be based at the **SAME** locations in a grid
  - *Caveat*: It would generally be unknown whether models were developed using IMS data (circularity)