Standard Form 424

PROPOSAL INFORMATION SUMMARY

1.	Regional Panel Destination:	NIW
2.	Project Title:	Calibration of Seismographic Stations for Improved Earthquake Location in 43 States
3.	Principal Investigator(s):	Paul Richards, PI Lamont-Doherty Earth Observatory of Columbia University 61 Rt. 9W, PO Box 1000 Palisades, NY 10964 Phone: 845-365-8389, Fax: 845-365-8150 E-mail richards@ldeo.columbia.edu
4.	Authorized Institutional Representative:	Veronica Murray, Associate Director Columbia University Office of Contracts and Grants 254 Engineering Terrace 1210 Amsterdam Ave., MC 2205 New York, NY 10027 Phone: 212-854-6851, Fax: 212-854-2738 E-mail: vm34@columbia.edu
5.	Element Designation	III
6.	Key Words	Seismology Source Characteristics
7.	Amount Requested:	$203,639
8.	Proposed Start Date:	December 1, 2005
9.	Proposed Duration:	24 months
10.	New or Renewal Proposal:	New
	Proposal is a continuation of:	
11.	Active Earthquake-Related Research Grants, and Level of Support:	See Current & Pending Statement
12.	Has this proposal been submitted to any other agency for funding, if so, which?	No
13.	Proposal Abstract:	See Attached
14.	Proposal Budget Summary	See Attached

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ABSTRACT

We propose to take a major step in improving estimates of earthquake location in the easternmost 40 States of the U.S. plus parts of Arizona, Nevada, and Idaho, by calibrating the seismographic stations routinely used by the NEIC for earthquake location in this region. Such calibration, which entails finding the travel time of seismic waves from all candidate locations to each of about 60 stations, represents a radical departure from current practice based on use of globally averaged travel time models. To this end we propose to use methodology developed during 2000–2003 in a major project, led by Lamont, to improve seismic locations throughout East Asia using regional seismic signals from stations of the International Monitoring System of the Comprehensive Test Ban Treaty Organization. That methodology uses Source Specific Station Corrections (SSSCs) and has been extensively documented. It achieved significantly improved locations.

The methodology consists of an integrated series of steps that for this proposal will include:

(1) development of regional velocity models of crust and upper mantle, with their associated travel times, for a few tens of sub-regions of continental North America;
(2) computation of regional travel times using 3D ray tracing for paths that cross between sub-regions, thus giving model-based 3D travel times prepared separately for each station;
(3) obtaining empirical travel times for stations to be calibrated (or their surrogates), using reference events (sometimes called ground truth events);
(4) application of kriging methods to empirical travel times (with the model-based 3D travel times as background) to obtain new 3D travel times, for a grid of candidate source locations out to several hundred km from each station to be calibrated. The outcome of (1) through (4) is a travel-time model satisfying empirical data as well as broad sets of information on Earth structure.
(5) The final work consists of assessing performance of the travel time model, and evaluation of standard metrics that assess the extent of location improvement when our model-based travel times and our kriged travel times are used for each station in the network of stations used for event location by the NEIC in 43 States of the U.S. (including the intermountain west).

Our project objectives are to assist the NEIC in meeting an important performance standard for event location put forward in the current document titled "Draft ANSS Performance Standards" — namely, that seismic events in sparsely instrumented regions should have average location uncertainty amounting to 5 km horizontally. We anticipate that we shall be able to document what location performance actually is at the present time for the 43-State region, using event location methods based on current practice (phase picks interpreted via the Earth model ak135); and to demonstrate that our methods of event location based upon use of SSSCs achieve more accurate locations in this region.

Since accurate locations are needed as the starting point for almost all quantitative earthquake studies (hazards, structure, engineering, earthquake physics, interactions between earthquakes in a sequence), as well as for emergency management, direction of fieldwork following a significant mainshock, and providing information to the public, our project will have wide implications. In particular our results will reduce losses from earthquakes in the United States by elevating the quality of almost all quantitative studies of earthquake hazard and earthquake interactions for the region we propose to study.

Budget SUMMARY

Project Title:	Calibration of Seismographic Stations for Improved Earthquake Location in 40 States
Principal Investigator(s)	Paul Richards, PI Won-Young Kim, Co-PI
Proposed Start Date:	December 1, 2004
Proposed Completion Date:	November 30, 2006

Cost Category	**Federal First Year**	**Federal Second Year[2]**	**Total Both Years[2]**
1. Salaries and Wages	$46,883	$45,352	$92,235
Total Salaries and Wages	$46,883	$45,352	$92,235
2. Fringe Benefits/Labor Overhead	$12,416	$12,101	$24,517
3. Equipment			
4. Supplies	$400	$400	$800
5. Services or Consultants			
6. Radiocarbon Dating Services			
7. Travel	$4,566	$5,070	$9,636
8. Publication Costs	$0	$2,550	$2,550
9. Other Direct Costs	$2,340	$2,376	$4,716
10. **Total Direct Costs (items 1-9)**	$66,605	$67,849	$134,454
11. Indirect cost/General and Administrative (G&A) cost	$34,272	$34,913	$69,185
12. Amount Proposed (items 10 & 11)	$100,877	$102,762	$203,639
13. Total Project Cost (Total of Federal and non-Federal amounts)			

[1] This form shows the format of the budget summary. Use this sheet for the Budget Summary which precedes the detailed budget. The detailed budget must be keyed directly to the Budget Summary page.

[2] These Columns are only for multi-year projects

PROPOSED RESEARCH BUDGET

TITLE: Calibration of Seismographic Stations for Improved Earthquake Location in 40 States

PRINCIPAL INVESTIGATOR: Paul Richards, PI,

DATE: December 1, 2004 - November 30, 2006

AMOUNT: $203,639 **Year 1:** $100,877 **Year 2:** $102,762

		12/1/04 - 11/30/05	12/1/05 - 11/30/06
	SALARIES AND WAGES		
Senior Personnel			
P. Richards, Professor	0.5, 1.0 summer	*	*
W.Y. Kim, Doherty Research Scientist	2.0, 1.0	*	*
W. Menke, Professor	1.0, 0.5 summer	*	*
F. Waldhauser, Doherty Assoc. Research Sci	0.5, 1.0	*	*
D. Schaff, Doherty Assoc. Research Sci.***	2.0, 2.0	*	*
	Total Salaries and Wages:	**$46,883**	**$45,352**
Fringe Benefits		$12,416	$12,101
	Total Salaries, Wages and Fringe Benefits:	**$59,299**	**$57,453**
	DOMESTIC TRAVEL		
Visit to USGS			
R/T NY/Denver	2 people @ $327 / person	$654	$654
Subsistence	2 people X 4 days @ $159/day	$1,272	$1,272
Ground transportation	2 people X $100 each	$200	$200
Annual SSA Meeting2005			
R/T NY/Reno, NV	2 people @ $347 / person	$694	$0
Subsistence	2 people X 4 days @ $122/day	$976	$0
Ground transportation	2 people X $100 each	$200	$0
Registration Fee	2 X $285	$570	$0
Annual SSA Meeting2006			
R/T NY/San Francisco, CA	2 people @ $327 / person	$0	$654
Subsistence	2 people X 4 days @ $190/day	$0	$1,520
Ground transportation	2 people X $100 each	$0	$200
Registration Fee	2 X $285	$0	$570
	Total Domestic Travel:	**$4,566**	**$5,070**
	OTHER DIRECT COSTS		
1. Materials and Supplies:	Misc. office /computer supplies	$400	$400
2. Publications	12 Pages in BSSA	$0	$2,550
4. Computer Services Assessment	3% Total Modified Direct Costs	$1,940	$1,976
6. Other: Communications and Shipping		$400	$400
	Total Other Direct Costs:	**$2,740**	**$5,326**
	Total Direct Costs:	**$66,605**	**$67,849**
	Modified Total Direct Costs (Base):	$64,665	$65,873
	Indirect Cost Recovery @ 53%:	$34,272	$34,913
	Total Direct and Indirect Costs:	**$100,877**	**$102,762**

* Travel: budgeted at a 14 day advance non-refundable penalty rate

** Computer Assessment - These costs are exempt from indirect cost assessment.

*** Promotion Anticipated

**** As of 30 June 1997, our federal cognizant agency is Department of Health and Human Services (DHHS). The cognizant DHHS official is:

Robert Aaronson, Branch Chief
DHHS/PSC/FMS/DCA
Jacob K Javitz Federal Building, Room 41-122
New York, NY 10278

PROPOSAL BODY

Significance of Project

Earthquake location estimates in the eastern, central, and intermountain west regions of the United States have often been significantly in error, by distances commonly amounting to 10–20 km. The low quality of such location estimates has long been a handicap to virtually all aspects of the study of seismic hazard in this vast region, and a handicap too in communications with the news media and between different scientific groups. Potentially, earthquake mislocations could have a deleterious effect on emergency management, to the extent that resources are directed to regions tens of km distant from regions of strongest shaking that sustain damage. Especially this could be a problem, for significant earthquakes in the general vicinity of population centers with unreinforced masonry structures, and/or near critical facilities such as nuclear power reactors. The problem has been around for more than 60 years, in that basic procedures for earthquake location have barely changed since the late 1930s: the great majority of earthquakes have been routinely located one-at-a-time by NEIC and its predecessor agencies using measurements of the arrival time of various seismic waves at different stations, and interpreting these arrivals in a globally-averaged Earth structure. Though seismic data has vastly improved in quality, quantity, and accessibility in recent decades, earthquake location methods have changed very little. Of particular significance, are the errors resulting from use of the same theoretical travel time curves to interpret arrival times at all stations for regional waves such as *Pg*, *Pn*, *Sn*, *Lg*, when (for example) *Pn* velocities are known to vary laterally in the range from 7.6 to 8.3 km/s within the continental U.S.

The expected results from our proposed work, are that we shall enable the National Earthquake Information Center of the U.S. Geological Survey to provide significantly more accurate earthquake locations in its widely used publications such as the "Quick Determination of Epicenters" (QDE) and the "Preliminary Determination of Epicenters" (PDE), for earthquakes throughout the eastern, central, and intermountain west of the U.S. The QDE and PDE are used by emergency managers, by those engaged in studies of earthquake hazard, and by scientists and engineers carrying our fundamental studies interpreting seismograms (including strong motion records) from events whose location is needed to be accurately known in order for the quantitative results to be used with confidence. Accurate locations are needed for the basic work of identifying active faults as well as for tomographic studies. Prompt accurate locations for mainshocks are needed for emergency management, and to provide guidance to those engaged in field work (for example to install temporary stations to carry out aftershock studies). Accurate earthquake locations are required as the *sine qua non* for essentially ALL quantitative studies of earthquake hazard. Our expected results will therefore reduce losses from earthquakes in the United States by elevating the quality of almost all quantitative studies of earthquake hazard.

We note that the Advanced National Seismic System (ANSS) in the current document titled "Draft ANSS Performance Standards" has set the standard for locations in sparsely instrumented regions as having average location uncertainty amounting to 5 km horizontally, i.e. considerably smaller than current uncertainties. Our proposal is directed toward the attainment of this capability for the ANSS.

Project plan

Background For decades, the U.S. Geological Survey (NEIC) and predecessor agencies responsible for earthquake monitoring have located earthquakes both globally and on U.S. territory by interpreting the observed arrival times of seismic waves using the Jeffreys-Bullen travel-time model. Beginning in January 2004 this procedure at the NEIC has been changed slightly, to use of the more modern travel-time model known as ak135. The main problem with these models, in application to earthquake location for events in the continental U.S. outside dense regional networks, is their failure to provide a framework within which regional travel times can be treated as path-dependent, and not merely a function of distance and depth. Note that *Pn* and *Sn* velocities can vary laterally by plus/minus about 5%.

A sense of the need to develop path-dependent travel times can be seen from Figure 1, which shows considerable scatter of *P*-wave arrivals for sources and stations in the central and eastern U.S., when compared with ak135 travel times.

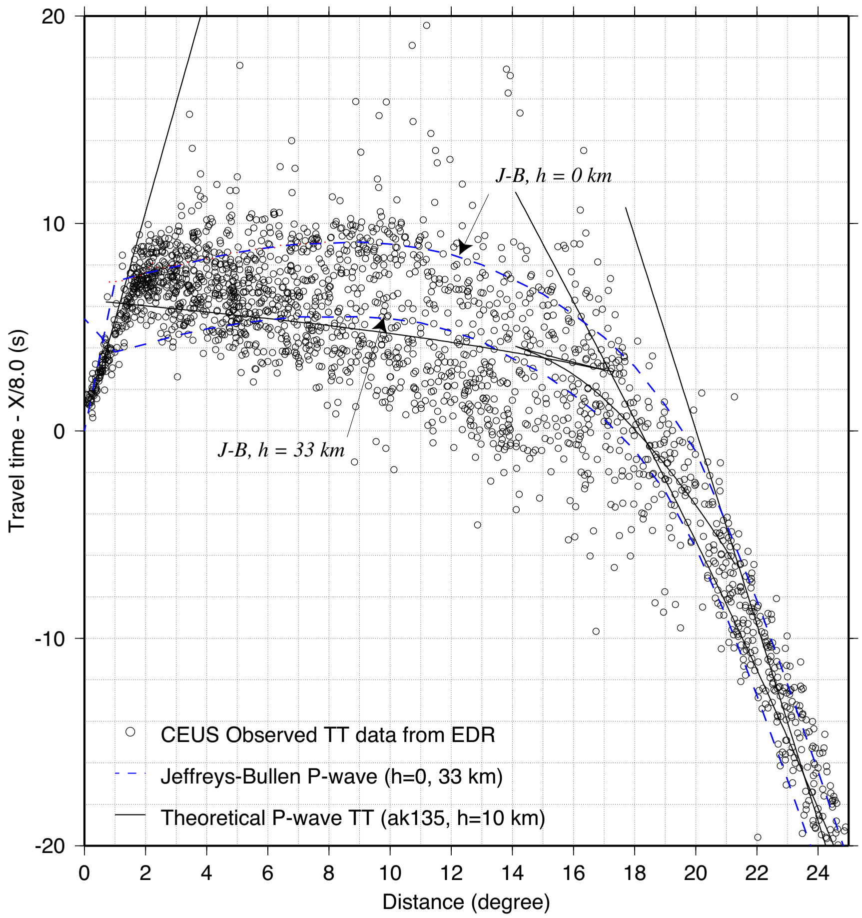

Figure 1. Reduced travel times for *P*-waves out to 24º. The data are taken from Earthquake Data Reports, for events and stations in the central and eastern U.S., and are shown in a comparison with the ak135 and J-B travel time models. Though some reduction in scatter would be obtained by use of the correct depth for each event, the main points are that scatter ranges over about ± 5 s, and it is impossible to fit these data well with a purely distance-dependent travel time model.

Recognition of the need for path-dependent travel times became very apparent following the GNOME nuclear explosion of December 1961 in a bedded salt formation near Carlsbad, NM, which led Romney et al. (1962) to write that "The travel times of *P* were ... as much as 12 seconds earlier in the eastern United States than at equivalent distances in the western part..." "The travel times eastward are so different from those westward that the epicenter of GNOME, based on the observed times and using the J-B table, was calculated to be about 30 kilometers to the east of the actual site." Herrin and Taggart (1962) wrote of GNOME that "For the first time, clear evidence of the existence of significant regional differences in *Pn* velocities is available. Any computational procedure attempting to use data in the *Pn* range for the determination of epicenters in the United States must take the resulting differences in travel times into account if significant, systematic errors in the location of the epicenter are to be avoided." The data quality for this event was very good, with about 100 stations reporting. Herrin and Taggart developed and applied a 3D velocity model for *Pn* interpretation, integrating along a great circle path to obtain theoretical travel times, and got much better results for the GNOME explosion (location within about 3 km). But approaches based on 3D structural models have not in practice found wide application for routine work. Below, we make the point that an equivalent approach, based on modeling to obtain relevant travel times for each station but combined with empirical travel time data, can do the job.

Despite the many efforts to obtain better velocity models of crust and upper mantle for North America[1], it is still the case that USGS/NEIC uses path-independent travel time curves. In recent years, examples of event mislocation show that the problem apparent for GNOME in 1961 has still not been adequately addressed.

Thus, on 09 December 2003 a pair of events 12 s apart (Mw ~ 4.3) in Central Virginia occurred beginning at T_0 = 20:59:18.7 (37.774ºNN 78.100ºW h = 10 km) as determined by special study (Kim and Chapman, 2004). Their location is confirmed by comparison with the region of strongest intensity on a Community Internet Intensity Map. The event was felt widely, including in the Washington, DC, area; the nearest seismometer may have been in a pair of nuclear reactors at North Anna, "40 miles NW of Richmond, VA", but these records have not been made available. The weekly PDE/NEIC location is given as 37.587ºN 77.903ºW and is thus more that 20 km from what appears to be the correct location.

There are other examples, and in each case there are particular issues concerning which stations were operating or not operating. But the bottom line is that PDE event locations have been significantly in error. A principal reason appears to be the problem, well-known but unaddressed for more than four decades (since GNOME), namely the reliance upon path-independent *Pn* travel times[2].

Detailed studies of the problem have appeared from time to time, but successful efforts to solve it in the context of routine processing for bulletins of seismicity have developed only in the last six years. The need for improved estimates of absolute seismic event locations over broad areas, using regional (and teleseismic) signals, became apparent to a new community in the late 1990s when the International Monitoring System (IMS) of the Comprehensive Test Ban Treaty Organization began partial operations. In 1999, at the first of a series of "location calibration workshops" organized in Oslo by Dr. Frode Ringdal under the auspices of the IMS, participants began to sketch a plan in which significant improvement in event location might be achieved. Essentially, the idea was to apply a variety of methods all directed towards obtaining for each station in the network used for event location a set of travel times to that station, for relevant seismic phases, for all candidate source locations. In practice, these travel times were reported as Source Specific Station Corrections (SSSCs) to the iasp91 travel time model (which, for regional *P*-waves, is essentially the same as model ak135). Thus, for station *A* and source position *X*, the travel time from *X* to *A* was regarded as the predicted time according to iasp91, plus the SSSC for source *X* at station *A*.

Approximately $10 million was spent during 2000–2003 by the Defense Threat Reduction Agency (DTRA) on contracts (including a major contract to a DTRA Consortium led by Lamont) to provide SSSCs for various subsets of IMS stations, and documentation of claims of location improvement. The Department of Energy is independently supporting an even larger effort.

In practice, SSSCs at a particular IMS station have typically been provided on a 1ºx1º grid centered on the station and going out to about 2000 km, for regional phases *Pn* and *Sn*, with most of the effort going into SSSCs for surface sources.

For stations commonly used to locate events in the continental U.S. east of about 110ºW longitude, the station density is somewhat greater than for the IMS in East Asia, and *Sn* waves (and occasionally *Lg* waves) can be useful. Therefore we anticipate the need to emphasize the use of *Pg* for at

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1 For example those based on three sets of chemical explosions in Lake Superior in the 1960s, including Project Early Rise (see Massé, 1973, for a review). Explosion studies of structure are critically reviewed by James and Steinhart (1966). Braile et al. (1989) provide extensive detail with *Pn* and *Pg* contour maps. More recently profiles associated with the O-NYNEX refraction experiment (Luetgert et al., 1990) have provided extensive data, useful for model generation and evaluation. For example, see Levin et al. (1995).

2 Anecdotally we understand that the NEIC will sometimes avoid using data from particular stations that in practice exhibit large residuals for locations in the likely source area. While this makes sense in the context of studying a particular event for which standard travel times (such as J-B) are thought to be inappropriate, it is not a strategy that makes sense for the long term. The need is to improve upon 1D travel times to enable the use, for purposes of event location, of arrival-time data from *all* stations having clear detections.

least some stations, to restrict the use of *Pn* to distances less than 2000 km, and for some stations to use *Sn* and *Lg*. We expect such issues will be explored with advice from NEIC personnel.

A number of studies of SSSCs for IMS stations in North America have been carried out, for example by Yang et al. (2001); and by Chun and Vasiliev (2003) for Canadian IMS stations. Yang et al. used only two different sub-regions to represent the whole North American continent: a model (RKSF) originally derived for Fennoscandia was taken to apply to the whole shield/platform of Eastern North America. They did not use 3D ray tracing, and did not use empirical travel time and kriging. But they were still able to demonstrate significant location improvement when their SSSCs were applied to locate 51 reference events. Thus, their approach was useful as a first start, although it did not use key methods that have emerged and been judged useful within the treaty monitoring community in the last three years.

We submit this proposal to the National/Intermountain West (NIW) panel because our work is in support of improved routine operations at the NEIC.

Proposed work We propose an integrated set of studies, to be carried out over two years, that effectively will apply the methodology developed by the Lamont Consortium during 2000–203 for East Asia, to the location of earthquakes in the forty most eastern States of the U.S., together with areas of sparse coverage in Nevada, Arizona, and Idaho that we understand occasionally present problems for event location.

We choose to focus on these 43 States, because the active seismicity in the remaining most western States is studied extensively with regional networks that are relatively dense, allowing crustal *P* and *S* waves often to be detected at local stations, so that methods other than the use of SSSCs are more appropriate for event location in those regions.

The integrated five steps we propose to apply for the 43 States region are:

(1) development of regional velocity models of crust and upper mantle, with their associated travel times, for a few tens of sub-regions of continental North America (this work will begin early in the project with an initial model, and will be refined throughout the first year);
(2) computation of regional travel times using 3D ray tracing for paths that cross between sub-regions, thus giving SSSCs centered on each station (this work will require a methodological extension from our procedures for East Asia, in order to handle a first order discontinuity at the Moho rather than a region of high gradient, allowing us to compute travel times for *Pg* and *Lg*);
(3) obtaining empirical travel times for stations to be calibrated (or their surrogates), using reference events (sometimes called ground truth events);
(4) application of kriging methods to empirical travel times (with the model-based 3D travel times as background) to obtain new SSSCs, for a grid of candidate source locations out to several hundred km from each station to be calibrated.
(5) The final step is the important one of assessing performance of the travel-time model, and overall performance characterized by metrics that assess the extent of location improvement when our kriged SSSCs are used for each station in the network of stations used for event location by the NEIC.

We note that the proposed work is very much a project in applied seismology. Though conceptually it is not particularly sophisticated, it represents a significant challenge as may be immediately recognized because the work has not been done before, even though the need for it was identified more than forty years ago. There are many practical details to be addressed, and the project must be managed in a fashion that is different in a number of ways from the typical scientific research effort supported by NEHRP in an academic setting. A wide variety of skills must be brought to bear in sequence and according to a timetable, in close liaison with NEIC personnel (see section below titled Project Management Plan). We could not think of attempting this project without having had more than three years of experience developing the methods we used successfully to improve the location of East Asian seismicity. Presumably, the reason this type of work has not been done before, is in part because this is a larger project than the typical academic effort engaging one or two people plus a student.

Tentatively, the stations we propose to calibrate include the following 48 USNSN stations: AAM, ACSO, AHID, ANMO, BINY, BLA, BW06, CBKS, CBN, CCM, COR, DUG, DWPF, ELK, EYMN, GOGA, HAWA, HKT, HLID, HRV, HWUT, ISCO, JCT, JFWS, KNB, LBNH, LKWY, LSCT, LTX,

MCWV, MIAR, MSO, MYNC, NCB, NEW, NHSC, OXF, PAL, PFO, RSSD, SDCO, SSPA, TPNV, TUC, WCI, WMOK, WUAZ, WVT, plus a number of broadband stations in regional networks, such as PAL, SLM. Though the area for which we propose to achieve improved locations is a part of the U.S., it is likely that stations in Canada and perhaps Mexico can contribute useful data, together with stations in the western U.S. outside our main area of interest. We therefore propose to calibrate (that is, provide SSSCs for) about 60 stations, the final list to be decided in consultation with NEIC personnel.

Concerning computation of travel times to obtain model-based SSSCs, we will employ Menke's (2005) Raytrace3d software. Raytrace3d is a freely-available ray-based code that can calculate travel times, locate earthquakes and perform tomographic inversion in a three-dimensional Earth model. It has been successfully applied previously in our DTRA Consortium work in East Asia, as well as in crustal imaging research (e.g., West et al. 2001; Menke et al. 2002).

A key element of construction of SSSCs is "interpolating" discrete "reference event" travel times into a fully two-dimensional function that represents the travel time from a fixed depth event at an arbitrary (lat, lon) to a given station. We use several conceptually-different methods to accomplish this interpolation, because we have found no single method works best for all stations, given the variability in amount and types of data available for them. One method is based on kriging, and uses only the travel time data plus assumptions about the smoothness of a typical travel-time surface. Another, which employs raytracing, builds a simple, but laterally-varying, Earth model that fits the observed reference travel times and that then can be used to predict travel time at arbitrary locations. This second method is not "travel time inversion" in the ordinary sense. First, the underlying Earth model is very simple. We typically divide the Earth into just a few (10-20) tectonically-distinct regions, with each region having a radially-stratified velocity structure that is represented by just a few parameters. Some of these parameters, like crustal thickness, may be constrained by published geophysical surveys or reflectivity studies. Second, the emphasis is on finding values for the unknown velocity structure parameters so that the travel times from a single station are best-fit (and hence can be well-interpolated). This emphasis is completely different from normal travel-time inversion, were the emphasis is finding a velocity structure that is compatible with travel-time data from all available stations.

Raytrace3d has the basic functionality to facilitate these travel time calculations. It uses tetrahedra with vertices that can lie at arbitrary points, so non-planar interfaces due to the Earth's sphericity (and ellipticity) or to variable crustal thickness can be well-represented. The Earth's velocity structure is represented with tetrahedral splines, with provisions being made to identify internal surfaces in the model, such as the Moho, which can act to reflect seismic waves. Velocity inversions can be performed using individual nodal velocities as unknowns and with the velocities of groups of nodes controlled by a single model parameter. The individual node approach leads to inversions with a huge number of unknowns and models with unconstrained variability. It implements tomographic inversion. The grouped nodes approach allows for highly constrained inversions, such as the tectonic regionalization method described above.

In the current implementation of Raytrace3d, all positions are specified in terms of Cartesian coordinates. This limitation does not preclude the use of spherical Earth models, but it does make their use cumbersome, since the more natural spherical coordinates must be converted to and from their corresponding Cartesian values by pre- and post-processing software. As part of this project, we will rewrite the Raytrace3d I/O to allow direct input and output of spherical coordinates. We will also make some enhancements targeted at better calculating travel times of multiply-reflected waves, as would be important in the calculation of *Pg* and *Lg* travel times. Currently Raytrace3d calculates only singly-reflected phases, such as *PP* and *PmP*. Finally, we will code some enhancements that allow for Earth models with first-order discontinuities. (Currently, the models are required to be continuous, so that discontinuities, such as the Moho, must be represented as thin high-gradient zones.)

Concerning the development of a set of reference events, There are 54 earthquakes that occurred in the eastern U.S. (east of 110º W) since 1990 that have magnitude $mb \geq 4.0$. These events are large enough and are mostly well enough recorded by USNSN and other permanent stations in the continental

U.S. and southern Canada to allow their use as reference events. They are shown in Figure 2, together with the 48 stations listed above (and a number of additional stations).

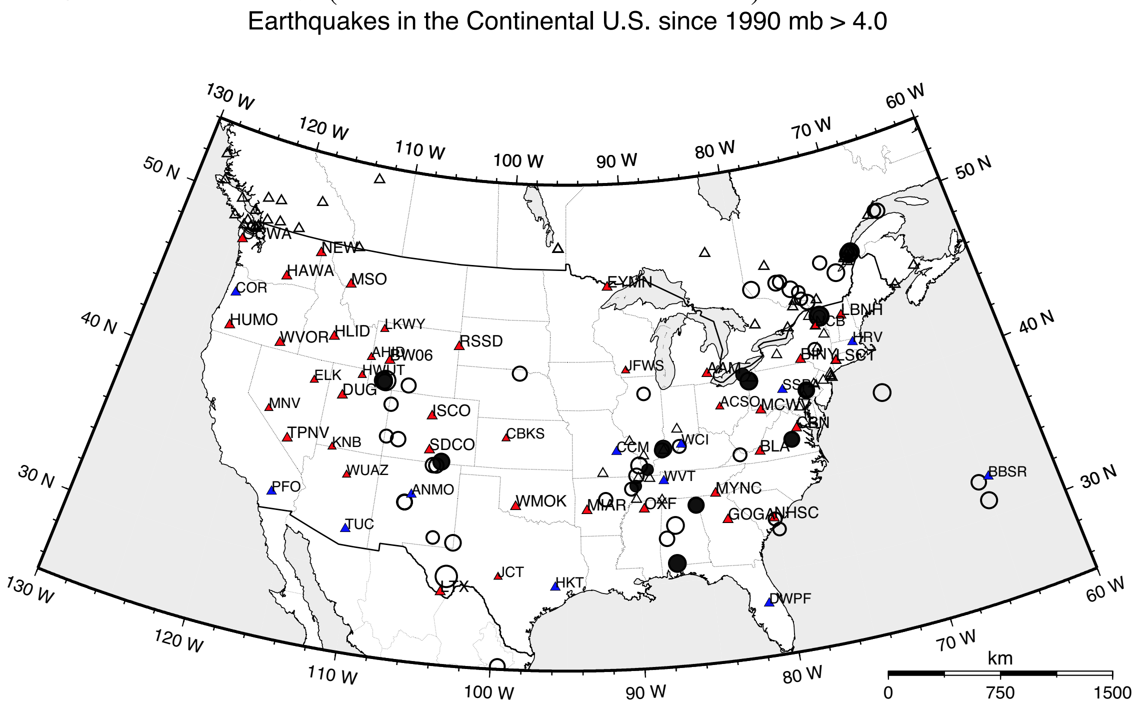

Figure 2. 54 earthquakes in our study region with magnitude greater than or equal to 4, since 1990; many of which (shown shaded) we expect to be suitable as reference events.

Additional reference events can be expected from well-recorded earthquakes that occurred earlier than 1990 (see for example Dewey and Kork, 2000). The following list of papers describes the mechanism and accurate location (including focal depth) of events shown in Figure 2, allowing many of them to be used as reference (ground truth) events: Kim and. Chapman (2004); Horton et al. (2004); Seeber et al. (1998, 2002, 2004); Kim (2003); Du et al. (2003); and Levin et al. (1995). Reference events will also be obtained from mineblasts (especially in the intermountain west), and from a limited number of underground nuclear explosions (including GNOME, SALMON, GASBUGGY, RULISON).

Date	**Time**	**Lat.**	**Long.**	**h**	**Magnitude**		**Location**
year-mo-dy	**hh:mm:ss**	**(N)**	**(W)**	**(km)**	**mb(Lg)**	**Mw**	
1995-02-03	15:26:13	41.518	109.808	4	5.1	5	Trona Mine, Wyoming
1997-10-24	08:35:17	31.12	87.34	4	5.1	4.9	Alabama
2000-01-01	11:22:57	46.87	78.90	13	5.1	4.6	Teminskaming, Canada
2000-04-20	08:46:55	43.95	74.25	8	3.9	4.3	Saranac Lank, NY
2001-01-26	03:03:19	41.99	80.83	2	4.2	3.9	Ashtabula, Ohio
2001-05-04	06:42:13	35.18	92.17	5	4.4	4.0	Enola, AR
2001-09-05	10:52:07	37.133	104.506		5.0	4.6	Trinidad, Colorado
2002-04-20	10:50:00	44.51	73.70	11	5.3	5.0	Au Sable Forks, NY
2002-06-	20:17:37	52.89	74.41	4	4.5	3.8	Northern Quebec

05							
2002-06-18	17:37:13	37.99	87.77	18	5.0	4.6	Caborn, Indiana
2002-11-03	20:41:46	42.81	98.91	8	4.3	3.9	Martin, Nebraska
2002-11-11	23:39:28	32.36	80.07	8	4.2	4.0	South Carolina
2003-04-29	08:59:38	34.54	85.63	13	5.3	4.9	Fort Payne, Alabama
2003-05-25	07:32:33	43.10	101.75	20	4.4	3.9	South Dakota
2003-06-06	12:29:33	36.89	88.99	1	4.5	4.0	Bardwell, Kentucky
2003-12-09	20:59:18.7	37.774	78.100	10	4.5	4.3	Central Virginia

Table 1 16 events (14 since 2000) with accurate locations and moment tensor determinations in our area.

Concerning assessment of performance of our SSSCs, we broadly expect two levels of capability for improved event location. For the whole region (43 States), there will be a first level of improvement derived from the model-based SSSCs. And then in the vicinity of reference events, we expect that kriged SSSCs will provide a second level of improved capability. We shall report capabilities firstly in terms of the residuals for travel times (observed minus calculated), seeing what reductions are attained when SSSCs (both model-based, and kriged) are applied; and secondly in terms of overall location improvement, using metrics derived originally for treaty monitoring (examples of these metrics are given below in Tables 2 and 3, in the section on Related Efforts).

It should be noted that we propose to deliver not only a set of SSSCs and a report on what degree of location improvement they can be expected to provide, but more generally the basic framework for solving the problem first made clearly apparent with the GNOME data of 1961. Thus, in future years as significant numbers of additional reference events become available, updated SSSCs can be provided with little additional effort because the framework can handle revisions easily. It can even handle additional stations, which at first could be provided with their own model-based SSSCs that subsequently would be kriged to the extent that empirical data from reference events become available for that station.

Final Report and Dissemination

Our final technical report will primarily be addressed to NEIC personnel. It will contain a description of our methods; files of hypocenter parameters for reference events; empirical travel time data for reference events; empirical travel time data for reference events observed at stations to be calibrated; SSSCs for these stations on a 1° x 1° grid for *Pn*- and *Sn*-waves and on a finer grid as needed for *Pg*-waves; an assessment of travel time residuals (of the type shown below as Table 2 for East Asia) for reference events, with and without SSSCs; and summary metrics (of the type shown in Table 3) that characterize the end-to-end degree of location improvement we achieve when our SSSCs are applied to the 40 most eastern States of the United States plus parts of Idoho, Arizona, and Nevada (and possibly Montana).

We expect to deliver not just a set of SSSCs that will enable locations with improved accuracy, but a framework that can be expected to support subsequent improvements in event location as new stations and new reference events become available.

We also expect to submit for publication in the Bulletin of the Seismological Society of America a scientific paper summarizing our methods and our practical results.

We expect to visit and consult regularly with NEIC personnel, in their Golden, CO, headquarters, or at Lamont; and to submit progress reports as appropriate.

Related Efforts

Because the seismicity of the 43 States to be studied in this proposal is for the most part quite low, it will be necessary to work largely within the framework of locating events one-at-a-time using conventional phase picks. Other projects on event location, ongoing at Lamont (see Current & Pending), include major projects to improve locations using multiple event location methods, often using relative arrival times measured from waveforms by cross-correlation (WCC). Some of these projects are being pursued for clusters of seismicity in the U.S. (for example, we have embarked upon a study of the New Madrid region, and a major study of more than 225.000 earthquakes in California is underway), as well as the Charlevoix region of Canada and continuing studies in China. Some of these other studies can be expected to contribute to the work proposed here, to the extent that WCC methods can be used to establish good reference events (for example in the New Madrid region).

For the last two years, Richards has co-chaired with Dr. E.R. Engdahl a IASPEI Working Group on Reference Events for the Commission on Seismological Observatory Practice. This effort is related to the present proposal. The Working Group is expected to continue for a number of years, gathering information (to be archived by the International Seismological Centre) on seismic events whose location is accurately known.

In March 2004, Paul Richards contacted Dr. Jim Dewey of NEIC to inquire on the possibility of a Lamont/NEIC collaboration in a project to apply the SSSC methodology (developed in 2000 – 2003 by the Lamont Consortium for East Asia), to achieve significant improvement in earthquake locations in the eastern, central and intermountain west regions of the United States. Dr. Dewey consulted with his colleagues in NEIC, and by e-mail on March 16 responded affirmatively, stating that it would be appropriate to list him as a collaborator. He went on to say "If the hypocenters from your methodology are a significant improvement over what we are obtaining with the methodology we are using at that time, the implementation of the process would then involve your working with someone who is actually writing code for NEIC operations." In April 2005, Won-Young Kim and Richards discussed this project further with Dr. Harley Benz and Dewey, and it is our understanding that this project is deemed relevant by NEIC personnel. The use of SSSCs would appear to us to be by far the most effective approach to making allowance for 3D structure in the interpretation of arrival times, because this method so directly summarizes the necessary travel-time information. Our approach based on SSSCs could not have been used with the legacy procedures used so long by NEIC and based on VAX hardware, but we understand that our approach can be incorporated into recently developed software at the NEIC and we at Lamont are willing to work with NEIC personnel to accomplish this, applying a framework in which SSSCs are invoked by software to generate travel times from candidate hypocenters to specific stations. Iteration on such hypocenters requires repeated use of interpolated SSSCs.

We shall welcome input from NEIC at all key phases of the project, beginning with decisions on stations to be calibrated, choices to be made on regionalization, and specialized knowledge on such details (for particular stations) as where the crossover distances are between *Pn*- and *Pg*-waves, and the utility of *Sn* phases (and possibly *Lg*) for event location in particular source regions. We shall very much appreciate being able to incorporate expert information (ad hoc for each station) into our SSSCs for this project, noting that for our East Asia project for the International Monitoring System, we had no opportunities to interact with analysts.

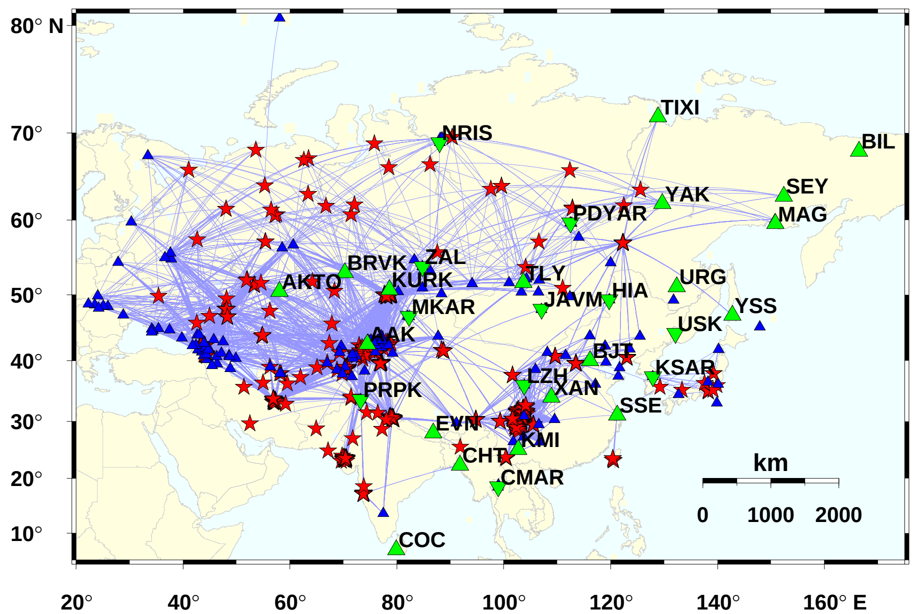

Figure 3. Map of events (red stars) and recording seismic stations (blue triangles) of the data set used for model validation. The green triangles represent the 30 IMS stations that the Lamont Consortium contracted to calibrate. Also shown are great circle *Pn* paths between events and stations.

In our DTRA-funded project to improve the location of seismic events in East Asia, we calibrated 127 stations including 30 IMS stations. We used 36 sub-regions to build a 3D velocity model and associated model-based SSSCs, and developed datasets based upon 525 reference (ground truth) events to obtain kriged SSSCs (both *Pn* and *Sn*). Figure 3 shows stations, reference events, and *Pn* paths.

The SSSCs were initially computed by the method of Bondár (1999), using regionalized 1D travel-time curves established after extensive review of published studies including many from the Russian literature. Subsequently we developed a 3D model of the *P*-wave velocity for East Asia (36 different regions, each with velocity as a function of depth), and used 3D ray tracing in the latter model to compute SSSCs. These model-based SSSCs were refined empirically by applying a kriging algorithm to travel-time residuals for reference/ground-truth (GT) events. Off-line validation tests were performed by evaluating travel-time residuals and by relocating GT events, with and without using SSSCs. To test the validity of the model directly, relocation tests were first performed using model-based SSSCs without kriging. Tests were then performed to evaluate the kriged SSSCs, using a leave-one-out approach so that events were not simultaneously used to both compute and test the SSSCs.

Nuclear explosions dominated our ground-truth datasets in the first two years of this project. In particular we used source parameters for Soviet-era Peaceful Nuclear Explosions (PNEs). But this approach, while quite satisfactory for calibrating stations in much of Russia and Central Asia (which made up approximately half the IMS stations we studied) could not be extended to the remaining stations, for which it was necessary to develop GT information on significant numbers of earthquakes. By use of the double-difference method and detailed fault maps, we obtained 64 GT5 (ground truth known to within 5 km) earthquakes by re-analyzing the Annual Bulletin of Chinese Earthquakes (ABCE) for a 15-year period (1985 to 1999). It contains phase picks for approximately 1000 earthquakes in and near China, each year. [As part of this work we conducted a preliminary examination of digital waveforms for about 14,000 events, in and near China, which showed that approximately 9% of them (1301 events) have the property that any one event has almost the same *Lg* waveform as at least one other event. These events are grouped into 494 sets of events, each of which has essentially the same short-period waveform and thus the events of each set must be within about 1 km of each other. These event sets provide a good method for assessing the quality of standard event catalogs. When combined with other information, they can provide high-quality absolute locations. Schaff and Richards had a paper in SCIENCE on this subject in February 2004.]

Case	IASP91		Model-Based SSSCs		Model + Kriged SSSCs	
	$\mu_{\Delta T}(s)$	$\sigma_{\Delta T}(s)$	$\mu_{\Delta T}(s)$	$\sigma_{\Delta T}(s)$	$\mu_{\Delta T}(s)$	$\sigma_{\Delta T}(s)$
Pn	1.89	1.77	1.33	1.48	0.22	1.01
Sn	6.08	4.24	3.08	3.76	1.34	3.76

Table 2. Mean and standard deviation of travel time residuals, for all stations calibrated in East Asia by the Lamont Consortium that recorded 3 or more reference events. Note the very significant reduction in mean and standard deviation, obtained by kriging.

As an overall indication of how well our SSSCs reduced the misfit between observed and calculated arrival times, Table 2 shows RMS values for the mean and standard deviation of the *Pn* and *Sn* travel-time residuals for all the stations that recorded at least 3 GT events. The kriged results were obtained via a leave-one-out approach in the generation of SSSCs, so that the arrival times from any one event were not used to provide the location estimate in that case. From this Table, we see that a very significant reduction of residuals was obtained by kriging.

Using Pn and Sn arrival times for our GT data sets, we relocated 525 events recorded by various combinations of 140 regional stations. Mislocations in East Asia were reduced for 66% of the events using the model-based SSSCs, and for 85% of the events using model-based SSSCs refined by kriging. In Table 3 we summarize the main location performance metrics when Pn and Sn arrivals were used with and without SSSCs. Extensive documentation is available (a 281-page technical report, and a CD with all supporting data).

Case	IASP91	Model-Based SSSCs	Model + Kriged SSSCs
Median mislocation (km)	16.9	11.4	6.5
Events with reduced mislocation		66%	85%
Median error ellipse area (km^2)	2,616	1,663	722
Events with smaller ellipses		99%	100%
90% coverage	89%	91%	92%

Table 3. Location performance metrics achieved by the Lamont Consortium for event location in East Asia using *Pn* and *Sn*. Note the significant reduction in mislocation, and in area of confidence ellipses, while retaining the property that the error ellipse contains the event ~90% of the time.

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CURRICULUM VITAE: PAUL G. RICHARDS

1965 B.A. (Mathematics), University of Cambridge
1966 M.S. (Geology) California Institute of Technology
1970 Ph.D. (Geophysics), California Institute of Technology
1987 - present Mellon Prof. of Nat. Sciences, Columbia Univ.
1985 - present Member, AFTAC Seismic Review Panel,
2000 – present Member, NAS panel on Technical Issues associated with CTBT Ratification

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CURRICULUM VITAE: WON-YOUNG KIM

1973 B. S. (Geology), Yonsei University, Seoul, Korea

1977 M. S. (Geophysics), Yonsei University, Seoul, Korea;
1980 Diploma di Perfezionamento in Fisica (Geophysics), University of Trieste, Italy;
1986 Ph.D. (Seismology), Faculty of Science, Uppsala University
1988 -1989 Post-Doctoral Fellow in Geology, Harvard University.
1989 - 2004 Research Scientist at Lamont-Doherty Earth Observatory of Columbia University
2004 - present Senior Research Scientist at LDEO, Columbia University

Professional Service:
Member of the IASPEI Working Group on magnitudes
Advanced National Seismic System (ANSS) - member of the ANSS-NE Regional Working Group.
Member, ANSS Working Group A on National Performance Standard.

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Synergistic Activities:
PI, Lamont-Doherty Cooperative Seismographic Network (LCSN; 1992-present)
PI, Installation and operation of 8 broadband seismographic stations in Kazakstan (1994-2001).

CURRICULUM VITAE: WILLIAM MENKE

1976 BS, MS (Earth and Planetary Science), MIT
1978 M.Phil. (Geological Sciences) Columbia University
1982 Ph.D. (Geological Sciences), Columbia University
1982 – 1986 Assistant Professor, Oregon State University
1986 – 1992 Associate Professor, Columbia University
1992 – present Professor, Columbia University
2002 – 2004 Chairman, Department of Earth and Environmental Sciences, Columbia Univ

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Ridge Multibeam Synthesis Project and associated database, 1995.

CURRICULUM VITAE: **DAVID SCHAFF**

1990 - 1994 B.A., Northwestern University
1994 - 2001 Ph.D. (Geophysics), Stanford University
1993 - 1994 Research Assistant, Geology, Northwestern University
1994 - 2001 Research Assistant, Geophysics, Stanford University
2001 - 2004 Postdoctoral Research Scientist, Columbia University
2004 - present Doherty Associate Research Scientists at Lamont-Doherty Earth Observatory

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CURRICULUM VITAE: **FELIX WALDHAUSER**

1992 Diploma (Geophysics), ETH-Zurich
1996 Ph.D. (Geophysics), ETH-Zurich
1993 - 1996 Research & Teaching Assistant, ETH-Zurich
1997 Postdoctoral Research Scientist, ETH-Zurich
1998 - 2000 Postdoctoral Fellow, U. S. Geological Survey, Menlo Park
1999 - 2000 Visiting Scholar/Research Scientist, Stanford University
2001 - present Doherty Associate Research Scientist, Lamont-Doherty Earth Observatory, Columbia Univ.

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Institutional qualifications

This proposed research will be carried out within the Seismology, Geology, and Tectonophysics group at the Lamont-Doherty Earth Observatory of Columbia University, which has conducted research for several decades in almost all facets of seismology, including hazard reduction.

All the scientists involved in this work have access to a network of high-performance Sun workstations, including four Blade 100s, each with 2GB of RAM, and one Ultra 80. All software needed for the proposed research is available to the researchers. They also have access to a 32-node Linux cluster with 64 processors (1.2 GHz Athons) having 1 GB RAM per node.

The scientists involved in this work have access to excellent library facilities. At no cost to the project, they will also be able to draw upon the experience of colleagues at Lamont, including Lynn Sykes, Klaus Jacob, Nano Seeber, Jim Gaherty, Art Lerner-Lam, and Charles Wilson, all of whom have considerable expertise in earthquake location and/or studies of shallow Earth structure.

Project management plan

The proposed work will engage five scientists at Lamont, who bring very different skills to the project. Bill Menke will lead in the practical work of travel time computation for regional seismic waves in 3D crust/mantle structures. Felix Waldhauser will lead in earthquake relocation efforts, needed as part of the work of accumulating reference events (which will entail relocation of event clusters) as well as in the work of validation of our claims of location improvement. David Schaff will take overall responsibility for data management and evaluation, so that at any give stage it is clear to all participants what is the current 3D model we are working with (and its associated travel times), what reference events we have accumulated (and the empirical data associated with them) and what capability we have achieved (in terms of reduced travel time residuals, and location improvements). Won-Young Kim will take the lead in data acquisition and waveform analysis as needed (travel time data and waveforms for reference events, establishing event depth and relative location of aftershocks). Paul Richards will take overall responsibility for project management, coordinating different elements of the work, interactions with NEIC personnel, writing reports, and communicating results in different forums.

We have included travel for two people from Lamont each year to work for four days at NEIC, there to facilitate identification of practical problems and their best practical solutions. We shall also welcome any visits of NEIC personnel to Lamont to participate in ongoing discussion of practical problems and their resolution.

Our plan for this two-year project includes the following steps, each associated with the names of one or more key personnel at Lamont:

YEAR 1
By month 2: Consult with NEIC personnel and agree on the list of stations to be calibrated in this project. A tentative list is included in the proposal text. [Richards, Kim]

Throughout this first year, and to be finalized after 12 months: Consult with NEIC personnel on the list of suitable reference events. See Figure 2 for candidates, which we expect can be augmented by large mineblasts in the intermountain west, and by well-recorded earthquakes earlier than 1990. [Richards, Kim]

Throughout this first year, and to be finalized after 12 months: Acquire hypocentral information and empirical travel times for reference events. Incorporate travel time information from explosion studies (Project Early Rise, O-NYNEX). [Kim, Schaff]

By month 3: Consult with NEIC personnel and others, to define an initial regionalization of the 40 most eastern states of the United States (sub-region boundaries, crustal/upper mantle P and S velocities in each sub-region), and also to agree on one or two depths (?5 km and 15km?) for which SSSCs will be obtained. [Menke, Waldhauser, Kim]

Throughout this first year, and to be finalized after 12 months: Adapt 3D raytracing software to our specific needs, to enable computation of model-based SSSCs for *Pg*, *Pn*, *Sn*, *Lg* (*Sg*). [Menke]

Throughout this first year, and to be finalized after 12 months: Begin comparison between model-based SSSCs and empirical travel-time data from reference events. [Menke, Schaff, Waldhauser, Kim]

Last 3 months of year 1: Refine regionalization as appropriate, to fit explosion datasets and (if possible) other reference event datasets, especially to identify cross-over distances (where *Pg* and *Pn* cross over as first arrivals). [Menke, Kim]

YEAR 2
First 2 months: Obtain kriged SSSCs. [Kim, Menke]

First 6 months: Assess the reduction in travel-time residuals, for explosion data and reference event data, when standard models (J-B, ak135) are compared with (a) model-based SSSCs, and (b) kriged SSSCs. [Menke, Schaff]

Throughout year 2: Carry out numerous relocations of reference events, to assess the effectiveness of model-based SSSCs and kriged SSSCs (contrasted with no SSSCs — the situation today); and the merits of using later arrivals. To the extent we achieve significant location improvement, use leave-one-out methods in kriging, for regions where reference events are close together, to allow reference events to be used for an overall validation of our claims of location improvement. [Waldhauser, Schaff, Kim, Richards]

Final Report and scientific paper. [Richards, Menke, Kim, Schaff, Waldhauser]

Current & Pending Support -- Kim

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