FORMAT 2

Submit originals (including syllabus) and one copy and electronic copy to the **Faculty Senate Office**
See http://www.uaf.edu/uafgov/faculty-senate/curriculum/course-degree-procedures-/ for a complete description of the rules governing curriculum & course changes.

CHANGE COURSE (MAJOR) and DROP COURSE PROPOSAL
Attach a syllabus, except if dropping a course.

SUBMITTED BY:

Department	Geosciences	**College/School**	CNSM
Prepared by	Carl Tape	**Phone**	X5456
Email Contact	ctape[a]alaska.edu	**Faculty Contact**	(same)

1. COURSE IDENTIFICATION: As the course now exists.

Dept	GEOS	Course #	626	No. of Credits	3

COURSE TITLE	Applied Seismology

2. ACTION DESIRED: √ Check the changes to be made to the existing course.

Change Course	X	If Change, indicate below what is changing.	Drop Course	

NUMBER		**TITLE**		**DESCRIPTION**	
PREREQUISITES*	X			***FREQUENCY OF OFFERING***	

*Prerequisites will be *required* before a student is allowed to enroll in the course.

CREDITS (including credit distribution)	4 (3+3)	***COURSE CLASSIFICATION***	

ADD A STACKED LEVEL *(400/600)* *Include syllabi.*		Dept.		Course #	

How will the two course levels differ from each other? How will each be taught at the appropriate level?:	

Stacked course applications are reviewed by the (Undergraduate) Curricular Review Committee and by the Graduate Academic and Advising Committee. Creating two different syllabi—undergraduate and graduate versions—will help emphasize the different qualities of what are supposed to be two different courses. The committees will determine: 1) whether the two versions are sufficiently different (i.e. is there undergraduate and graduate level content being offered); 2) are undergraduates being overtaxed?; 3) are graduate students being undertaxed? In this context, the committees are looking out for the interests of the students taking the course. Typically, if either committee has qualms, they both do. More info online – see URL at top of this page.

ADD NEW CROSS-LISTING		Dept. & No.		Requires approval of both departments and deans involved. Add lines at end of form for additional signatures.
STOP EXISTING CROSS-LISTING		Dept. & No.		Requires notification of other department(s) and mutual agreement. Attach copy of email or memo.
OTHER (specify)				

3. COURSE FORMAT

NOTE: Course hours may not be compressed into fewer than three days per credit. Any course compressed into fewer than six weeks must be approved by the college or school's curriculum council **and** the appropriate Faculty Senate curriculum committee. Furthermore, **any core course compressed to less than six weeks must be approved by the Core Review Committee.**

COURSE FORMAT: (check **all** that apply)		*1*		*2*		*3*		*4*		*5*	X	*6 weeks to full semester*

OTHER FORMAT (specify all that apply)	
Mode of delivery (specify lecture, field trips, labs, etc.)	1. lectures 2. computational laboratory sessions

RECEIVED

SEP 1 9 2014

Dean's Office
College of Natural Science & Mathematics

Governance
9/30/14 TLP

4. **COURSE CLASSIFICATIONS:** (undergraduate courses only. Use approved criteria found in Chapter 12 of the curriculum manual. If justification is needed, attach separate sheet.)

H = Humanities		S = Social Sciences	

Will this course be used to fulfill a requirement for the baccalaureate core?	**YES**		**NO**	X

IF YES*, check which core requirements it could be used to fulfill:

O = Oral Intensive, ***Format 6** also submitted		W = Writing Intensive, ***Format 7** submitted		X = Baccalaureate Core	

4.A ***Is course content related to northern, arctic or circumpolar studies? If yes, a "snowflake" symbol will be added in the printed Catalog, and flagged in Banner.***

YES	X	NO	

5. **COURSE REPEATABILITY:**

Is this course repeatable for credit?	**YES**		**NO**	X

Justification: Indicate why the course can be repeated (for example, the course follows a different theme each time).	

How many times may the course be repeated for credit?		**TIMES**
If the course can be repeated with variable credit, what is the maximum number of credit hours that may be earned for this course?		**CREDITS**

6. ***COMPLETE CATALOG DESCRIPTION including dept., number, title, credits, credit distribution, cross-listings and/or stacking, clearly showing the changes you want made. (Underline new wording ~~strike through old wording~~ and use complete catalog format including dept., number, title, credits and cross-listed and stacked.)***

Example of a complete description:

PS F450 Comparative ~~Aboriginal~~ Indigenous Rights and Policies (s)
3 Credits
Offered As Demand Warrants
~~Case study~~ Comparative approach ~~in assessing Aboriginal~~ to analyzing Indigenous rights and policies in different nation-state systems. ~~Seven Aboriginal situations~~ Multiple countries and specific policy developments examined for factors promoting or limiting self-determination. Prerequisites: Upper division standing or permission of instructor. (Cross-listed with ANS F450.) (3+0)

GEOS F626 Applied Seismology
~~3~~4 Credits
Offered Spring Even-numbered Years
Presentation of modeling techniques for earthquakes and Earth structure using wave propagation algorithms and real seismic data. Covers several essential theories and algorithms for applications in seismology, as well as the basic tools needed for processing and using recorded seismograms. Topics include the seismic wavefield (body waves and surface waves), earthquake moment tensors, earthquake location, and seismic tomography. Assignments require familiarity with vector calculus, linear algebra, and computational tools such as Matlab. Prerequisites: ~~GEOS F431 or GEOS F631~~ MATH F202X and MATH F314; or permission of instructor. (3+~~0~~3)

7. ***COMPLETE CATALOG DESCRIPTION AS IT SHOULD APPEAR AFTER ALL CHANGES ARE MADE:***

GEOS F626 Applied Seismology
4 Credits
Offered Spring Even-numbered Years
Presentation of modeling techniques for earthquakes and Earth structure using wave propagation algorithms and real seismic data. Covers several essential theories and algorithms for applications in seismology, as well as the basic tools needed for processing and using recorded seismograms. Topics include the seismic wavefield (body waves and surface waves), earthquake moment tensors, earthquake location, and seismic tomography. Assignments require familiarity with vector calculus, linear algebra, and computational tools such as Matlab. Prerequisites: MATH F202X and MATH F314; or permission of instructor. (3+3)

8. *GRADING SYSTEM:* *Specify only one.*

LETTER:	X	PASS/FAIL:	

9. *ESTIMATED IMPACT*

WHAT IMPACT, IF ANY, WILL THIS HAVE ON BUDGET, FACILITIES/SPACE, FACULTY, ETC.

10. *LIBRARY COLLECTIONS*

Have you contacted the library collection development officer (kljensen@alaska.edu, 474-6695) with regard to the adequacy of library/media collections, equipment, and services available for the proposed course? If so, give date of contact and resolution. If not, explain why not.

No		Yes	X	For the original course, I spoke with Karen Jensen on 9/8/2011 and also informed Flora Grabowska. The reserve books are held at Mather Library.

11. *IMPACTS ON PROGRAMS/DEPTS:*

What programs/departments will be affected by this proposed action?

Include information on the Programs/Departments contacted (e.g., email, memo)

The change means that Applied Seismology (GEOS 626) will require computational labs from now onwards. This is a major undertaking for teaching the class, whether it is I or someone else. But this is what is needed to train graduate students in seismology.

This change will increase my teaching workload for this course from 3 to 4 units. In principle, this makes me slightly less available to fill in where teaching units are needed in the Department of Geology and Geophysics.

12. *POSITIVE AND NEGATIVE IMPACTS*

*Please specify **positive and negative** impacts on other courses, programs and departments resulting from the proposed action.*

I do not see impacts on other courses, programs, or departments, though there could be some impact on students. The positive impact is that a MS student taking this class will get the 4 credits that the work amounts to; this extra credit can be used to fulfill the degree requirement (MS only). The negative impact is potentially that some students might be deterred from the workload implied by the 4 credits instead of 3. However, all students thus far have been graduate students who need applied experience in seismology; my sense is that the number of credits would be no deterrent.

13. *JUSTIFICATION FOR ACTION REQUESTED*

The purpose of the department and campus-wide curriculum committees is to scrutinize course change and new course applications to make sure that the quality of UAF education is not lowered as a result of the proposed change. Please address this in your response. This section needs to be self-explanatory. If you ask for a change in # of credits, explain why; are you increasing the amount of material covered in the class? If you drop a prerequisite, is it because the material is covered elsewhere? <u>If course is changing to stacked (400/600), explain higher level of effort and performance required on part of students earning graduate credit</u>. Use as much space as needed to fully justify the proposed change and explain what has been done to ensure that the quality of the course is not compromised as a result.

I taught Applied Seismology in 2012 (6 graduate students) and in 2014 (7 graduate students). Based on the design of the course and the feedback from the students (to each problem set and within the 2012 course evaluations), I have come to realize that a formal lab is needed in order to (1) reflect the nature of the course, which has regular computational labs (each student is given a Linux account) and (2) better reflect the high workload demand of the course. The course is centered on 10 challenging problems sets, all of which have separate computational lab exercises associated with them. I ask the students how many hours each problem set takes, and the average is about 15 hours. This number can be reduced by introducing formal computational lab exercises to give the students targeted training for the problem sets. Applied training in seismology requires considerable hands-on experience with computer programs and real seismic waveforms. I do not believe that this can be achieved without the high workload and computational lab sessions. Therefore I am seeking to formally introduce computational lab sessions, thereby increasing the credits from 3 (3+0) to 4 (3+3).

I encourage the reviewer of this proposed course change to examine the course content (problem sets and labs) that are posted on this website:

http://www.giseis.alaska.edu/input/carl/teaching/seis/aseis.html

This helps to convey the importance of the computational labs within the course. (Note: not all labs are posted.)

The minor change in the prerequisites reflects the fact that what is needed for this class is linear algebra and vector calculus. There is the possibility that a student could take GEOS 631 (the current prerequisite) while not having taken linear algebra. The proposed prerequisites make this explicit.

Please feel free to contact me directly if you have any questions (carltape@gi.alaska.edu).

APPROVALS: (Additional signature blocks may be added as necessary.)

[signature]	Date	9-18-14
Signature, Chair, Program/Department of:	GEOSCIENCES	
[signature]	Date	9-25-14
Signature, Chair, College/School Curriculum Council for:	CNSM	
[signature]	Date	9/26/14
Signature, Dean, College/School of:	CNSM	

Offerings above the level of approved programs must be approved in advance by the Provost:

	Date	
Signature of Provost (if applicable)		

ALL SIGNATURES MUST BE OBTAINED PRIOR TO SUBMISSION TO THE GOVERNANCE OFFICE.

	Date	

Signature, Chair
Faculty Senate Review Committee: ___Curriculum Review ___GAAC

___Core Review ___SADAC

ADDITIONAL SIGNATURES: (As needed for cross-listing and/or stacking; add more blocks as necessary.)

	Date	
Signature, Chair, Program/Department of:		
	Date	
Signature, Chair, College/School Curriculum Council for:		
	Date	
Signature, Dean, College/School of:		

Note: If removing a cross-listing, attach copy of email or memo to indicate mutual agreement of this action by the affected department(s). If degree programs are affected, a Format 5 program change form must also be submitted.

UNIVERSITY OF ALASKA FAIRBANKS

QUICK REFERENCE: Section 8 contains the calendar of topics and deadlines.

Last compiled: April 4, 2014

1. **Course information.**

GEOS 626	**Applied Seismology**, 4 credits (3+3), Spring 2016
Lecture times:	Tuesday and Thursday, 9:45–11:15
Lab time	Tuesday, 11:30–14:30
Meeting location:	TBA
Prerequisites:	MATH 314 (Linear Algebra) and MATH 202 (Calculus III) GEOS 604 (Seismology) is a recommended prerequisite

2. **Instructor information.**

Instructor:	**Carl Tape**
Office:	413D Elvey (Geophysical Institute)
Email:	`carltape@gi.alaska.edu`
Phone:	(907) 474-5456
Office hours:	Wednesday, 10:00–11:00, or by appointment

3. **Course materials.**

   (a) **Textbooks.** The required (R) and supplemental (S) textbooks are (see "References" at the end of this syllabus) listed in the following table. The G.I. Mather library is located in the IARC/Akasofu building.

Textbook	R	S	Availability: UAF bookstore	Mather reserve	PDF	UAF e-book
[1] Stein and Wysession	X			X		X
[2] Shearer	X			X		
[3, 4, 5, 6, 7, 8, 9]		X		X		

   (b) Journal articles assigned as reading will be available as PDFs through the course website on UAF Blackboard.

   (c) Students will need computers for their homework. General-use computers in UAF labs will be made available to students if needed.

   (d) Matlab will be the primary computational program for the course. Matlab is available via a UAF-wide license.

4. **Course description.**

   Seismology combines observational data (seismograms) with numerical modeling methods to obtain powerful inferences about earthquake sources and the three-dimensional structure of Earth's interior. *Applied Seismology* will provide essential training for students' interested in academic, industrial, or governmental careers in seismology.

   Catalog description: Presentation of modeling techniques for earthquakes and Earth structure using wave propagation algorithms and real seismic data. Covers several essential theories and algorithms for applications in seismology, as well as the basic tools needed for processing and using recorded seismograms. Topics include the seismic wavefield (body waves and surface waves), earthquake moment tensors, earthquake location, and seismic tomography. Assignments require familiarity with linear algebra and computational tools such as Matlab.

5. **Course goals.**

   We will explore the study of earthquakes and Earth's interior structure using seismological theories and algorithms. The underlying physical phenomenon we will examine is the seismic wavefield: the time-dependent, space-dependent elastic waves that originate at an earthquake source (for example, a fault slips) and propagate though the heterogeneous Earth structure, then are finally recorded as time series at seismometers on Earth's surface. Students will examine real seismic data and use computational models to estimate properties about earthquake source and Earth structure. Students will acquire practical, advanced seismological training that will prepare them for seismological investigations in the future, whether in academic, industry, or government jobs.

6. **Student learning outcomes.**

   Upon completion of this course, students should be able to:

   (a) Understand the relevant temporal, spatial, and magnitude scales in the field of seismology.

   (b) Describe the physical quantities that govern seismic wave propagation.

   (c) Describe the seismic phases that arise in a regional or global layered Earth model.

   (d) Describe the seismic moment tensor, the fundamental model of an earthquake source.

   (e) Understand the basic framework of inverse problems within the context of seismology.

   (f) Describe several different seismological tools that can be used to investigate an individual earthquake.

   (g) Understand the connection between earthquakes, continental deformation, and plate tectonics.

   (h) Understand the distinction between one-dimensional and three-dimensional Earth structure, and how this affects theory and algorithms in seismology.

   (i) Read seismological journal articles and summarize the content efficiently.

   (j) Write, improve, and run simple computational algorithms in Matlab.

   (k) Plot and manipulate recorded seismograms.

7. **Instructional methods.**

   (a) Assignments and grades (along with general course information and handouts) will be posted on Blackboard: `classes.uaf.edu`.

   (b) Lectures will be the primary mode of instruction. Some lectures will be supplemented with computational examples to prepare students for homework problems.

8. **Course calendar (tentative).**

	Day	Date	Topic	Reading Due†	Homework Due	Homework Assigned
1	Thurs		Seismology in 1916, 2016, and 2116	SW1, S1	—	HW-1
2	Tues		Introduction to Seismology	SW1, S1		
	Tues		LAB: Linux and Matlab			
3	Thurs		Linear algebra and vectors	SW-A, S-B	HW-1	HW-2
4	Tues		Linear algebra and vectors	SW-A, S-B		
	Tues		LAB: linear algebra			
5	Thurs		Seismic moment tensor	SW4.4, S9	HW-2	HW-3
6	Tues		Seismic moment tensor	notes		
	Tues		LAB: Seismic moment tensors (`lab_mt.pdf`)			
7	Thurs		Fourier transform	SW6, S-E	HW-3	HW-4
8	Tues		Fourier transform	notes		
	Tues		LAB: Fourier transform, seismic spectra (`lab_fft.pdf`)			
9	Thurs		The 2004 Sumatra earthquake	[10, 11, 12, 13]		
10	Tues		Processing seismic data	SW6, [14]		
	Tues		LAB: Instrument response (`lab_response.pdf`)			
11	Thurs		Waves on a string	SW2	HW-4	HW-5
12	Tues		Normal modes: theory and observations	SW2.9, S8.6		
	Tues		LAB: spherical harmonics; toroidal modes			
13	Thurs		Normal modes: theory and observations	DT10.5	HW-5	
14	Tues		Review HW4 and HW5			HW-6
	Tues		LAB: Analyzing seismic data (`lab_seismo_rs.pdf`)			
15	Thurs		Seismic data analysis			
16	Tues		The 2004 Sumatra earthquake	[10, 11, 12, 13]		
	Tues		LAB: Sumatra earthqquake			
17	Thurs		Great earthquakes since 2000		HW-6	HW-7
	Tues		SPRING BREAK			
	Thurs		SPRING BREAK			
18	Tues		Surface waves: theory and observations	SW2.7-2.8, S8		
	Tues		LAB: Love waves layer-over-halfspace model			
19	Thurs		Surface waves: theory and observations	SW2.7-2.8, S8	HW-7	HW-8
20	Tues		Introduction to inverse problems	SW7		
	Tues		LAB: least squares (`lab_linefit.pdf`)			
21	Thurs		Introduction to least squares	SW7, notes	HW-8	HW-9
22	Tues		Seismic tomography: global	S5, SW7.3		
	Tues		LAB: seismic tomography			
23	Thurs		Seismic tomography: crustal	SW3.2-3.3	HW-9	HW-10
24	Tues		Least-squares inverse theory	T3		
	Tues		LAB: Newton method (`lab_newton.pdf`)			
25	Thurs		Iterative methods	T6.22		
26	Tues		Adjoint methods in seismology	[15, 16]	HW-10	
	Tues		LAB: surface wave dispersion (`lab_dispersion.pdf`)			
27	Thurs		Finite source models	S9.8, WS4.5		
28	Tues		Seismology in the oil industry	S7, WS3.3		
	Tues		LAB: TBD			
29	Thurs		Seismic monitoring for nuclear activity	[17]		

†SW = Ref. [1]; S = Ref. [2]; DT = Ref. [5]; T = Ref. [18]
For example, "SW2.9" means Section 2.9 of Stein and Wysession (Ref. [1])

Some Important Dates:

First class:	Thursday	January XX
Last day to add class:	Friday	January XX
Last day to drop class:	Friday	January XX
Last day for student- or faculty-initiated withdraw:	Friday	March XX
Last class:	Thursday	May XX

9. **Course policies.**

(a) **Attendance:** All students are expected to attend and participate in all classes.

(b) **Participation and preparation:** Students are expected to come to class with assigned reading and other assignments completed as noted in the syllabus.

(c) **Assignments:**

i. All assignments are due **at the start of class** on the due date.

ii. Late assignments will be accepted with a 10% penalty per day late, up to five days late; an assignment that is ≥ 5 days late will receive a zero. (An assignment that is "one day late" would be handed in less than 24 hours after the start time of class on the due date.)

iii. No digital submission of assigments will be accepted (e.g., email or Blackboard).

Homework Tips: Please type or write neatly, keep the solutions in the order assigned and staple pages together. Include only relevant computer output in your solutions (a good approach is to cut and paste the relevant output for each problem into an editor such as MS Word or Latex). Also clearly circle or highlight important numbers in the output, and label them with the question number.

I also suggest that you to include the most relevant portions of your Matlab code in your answers, especially in cases when you think your code is not working. Display numerical answers with a reasonable number of significant figures and with *units* if the quantity is not dimensionless.

Homework scores are based on clarity of work, logical progression toward the solution, completeness of interpretation and summaries, and whether a correct solution was obtained.

(d) **Graded Assignments:** Assignments will be graded for students within seven days of their receipt.

(e) **Reporting Grades:** All student grades, transcripts and tuition information are available on line at `www.uaonline.alaska.edu`.

(f) **Consulting fellow students:** Students are permitted to discuss with each other general strategies for particular homework problems. However, the write-up that is handed in—including any computer codes—must be individual work.

(g) **Plagiarism:** Students must acknowledge any sources of information—including fellow students—that influenced their homework assignments or final project. Any occurrence of plagiarism will result in forfeiture of all points for the particular homework assignment. If the plagiarism is between two students, then both students will potentially receive the penalty.

(h) All UA student academics and regulations are adhered to in this course. You may find these in the UAF catalog (section "Academics and Regulations").

10. **Evaluation.**

(a) Grading is based on:

5%	Attendance and participation in lectures and labs
95%	Homework assignments

(b) Overall course grades are based on the following criteria:

A	$x \geq 93$	excellent performance:
A–	$90 \leq x < 93$	student demonstrates deep understanding of the subject
B+	$87 \leq x < 90$	strong performance:
B	$83 \leq x < 87$	student demonstrates strong understanding of the subject,
B–	$80 \leq x < 83$	but the work lacks the depth and quality needed for an 'A'
C+	$77 \leq x < 80$	mediocre performance:
C	$73 \leq x < 77$	student demonstrates comprehension of some
C–	$70 \leq x < 73$	essential concepts only
D	$60 \leq x < 70$	poor performance:
		student demonstrates poor comprehension of concepts
F	$x < 60$	Failure to complete work with 60% quality

(c) **Research Project.** Students have the option of of substituting a research project for any 2 homework assignments. The project will involve independent research into one aspect of seismology. It will require some computation and will be presented in the form of a written report, due on the last lecture class of the semester, and a short in-class presentation at the end of the semester. The report will be written in manuscript-submission style and format, using the guidelines for *Geophysical Research Letters.* Additional details, including project suggestions, will be provided by the instructor midway through the course.

11. **Support Services.**

The instructor is available by appointment for additional assistance outside session hours. UAF has many student support programs, including the Math Hotline (1-866-UAF-MATH; 1-866-6284) and the Math and Stat Lab in Chapman building (see `www.uaf.edu/dms/mathlab/` for hours and details).

12. **Disabilities Services.**

The Office of Disability Services implements the Americans with Disabilities Act (ADA), and it ensures that UAF students have equal access to the campus and course materials. The Geophysics Program will work with the Office of Disability Services (208 Whitaker, 474-5655) to provide reasonable accommodation to students with disabilities.

13. **References listed in syllabus.**

[1] S. Stein and M. Wysession, *An Introduction to Seismology, Earthquakes, and Earth Structure.* Malden, Mass., USA: Blackwell, 2003.

[2] P. M. Shearer, *Introduction to Seismology.* Cambridge, UK: Cambridge U. Press, 2 ed., 2009.

[3] B. L. N. Kennett, *The Seismic Wavefield: Introduction and Theoretical Development*, vol. 1. Cambridge, UK: Cambridge U. Press, 2001.

[4] B. L. N. Kennett, *The Seismic Wavefield: Interpretation of Seismograms on Regional and Global Scales*, vol. 2. Cambridge, UK: Cambridge U. Press, 2002.

[5] F. A. Dahlen and J. Tromp, *Theoretical Global Seismology.* Princeton, New Jersey, USA: Princeton U. Press, 1998.

[6] T. Lay and T. C. Wallace, *Modern Global Seismology.* San Diego, Calif., USA: Academic Press, 1995.

[7] K. Aki and P. G. Richards, *Quantitative Seismology.* San Francisco, Calif., USA: University Science Books, 2 ed., 2002. 2009 corrected printing.

[8] L. E. Malvern, *Introduction to the Mechanics of a Continuous Medium.* Upper Saddle River, New Jersey, USA: Prentice-Hall, 1969.

[9] R. C. Aster, B. Borchers, and C. H. Thurber, *Parameter Estimation and Inverse Problems.* Waltham, Mass., USA: Elsevier, 2 ed., 2012.

[10] T. Lay, H. Kanamori, C. J. Ammon, M. Nettles, S. N. Ward, R. C. Aster, S. L. Beck, S. L. Bilek, M. R. Brudzinski, R. Butler, H. R. DeSchon, G. Ekström, K. Satake, and S. Sipkin, "The great Sumatra-Andaman earthquake of 26 December 2004," *Science*, vol. 308, pp. 1127–1133, 2005.

[11] C. J. Ammon, C. Ji, H.-K. Thio, D. Robinson, S. Ni, V. Hjorleifsdottir, H. Kanamori, T. Lay, S. Das, D. Helmberger, G. Ichinose, J. Polet, and D. Wald, "Rupture process of the 2004 Sumatra-Andaman earthquake," *Science*, vol. 308, pp. 1133–1139, 2005.

[12] J. Park, T.-R. A. Song, J. Tromp, E. Okal, S. Stein, G. Roult, E. Clevede, G. Laske, H. Kanamori, P. Davis, J. Berger, C. Braitenberg, M. V. Camp, X. Lei, H. Sun, H. Xu, and S. Rosat, "Earth's free oscillations excited by the 26 December 2004 Sumatra Andaman earthquake," *Science*, vol. 308, pp. 1139–1144, 2005.

[13] S. Ni, D. Helmberger, and H. Kanamori, "Energy radiation from the Sumatra earthquake," *Nature*, vol. 434, p. 582, 2005.

[14] C. G. Reyes and M. E. West, "The Waveform Suite: A robust platform for manipulating waveforms in MATLAB," *Seis. Res. Lett.*, vol. 82, pp. 104–110, 2011.

[15] Q. Liu and J. Tromp, "Finite-frequency kernels based on adjoint methods," *Bull. Seis. Soc. Am.*, vol. 96, no. 6, pp. 2383–2397, 2006.

[16] C. Tape, Q. Liu, and J. Tromp, "Finite-frequency tomography using adjoint methods—Methodology and examples using membrane surface waves," *Geophys. J. Int.*, vol. 168, pp. 1105–1129, 2007.

[17] D. Bowers and N. D. Selby, "Forensic seismology and the Comprehensive Nuclear-Test-Ban Treaty," *Annu. Rev. Earth Planet. Sci.*, vol. 37, pp. 209–236, 2009.

[18] A. Tarantola, *Inverse Problem Theory and Methods for Model Parameter Estimation.* Philadelphia, Penn., USA: SIAM, 2005.