Supplemental Material—Recording earthquakes for tomographic imaging of the mantle beneath the South Pacific by autonomous MERMAID floats

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S1 DESCRIPTION OF SUPPLEMENTAL TEXT FILES

S1.1 *First-arrival travel-time residuals in the MERMAID catalog:* `simon2020_supplement_residuals.txt`

We use `irisFetch.Events.m` version 2.0.10, one method of a larger software class written in MATLAB and distributed by the Incorporated Research Institutions for Seismology (IRIS; `https://www.iris.edu/hq/`), to query `http://service.iris.edu/fdsnws/event/1/` for event metadata archived at the the IRIS Data Management Center (DMC; `http://ds.iris.edu/ds/nodes/dmc/`). In our supplementary text files we only list the "Preferred" metadata returned by `irisFetch.Events.m`, which we understand to be those metadata preferred by the USGS National Earthquake Information Center (NEIC; `https://earthquake.usgs.gov/contactus/golden/neic.php`, which compiles a global bulletin of earthquake metadata called the PDE for Preliminary Determination of Epicenters), at the time those metadata were reported to IRIS; i.e., they are not necessarily the most up-to-date or currently-preferred values in the NEIC-PDE catalog. For reference, we list both the IRIS event identification number (`http://ds.iris.edu/ds/nodes/dmc/tools/event/<IRIS_ID>`), and an NEIC-PDE event identification number (`https://earthquake.usgs.gov/earthquakes/eventpage/<NEIC_ID>`), and note that the latter may reference multiple origins and/or contributors whose metadata differ from what we print in our supplementary text files. Generally, the NEIC-PDE event identification number we print is prefixed with "us" (Albuquerque Seismological Laboratory (ASL)/USGS 1990, doi:10.7914/SN/US) meaning the preferred event origin metadata was contributed by the NEIC itself, however we also include 16 prefixed with "ak" (Alaska Earthquake Center, University of Alaska Fairbanks (AEC) 1987, doi: 10.7914/SN/AK), and one prefixed with "ci" (California Institute of Technology and United States Geological Survey Pasadena (Caltech and USGS) 1926, doi: 10.7914/SN/CI) in cases when it appears that those authors had contributed the preferred origin-metadata to the NEIC-PDE at the time of archival in the DMC. Therefore, future researchers that utilize the supplemental text files compiled during this study are strongly advised to check for updates to the event metadata included here, especially once they are published in the International Seismological Centre (2015) catalog (Bondár & Storchak 2011).

We use `MatTaup`, written in MATLAB by Qin Li while at the University of Washington (dated November 2002 but without a version number), to compute theoretical travel times in the ak135 model (Kennett et al. 1995), and `LLNL-Earth3D` (`https://www-gs.llnl.gov/nuclear-threat-reduction/nuclear-explosion-monitoring/global-3d-seismic-tomography/`), to compute theoretical travel times in the LLNL-G3Dv3 model of Simmons et al. (2012). Note that `LLNL-Earth3D` provides two timing "water corrections," one corresponding to the event and corresponding to the station, which are to abe added to the travel times in cases when one (or both) appears to be in water due to the limits of the model resolution at that location, but one (or both) are known to be in or on solid rock. All event-side corrections are exactly 0 s in our case, meaning that the model properly located our events in solid rock. Our station-side corrections are not all zero, but they are also *not* included in the 3-D travel times reported in column 28 of the text file described next because MERMAID is known to have been in water at the time of recording. Ocean depths in column 12 are interpolated from GEBCO 2014 (Weatherall et al. 2015). MERMAID station latitude and longitude at the time of recording (around 1500 m depth) are interpolated using the method of Joubert et al. (2016). See the additional text files described in Section S1.3 for those raw GPS fixes.

The supplemental data file `simon2020_supplement_residuals.txt` contains travel-time residuals and other calculations relating only to first-arriving p and P phases identified in our data set. It excludes, for example, the arrival times discussed in Section 8. Note that all times are rounded to two decimals, which means that columns that should sum exactly (e.g., column 24 = column 20 + column 23) may differ by 1/100 s, which is smaller than MERMAID's nominal sampling interval of 1/20 s. Note as well that we use the moniker "'travel" time to refer to the time difference between our AIC pick and the event time, and "arrival" time to refer to the time difference between the same AIC pick and the start of the seismogram.

Lastly, we will use `20180808T014200.08_5B736FA6.MER.DET.WLT5.sac`, the first MERMAID SAC file quoted in the following residuals text file, to explain how MERMAID files are named: "20180808T014200" is the UTC date corresponding to the first sample of the seismogram (truncated to integer seconds), in this case, 8 August 2018 01:42:00 UTC; "08" is the MERMAID serial number excluding the "P0" prefix; "5B736FA6.MER" names the corresponding MERMAID data file from which this SAC file was generated; "DET" means that this seismogram contains a signal detected by MERMAID's onboard algorithm, as opposed to one requested by us; "WLT5" shows that WaveLet Transform coefficient sets corresponding to five (out of a total six) scales were transmitted in the .MER file (resulting in a seismogram with a nominal sampling frequency of 20 Hz after reconstruction via inverse wavelet transform because MERMAID's nominal sampling rate is 40 Hz); and "sac" denotes that this file follows the SAC (Seismic Analysis Code) file format (Helffrich et al. 2013).

The columns of `simon2020_supplement_residuals.txt` are:

(1) SAC filename
(2) Event origin time [UTC]
(3) Event longitude [decimal degrees]
(4) Event latitude [decimal degrees]
(5) Event magnitude value (e.g., 8.1)
(6) Event magnitude type (e.g., $M_{\rm W}$ or $m_{\rm b}$)
(7) Event depth [m]

(8) Timestamp at first sample of seismogram (i.e., the “reference” time in the SAC header (NYZEAR, NZJDAY, ..., NZMSEC) plus any offset in the “B” header field) [UTC]
(9) Interpolated station longitude at time of recording using the method of Joubert et al. (2016) [decimal degrees]
(10) Interpolated station latitude at time of recording using the method of Joubert et al. (2016) [decimal degrees]
(11) Station depth at time of recording [m]
(12) Ocean depth at station location at time of recording according to GEBCO 2014 (Weatherall et al. 2015) [m]
(13) ak135 epicentral distance [decimal degrees]
(14) Difference between ak135 (adjusted for bathymetry and cruising depth) and ak135 epicentral distances (always 0) [decimal degrees]
(15) ak135 (adjusted for bathymetry and cruising depth) epicentral distance (always equal to column 13) [decimal degrees]
(16) Difference between LLNL-3DGv3 and ak135 epicentral distances (the former model is elliptical and the latter is spherical; $=$ column 17 $-$ column 13) [decimal degrees]
(17) LLNL-3DGv3 epicentral distance ($=$ column 13 $+$ column 16) [decimal degrees]
(18) Observed travel time using our AIC pick as described in Section 7 (think “seconds after event”) [s]
(19) Observed arrival time using our AIC pick as described in Section 7 (this is the same AIC pick of column 18, but it is in reference to the time at the start of the seismogram and not the origin time of the event; think “seconds into seismogram”) [s]
(20) Predicted travel time in ak135 [s]
(21) Predicted arrival time in ak135 [s]
(22) Travel-time residual in ak135 (eq. 2; $=$ column 18 $-$ column 20) [s]
(23) Difference between ak135 (adjusted for bathymetry and cruising depth) and ak135 predicted travel times (eq. 6; $=$ column 24 $-$ column 20) [s]
(24) Predicted travel time in ak135 (adjusted for bathymetry and cruising) depth (eq. 5; $=$ column 20 $+$ column 23) [s]
(25) Predicted arrival time in ak135 (adjusted for bathymetry and cruising) depth [s]
(26) Travel time residual in ak135 (adjusted for bathymetry and cruising) depth (eq. 3; $=$ column 18 $-$ column 24) [s]
(27) Difference between LLNL-G3Dv3 and ak135 predicted travel times ($=$ column 28 $-$ column 20) [s]
(28) Predicted travel time in LLNL-G3Dv3 (no event-side correction; station-side correction *not* included because MERMAID in water; $=$ column 20 $+$ column 27) [s]
(29) Predicted arrival time in LLNL-G3Dv3 [s]
(30) Travel time residual in LLNL-G3Dv3 (eq. 4; $=$ column 18 $-$ column 28) [s]
(31) Two-standard deviation estimate of the uncertainty on our AIC pick (i.e., on the observed travel and arrival times, columns 18 and 19, both of which tag the same UTC time, but are given as different elapsed times) using the M1 Method of Simon et al. (2020) [s]
(32) Signal-to-noise ratio using eq. 1 and the definitions of the "signal" and "noise" in Section 7 [rounded, dimensionless]
(33) Maximum amplitude of signal within 1.75 s of arrival [rounded counts]
(34) Time difference between the maximum amplitude and the onset of the signal (think “seconds after AIC pick”) [s]
(35) NEIC-PDE event identification number
(36) IRIS event identification number

Computer code to read and parse `simon2020_supplement_residuals.txt` into a MATLAB structure is available at `https://github.com/joelsimon/omnia/` in a routine called `read_simon2020_supplement_residuals.m`

S1.2 *All events in the MERMAID catalog: `simon2020_supplement_events.txt`*

We also include `simon2020_supplement_events.txt`, a file similar to `simon2020_supplement_residuals.txt`, except that it includes a line for each of the 1345 SAC files processed in the main text. This means that it includes lines for unidentified SAC files (for which we fill event metadata columns with NaNs), as well as identified SAC files that are not, for one reason or another, included in the first-arrival text file above. Reasons for this included: the first arriving phase is not *p* or *P*, e.g., the core-phase arrivals shown in Section 8; or the thresholds discussed in Section 10 on the pick itself were exceeded.

The columns of each `simon2020_supplement_events.txt` are:

(1)–(13) Identical to columns 1–13 in `simon2020_supplement_residuals.txt`, or NaN in columns corresponding to event data for unidentified seismograms
(14)–(15) Identical to columns (35)–(36) `simon2020_supplement_residuals.txt`, or NaN for unidentified seismograms

Computer code to read and parse `simon2020_supplement_events.txt` into a MATLAB structure is available at `https://github.com/joelsimon/omnia/` in a routine called `read_simon2020_supplement_events.m`

S1.3 *Every GPS fix from the SPPIM deployment:* `simon2020_supplement_P0??_gps.txt`

Should other researchers be interested in relocating our stations at the time of recording we also provide individual text files of every GPS fix recorded by MERMAID while at the surface through the first dive cycle completed in 2020. MERMAID records data at depth and then ascends to the surface to transmit those data at a later date with the location at the time of recording interpolated using the method of Joubert et al. (2016). We name these files
`simon2020_supplement_P0??_gps.txt`, where the "??" in "P0??" is understood to mean the unique two-digit serial number of the recording MERMAID; one from the inclusive list $[08, \ldots, 25]$, excluding 14 and 15, which never existed. Note that these text files are truncated versions of larger text files, which themselves are published and continuously updated online, and which include various state-of-health and data-transmission measurements that are useful to the authors and potentially to other scientists. Those fuller text files are available at `http://geoweb.princeton.edu/people/simons/SOM/P0??_all.txt`, using the same "??" notation. The web address
`http://geoweb.princeton.edu/people/simons/SOM/hdr.txt` contains a description of the content and format those text files, and the public repository `https://github.com/earthscopeoceans/serverscripts/` hosts the software used to write them.

The columns of each `simon2020_supplement_P0??_gps.txt` are:

(1) The date and time separated by a single white space character, e.g. 05-Aug-2018 13:25:04
(2) Station GPS latitude [decimal degrees]
(3) Station GPS longitude [decimal degrees]
(4) Horizontal dilution of precision
(5) Vertical dilution of precision

Compute code to read and parse `simon2020_supplement_P0??_gps.txt` into a MATLAB structure is available at `https://github.com/joelsimon/omnia/` in a routine called `read_simon2020_supplement_gps.m`

S2 COMPARING THE HIGHEST-SNR SEISMOGRAMS ACROSS THE INSTRUMENT CLASSES

Fig. S1 redraws Fig. 10 but considering only the subset of data representing events in the MERMAID catalog that occurred while at least one traditional and one Raspberry Shake instrument were installed—i.e., the catalog of events common to all instrument classes. This comparison is made here because some of the larger events present in the data included in Figs 10 and 19 are not in the Raspberry Shake catalog because those stations had not yet been installed.

Figs S2–S4 each plot the 12 highest-SNR signals in this catalog of common events for traditional island stations, MERMAID, and Raspberry Shake island stations, respectively. It is readily apparent that Raspberry Shake instruments are generally noisier than either of the other two instrument classes because the variance of the gray noise segment that precedes the colored signal segment is often visible, whereas for the other two instrument classes this not the case (the noise looks flat at this range of ordinate values). Also, the uncertainties associated with Raspberry Shake seismograms are generally higher than those of the other two instrument classes.

S3 WRITING SAC POLE-ZERO FILES FOR RÉSEAU SISMIQUE POLYNÉSIEN STATIONS

S3.1 *The SACPZ file*

Seismic Analysis Code (SAC) pole-zero (SACPZ) files specify the frequency response of a digital seismic instrument. They describe how a seismometer converts ground motion to digital counts. Therefore, the output in digital counts of a seismometer may be considered to be a record of true ground motion multiplied by the response of the instrument in the frequency domain. With a SACPZ file, one may recover an accurate record of ground motion via deconvolution (division in the frequency domain) of the seismogram with the frequency response. This process is commonly referred to as "removing the instrument response," and it can be accomplished in the SAC program with the *TRANSFER* command (Helffrich et al. 2013).

Ignoring optional comments, SACPZ files contain three main components: poles, zeros, and a constant. The first two are the complex roots (poles: denominator; zeros: numerator) of the transfer function of the analog component of the instrument, and the last is a constant factor that describes the gain of the entire system. By analog we mean the physical seismic instrument—for example, an inertial mass held in place by a varying electric current, such that the input is ground motion (e.g., m/s) and the output is voltage (V). Following the analog stage, seismometers pass their data through multiple stages of digitization where the voltage is converted to digital counts. Ignoring any frequency effects during digitization (which SACPZ files do not include), the poles and zeros are sufficient to describe the phase response of the system—i.e., with no constant, the ungained seismogram after deconvolution will have the proper shape but incorrect amplitude. Note that phase shifts acquired during the digital stages are usually negligible and can be ignored. This

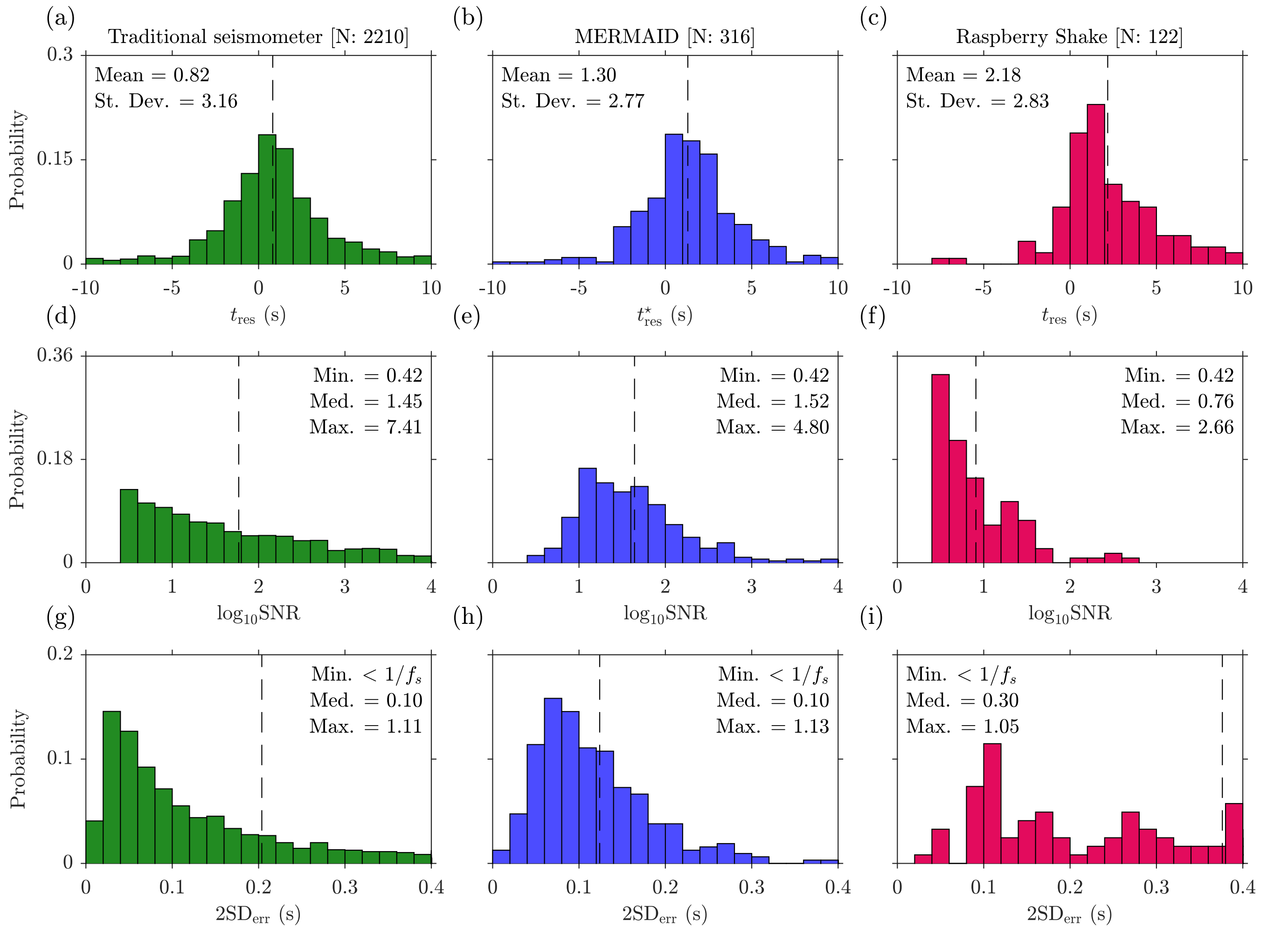

Figure S1. Fig. 19 remade considering only the subset of events for which data existed for at least one station within each instrument class.

fact is noted (in bold) on page 152 of the Standards for the Exchange of Earthquake Data (SEED) Reference Manual Version 2.4 (2012, `https://fdsn.org/pdf/SEEDManual_V2.4.pdf`; hereafter referred to as the SEED manual), page 409 of the Seismic Analysis Code Users Manual Version 101.6a (2014, `https://ds.iris.edu/files/sac-manual/sac_manual.pdf`; hereafter referred to as the SAC manual), and has been independently verified by the authors by comparing waveforms deconvolved with SACPZ and RESP files (the latter of which take into account all digitization stages). We include this comment to make the point that our method of removing the instrument response using the SACPZ file (and not other file standards like RESP or StationXML, which encode information concerning the full cascade of digital filters) is sufficient to recover an accurate record of ground motion for the Réseau Sismique Polynésien (RSP) instruments used in this study.

A SACPZ file may be specified in terms of displacement, velocity, or acceleration, with the values varying in each case for the same seismometer. Very commonly a seismometer will physically measure ground velocity, in which case the poles and zeros will likely be reported for the velocity transfer function of the analog stage, and the gain constant (also called the "sensitivity") will be given in units like counts/(m/s). SACPZ files were not available for the six stations used in this study from the RSP. However, we were provided the poles and zeros, and a gain constant at a specific frequency, which is enough to write our own SACPZ file. It is important to note that a *gain constant at a single frequency is not the same thing as the constant of a SACPZ file*. To be unambiguous we will hereafter refer to the former as the sensitivity. Indeed the sensitivity describes a gain factor at a single frequency, while the SACPZ constant describes the gain factor at all frequencies. Using the notation of the SEED manual, and the pole-zero representation of the transfer function, the frequency response at any stage of the system is (eq. 4 p. 158),

$$G(f) = S_d R(f), \tag{S1}$$

where $R(f)$ is some function of frequency and the S_d is the sensitivity. For the analog stage,

$$R(f) = A_0 H_p(s), \tag{S2}$$

where A_0 is a normalization factor at frequency f_s in Hz (note that the normalization factor may be derived at a frequency, f_n, different from f_s, but this is goes against the SEED convention (p. 157), and is not done here), and $H_p(s)$ is the transfer function at $s = 2\pi i f$ rad/s. Note

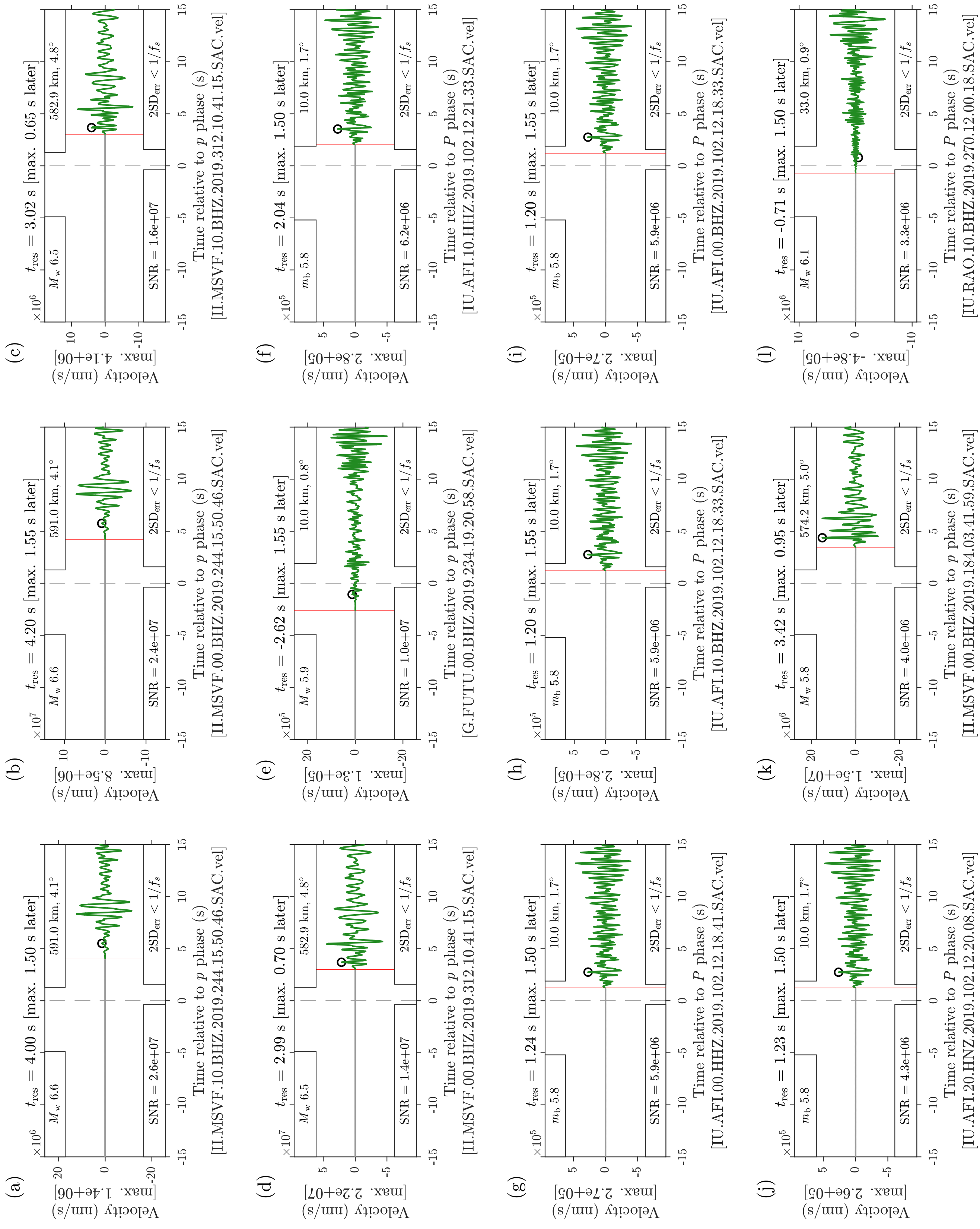

Figure S2. The 12 highest-SNR signals recorded by traditional island stations considering the catalog of events common to all three instrument classes. They are presented in the same format as Fig. 10, except that the residuals are in reference to the standard ak135 model (eq. 2), the seismograms are plotted in units of velocity (nm/s), and the signals are colored green.

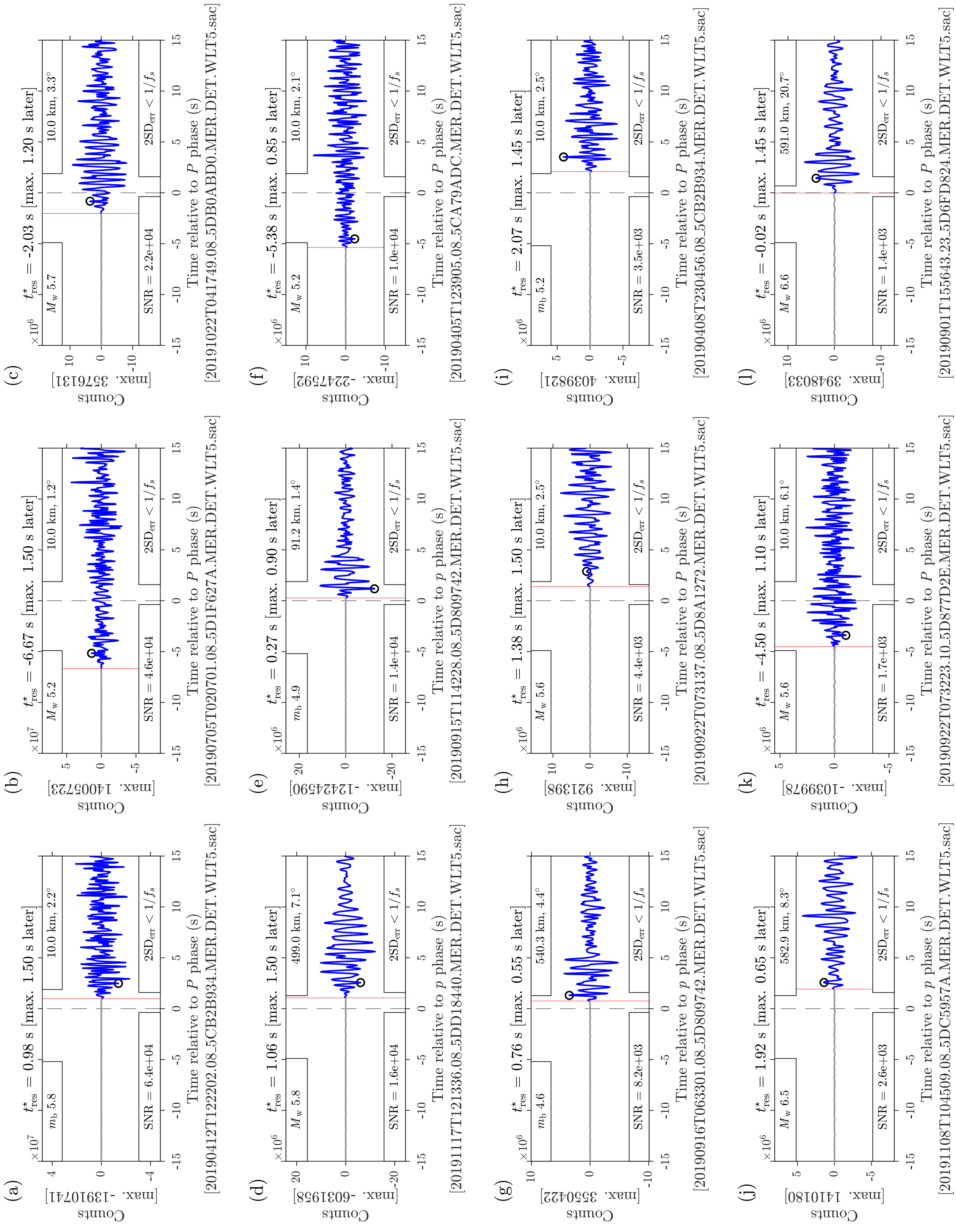

Figure S3. The 12 highest-SNR signals recorded by MERMAID considering the catalog of events common to all three instrument classes, presented in the same format as Fig. 10.

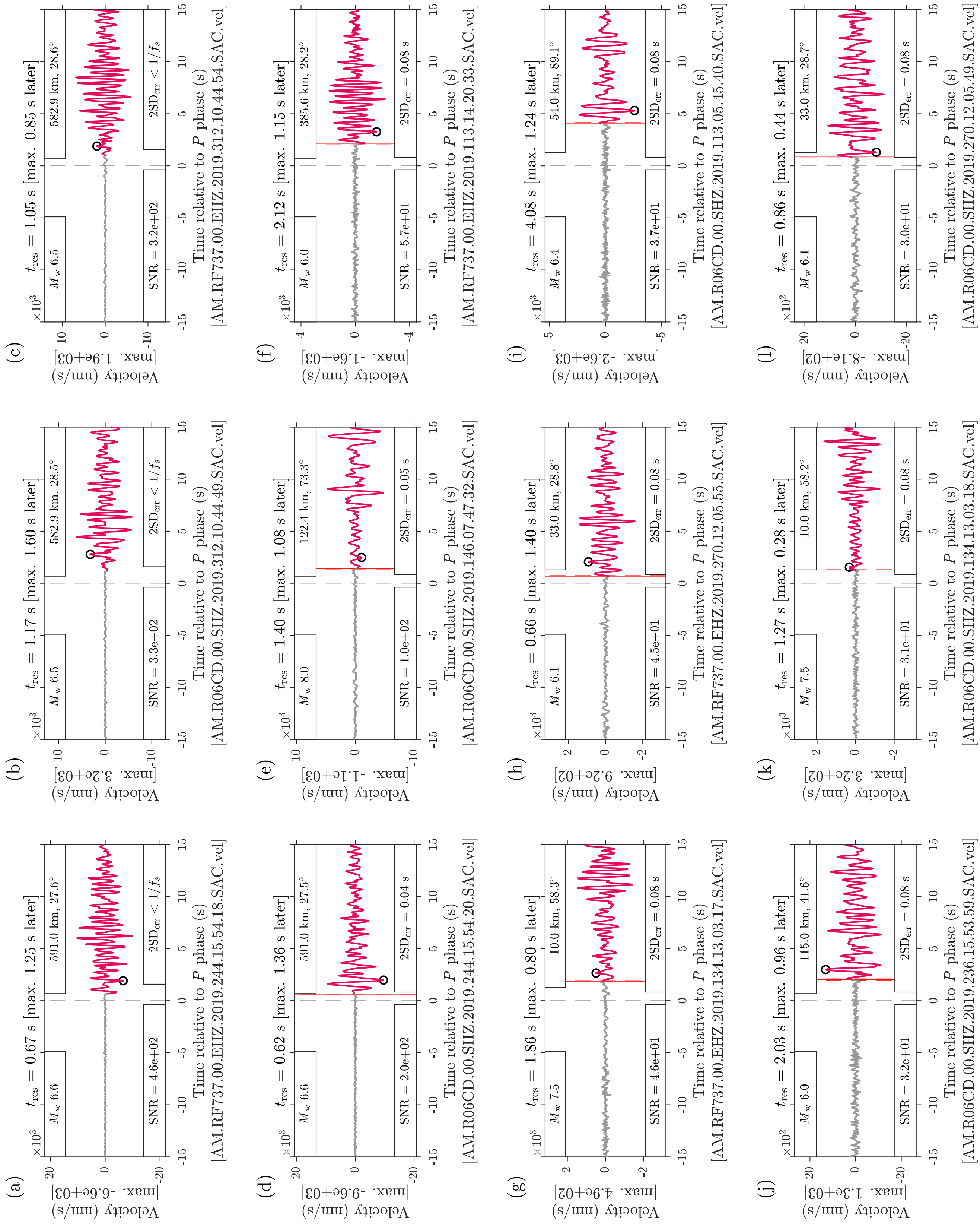

Figure S4. The 12 highest-SNR signals recorded by Raspberry Shake island stations considering the catalog of events common to all three instrument classes. They are presented in the same format as Fig. 10, except that the residuals are in reference to the standard ak135 model (eq. 2), the seismograms are plotted in units of velocity (nm/s), and the signals are colored raspberry.

as well that it is assumed here the poles and zeros of $H_p(s)$ are in terms of rad/s (SEED type “A”), and not in Hz (SEED type “B”), as is the convention used in the SEED manual, and which has been our experience when retrieving RESP and StationXML files from both the IRIS and the International Federation of Digital Seismogram Networks (FDSN) Web Services. At all stages $R(f)$ is defined such that its modulus is unity at the specified frequency of the sensitivity, $f = f_s$,

$$\big|R(f_s)\big| = 1, \tag{S3}$$

leading to the relationship at the analog stage,

$$A_0 = 1/H_p(s_s). \tag{S4}$$

Therefore, ignoring frequency effects beyond the analog stage, and defining S_D to be the multiplicative combination of sensitivities at all stages, the complete frequency response of the entire system at any frequency in Hz is

$$G(f) = S_D A_0 H_p(s) \tag{S5}$$
$$= \mathcal{C} H_p(s), \tag{S6}$$

where $\mathcal{C}$ is the constant included in the SACPZ file.

S3.2 *The SACPZ constant*

With the delivery of seismic data from the Réseau Sismique Polynésien (RSP) by Dr. Olivier Hyvernaud, a geophysicist at Laboratoire de Géophysique Centre Polynésien de Prévention des Tsunamis (CPPT), we were also provided poles, zeros, and a sensitivity corresponding to each station. Equal for all six stations were their two zeros (0;0)(0;0) and two poles (−4.44;−4.44)(−4.44;+4.44). The sensitivity of stations PAE and TVO was given as 0.5236 (nm/s)/LSB at 1 Hz, and for stations PMOR, VAH, TBI, and RKT as 0.212 (nm/s)/LSB at 1 Hz. Here, LSB stands for “least significant bit,” and in this case refers to digital counts. Therefore, for all six stations, the poles, zeros, and sensitivity frequency of $fs = 1$ Hz are identical, but the sensitivities differ.

Before computing the constant of eq. (S6) for each station we must transform the given data slightly. First, the sensitivities were given in terms of velocity per counts, whereas the convention used in the SEED manual and the IRIS and FDSN Web Services specifies those data in terms of counts per unit of ground motion. Therefore, the sensitivities were inverted to convert them to counts/(nm/s). Next, they were converted from nm to m by multiplication with 10^9 to conform to the SEED convention that the transfer function be given in SI units (p. 12).

Finally, we converted the pole and zero data from velocity (describing the transformation from digital counts to m/s) to displacement (counts to m). This was done to conform to the SAC standard that a *TRANSFER* to *NONE* (deconvolution in the SAC program) results in a displacement seismogram. Otherwise, if left as is, *TRANSFER* to *NONE* would produce a velocity seismogram—when using SACPZ files, the SAC *TRANSFER* function does not automatically convert ground motion units to displacement, if required, like it does with RESP files (SAC Manual, p. 406). To that end, the sensitivities were multiplied by $2\pi f_s$ (recalling that the sensitivities are true at a specific frequency in Hz, but were computed from the transfer function in rad/s), and a zero was added to the set of poles and zeros (resulting from the integration of the complex transfer function). Note that SAC does not use SI units, but rather assumes (and populates the relevant header variables accordingly) that a *TRANSFER* to *NONE* results in a displacement seismogram in units of nm/s. However, we chose to prioritize SEED standards over SAC standards (which, again, is true for the IRIS and FDSN Web Services in our experience), and thus we were careful to apply the proper multiplication factor of 10^9 in the SAC program after deconvolution such that the resultant waveforms were in nm (or nm/s for a *TRANSFER* to *VEL*, as was done with all data in the main text from nearby island stations), to properly match the units written to the SAC header variable “IDEP.”

We therefore report the following displacement SACPZ files in SI units for RSP stations PAE and TVO,

```
ZEROS 3
+0.000000e+00 +0.000000e+00
+0.000000e+00 +0.000000e+00
+0.000000e+00 +0.000000e+00
POLES 2
-4.440000e+00 -4.440000e+00
-4.440000e+00 +4.440000e+00
CONSTANT  2.699191e+09
```

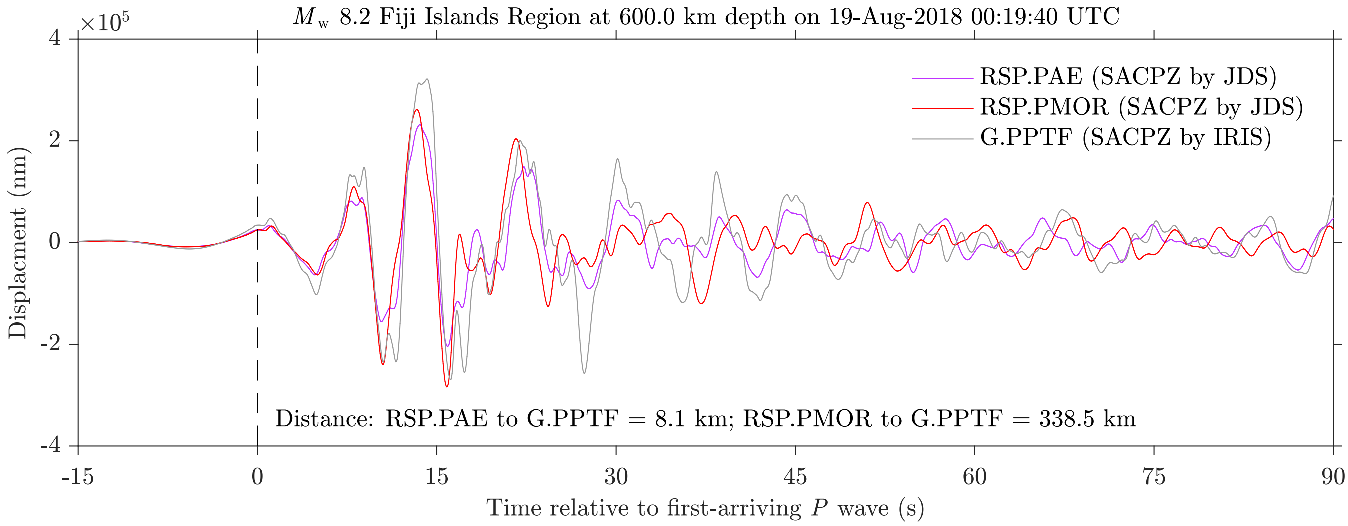

Figure S5. Unfiltered seismograms from RSP.PAE (purple), RSP.PMOR (red), G.PPTF (gray) of a nearby great earthquake. The SACPZ files corresponding to the two RSP stations were written by the authors, and that corresponding to G.PPTF was provided by IRIS. The similarity of the waveforms, both in phase and amplitude, proves that our SACPZ files are correct.

and for stations PMOR, VAH, TBI, RKT,

```
ZEROS 3
+0.000000e+00 +0.000000e+00
+0.000000e+00 +0.000000e+00
+0.000000e+00 +0.000000e+00
POLES 2
-4.440000e+00 -4.440000e+00
-4.440000e+00 +4.440000e+00
CONSTANT  6.666493e+09
```

We include with this study software to compute the SACPZ constant, $\mathcal{C}$, as well as the normalization factor, A_0. The functions relevant to this section are printed at the end of this supplement and are accessible at `github.com/joelsimon/omnia/`. Included there as well is `transfunc.m`, a function which may be of use to those interested in the conversion between SACPZ, RESP, and StationXML files, as well as the transformation of them between velocity and displacement responses.

S3.3 *Verification*

Fig. S5 proves that the displacement SACPZ files we wrote for RSP stations is correct. It compares the unfiltered (apart from those corner frequencies specified during deconvolution, see Section 9.2) seismograms, plotted in displacement (nm), corresponding to a great earthquake in the Fiji Islands region that was recorded by three nearby stations. The traces are each aligned on the theoretical arrival time of the first-arriving *P* wave computed in the ak135 velocity model. Two of the seismograms were recorded by stations in the RSP (PAE and PMOR, in purple and red seismograms), each serving as the archetypal station for their respective group's SACPZ file written by the authors, and the other by station G.PPTF (in gray), for which the displacement SACPZ file was available from IRIS. The distance between each RSP station and G.PPTF is listed inside the axis (8.1 km for PAE and 338.5 km for PMOR), and they are near enough to one another that we would expect the ground motion at the three stations to be very similar, given the magnitude of earthquake. We see that the waveforms agree very well, both in amplitude and phase, both before and after the first-arrival, but especially for the first fifteen seconds after the first arrival. Therefore, we conclude that the two SACPZ files we wrote in Section S3.2 corresponding to six stations in the RSP are correct.

We include as further verification an example in the header of `sacpzconstant.m`, software that we wrote and which is explained in the next section, which rederives the values printed on an IRIS help page that explains how to convert a velocity RESP file to a displacement SACPZ file (`ds.iris.edu/ds/support/faq/24/what-are-the-fields-in-a-resp-file/`). That example shows that our SACPZ constant agrees with the one provided by IRIS to within 0.003%, well within acceptable error.

S3.4 *Software*

Finally we reproduce below the two functions written in MATLAB used to derive the RSP SACPZ files of Section S3.2. First we print `sacpzconstant.m`, a function that is not specific to RSP data, and which will compute a displacement SACPZ constant, $\mathcal{C}$, and normalization factor, A_0, assuming the poles, zeros, and sensitivity are provided in the format explained in Section S3.2. Next we print the function, `cpptsacpzconstant.m`, which is specific to the RSP SACPZ files derived in Section S3.2. Within that code we explain how to convert transfer function data in non-SI velocity units to SI displacement units so that they may be processed by `sacpzconstant.m`.

Note that in both cases the codes are short and the comments are long, reflecting our experience that the interplay between these variables and files is often confusing, and the fact that these codes will live a life separate of this supplement. Also, we have done our best to compile this information from various sources, but errors may have been made, and we will correct them to the best of our ability as they arise. As such, we leave these codes printed here but note that the most up-to-date versions will be found at `github.com/joelsimon/omnia/`.

The following functions were typeset in LaTeXusing the `mcode` style guide written by Knorn (2020).

```
function [CONSTANT, A0] = sacpzconstant(SD, fs, P, Z)
% [CONSTANT, A0] = SACPZCONSTANT(SD, fs, P, Z)
%
% SACPZCONSTANT returns the CONSTANT and A0 normalization factor for a
% displacement SACPZ file.
%
% Input:
% SD          Gain constant or sensitivity, true at fs [counts/m]
% fs          Frequency at which the gain constant is true [Hz]
% P           Complex poles of the transfer function [rad/s]
% Z           Complex zeros of transfer function [rad/s]
%
% Output:
% CONSTANT    SACPZ file CONSTANT (TRANSFER to NONE = meters)
% A0          A0 normalization factor at fs
%
% In the parlance of the SEED Manual v2.4, SD (uppercase "D;" my notation)
% corresponds to the combined sensitivity considering all stages, and Sd
% (lowercase "d"; their notation) is the sensitivity at a single stage, e.g.,
% the analog stage. In the example on pg. 166, the first stage is the
% seismometer [V/(m/s^2)], and the second stage is the digitizer [counts/V].
% These two sensitivities are multiplied in stage 0 to compute the total
% sensitivity (SD) of the system (we are ignoring other digital stages (3+; FIR
% filters etc.), which also contribute to the stage 0 sensitivity, but
% negligibly).  Ultimately, the combined sensitivity, SD, of the system is
% quoted in units like [counts/(m/s^2)], though here it must be input in terms
% of counts/m.
%
% Therefore, using eq. (6) on pg. 159, ignoring frequency effects after the
% analog stage, and substituting the total sensitivity at SD for the
% analog-stage sensitivity, Sd, "...at any frequency f (in Hz) the response is,"
%
%                 G(f) =  SD * A0 * Hp(s)
%                      = CONSTANT * Hp(s), (author's interpretation)
%
% where (pg. 158), "...Hp(s) represents the transfer function ratio of
% polynomials specified by their roots," the roots being the poles and zeros
% when s = 2pi*i*f rad/s (f in Hz).
%
% While I have never seen it explicitly stated in either the SEED or SAC manuals
% that the SACPZ CONSTANT = SD * A0, I have...
%
% (1) Seen that statement in ObsPy (1.2.0) source code --
%     https://docs.obspy.org/_modules/obspy/io/sac/sacpz.html
% (2) Seen that statement on the IRIS' help pages --
%     https://ds.iris.edu/ds/support/faq/24/what-are-the-fields-in-a-resp-file/
% (3) Verified that relation through pers. comm. with Olivier Hyvernaud
% (4) Concluded it must be so given the definition of the G(f)
%
% SACPZCONSTANT assumes the input poles and zeros correspond to a a "Transfer
% function type: A", i.e., "Laplace transform analog response, in rad/sec"
% (pg. 53).  Further, the transfer function must be described by its roots
% (poles, 'P', and zeros, 'Z'), not the the coefficients of its numerators and
% denominators.  This is the SEED "preferred" standard (pg. 159), and the only
% way I have ever seen these data represented (they are called "Pole-Zero
% files," not "transfer-function coefficient files" for a reason.  Finally, 'SD'
% is sensitivity at 'fs' Hz, and must be given in counts/m to conform to the
% SEED standard of SI units (meters, not nanometers), and the SAC standard that
% a TRANSFER to NONE results in a displacement seismogram.  Note these conflict:
% in SAC a TRANSFER to NONE assumes displacement units of nanometers.  Here we
% prioritize SEED standards.
%
```

```
% All this is to say that if you get any random RESP or StationXML file, those
% values are more than likely already in the UNITS required as input here to
% result in a DISPLACEMENT poles and zeros file, however, their VALUES may need
% to be adjusted to move from, e.g., velocity to displacement (add one zero;
% multiply SD by 2pi*fs).
%
% Ex:( velocity RESP file to displacement SACPZ file, following the example of:  )
%    ( https://ds.iris.edu/ds/support/faq/24/what-are-the-fields-in-a-resp-file/ )
%    SD_vel =  9.630000E+08; % counts/(m/s)
%    fs = 0.02; % Hz
%    P_vel = [-0.0123+0.0123i, -0.0123-0.0123i, -39.1800+49.1200i, -39.1800-49.1200i];
%    Z_vel = [0, 0];
%    % Convert SD from vel. to disp, by multiplication with 2pi*fs (SD computed in rad/s)
%    SD_disp = SD_vel*2*pi*fs; % counts/m
%    % Convert PZ from vel. to disp. by addition of one zero (poles unchanged)
%    Z_disp = [Z_vel 0];
%    P_disp = P_vel;
%    [CONSTANT, A0] = SACPZCONSTANT(SD_disp, fs, P_disp, Z_disp);
%    fprintf('Displacement SACPZ CONSTANT and A0 given by IRIS: 3.802483e+12, 31421.7\n')
%    fprintf('Displacement SACPZ CONSTANT and A0 computed here: %.6e, %.1f\n', CONSTANT, A0)
%    fprintf('The CONSTANT differs by %.4e%s\n', ...
%             abs((CONSTANT-3.802483e+12)/3.802483e+12)*100, '%')
%
% For myriad verifications,
% see also: transfunc.m
%
% Author: Dr. Joel D. Simon
% Contact: jdsimon@princeton.edu | joeldsimon@gmail.com
% Last modified: 07-Apr-2020, Version 9.3.0.948333 (R2017b) Update 9 on MACI64

% Convert transfer function from pole-zero representation to
% numerator-denominator coefficient sets.
[b, a] = zp2tf(Z(:), P(:), 1);

% Convert sensitivity frequency from Hz to rad/s.
fs = 2*pi*fs;

% Compute the complex frequency response of the transfer function, which
% requires at least two frequencies as input. Don't multiply 'w' by complex 'i'
% (or 'j') because freqs.m does that internally with the frequency vector.
w = [fs-pi, fs, fs+pi];
Hp = freqs(b, a, w);

% Return the frequency response evaluated at the sensitivity frequency.
Hp_fs = Hp(2);

% The normalization factor is the modulus of the transfer function evaluated at
% the sensitivity frequency, and the SACPZ CONSTANT is that factor multiplied by
% the sensitivity.
A0 =  1/abs(Hp_fs);
CONSTANT = A0*SD;
```

```matlab
function [CONSTANT1, CONSTANT2] = cpptsacpzconstant
% [CONSTANT1, CONSTANT2] = CPPTSACPZCONSTANT
%
% Returns the displacement SACPZ CONSTANT for six stations in the Reseau
% Sismique Polynesien (RSP).
%
% Input:
% --none--
%
% Output:
% CONSTANT1   Displacement SACPZ CONSTANT corresponding to PAE, TVO
% CONSTANT2   Displacement SACPZ CONSTANT corresponding to PMOR, VAH, TBI, RKT
%
% See also: sacpzconstant.m
%
% Author: Dr. Joel D. Simon
% Contact: jdsimon@princeton.edu | joeldsimon@gmail.com
% Last modified: 07-Apr-2020, Version 9.3.0.948333 (R2017b) Update 9 on MACI64

%% Relevant bits of original email.
%%______________________________________________________________________________________%%
% SUBJECT: Polynesian seismic data
% SENT: Fri 24-Jan-2020
%
% Hi Joel,
%
% Sensitivity :
%
% 0.5236 nm/s/LSB  at 1 Hz for PAE, TVO
% 0.212 nm/s/LSB at 1 Hz for PMOR, VAH, TBI, RKT
%
% Response for PAE, TVO, PMOR, VAH, TBI, RKT  (high pass filter at 1 Hz, order 2) :
%
% 2 zeroes : (0;0) (0;0)
%
% 2 poles : (-4.44;-4.44)(-4.44;4.44)
%
% Regards,
%
% Olivier
%%______________________________________________________________________________________%%

%% Frequency of sensitivity.

% The frequency of sensitivity is always quoted in Hz.
fs_Hz = 1;
fs_rad = 2*pi*fs_Hz;

%% Poles and zeros (the same for all stations).

% They were provided to me in terms of velocity.
Z_vel = [0+0i ...
         0+0i];
P_vel = [-4.44-4.44i ...
         -4.44+4.44i];

% Add one zero to convert to displacement. The poles are unchanged.
Z_disp = [Z_vel ...
          0+0i];
P_disp = P_vel;

%% Sensitivities (Sd in SEED parlance) -- NB, Sd is the sensitivity at a single
```

```
%% stage (e.g., analog; V/(m/s)); I use SD to represent the combined
%% sensitivities after all stages (digital; counts/(m/s)).

% NB, the equality of (nm/s/LSB)^-1 = counts/(nm/s) was verified by Olivier
% Hyvernaud 22-Feb-2020, pers. comm.
%
% We must convert SD from <physical_unit>/count --> count/<physical_unit> (the
% convention in the SEED manual, and how SACPZ, RESP, and StationXML files are
% delivered from IRIS).  Next we must convert SD velocity to displacement, such
% that a TRANSFER to NONE in SAC produces a displacement seismogram. Finally, in
% keeping with SEED standard of SI units, we must convert SD from
% counts/nanometer to counts/meter.

% I will refer to stations PAE, TVO as group 1 and all others as group 2.  These
% are the sensitivities as provided in nm/s/LSB.
SD1_vel = 0.5236;
SD2_vel = 0.212;

% Convert from nm/s/LSB to counts/(m/s).
SD1_vel = SD1_vel^-1 * 1e9;
SD2_vel = SD2_vel^-1 * 1e9;

% Convert from velocity sensitivities to displacement sensitivities.  This
% requires multiplying by the frequency of sensitivity in rad/s because the
% sensitivity (while quoted in Hz) was computed in rad/s.
SD1_disp = SD1_vel*fs_rad;
SD2_disp = SD2_vel*fs_rad;

% Finally, compute the constants.
CONSTANT1 = sacpzconstant(SD1_disp, fs_Hz, P_disp, Z_disp);
CONSTANT2 = sacpzconstant(SD2_disp, fs_Hz, P_disp, Z_disp);
```

REFERENCES

Alaska Earthquake Center, University of Alaska Fairbanks (AEC), 1987, *Alaska Regional Network*, International Federation of Digital Seismograph Networks, http://earthquake.alaska.edu. doi: 10.7914/SN/AK.

Albuquerque Seismological Laboratory (ASL)/USGS, 1990, *United States National Seismic Network (USNSN)*, International Federation of Digital Seismograph Networks, https://earthquake.usgs.gov/contactus/golden/neic.php. doi: 10.7914/SN/US.

Bondár, I. & Storchak, D., 2011. Improved location procedures at the International Seismological Centre, *Geophys. J. Int.*, **186**(3), 1220–1244 doi: 10.1111/j.1365-246X.2011.05107.x.

California Institute of Technology and United States Geological Survey Pasadena (Caltech and USGS), 1926, *Southern California Seismic Network*, International Federation of Digital Seismograph Networks, http://www.scsn.org. doi: 10.7914/SN/CI.

Helffrich, G., Wookey, J. & Bastow, I., 2013. *The Seismic Analysis Code. A Primer and User's Guide*, Cambridge Univ. Press, Cambridge, UK.

International Seismological Centre, 2015, *On-line Bulletin*, http://www.isc.ac.uk. doi: 10.31905/D808B830.

Joubert, C., Nolet, G., Bonnieux, S., Deschamps, A., Dessa, J.-X. & Hello, Y., 2016. *P*-delays from floating seismometers (MERMAID), part I: Data processing, *Seismol. Res. Lett.*, **87**(1), 73–80, doi: 10.1785/0220150111.

Kennett, B. L. N., Engdahl, E. R. & Buland, R., 1995. Constraints on seismic velocities in the Earth from travel-times, *Geophys. J. Int.*, **122**(1), 108–124, doi: 10.1111/j.1365-246X.1995.tb03540.x.

Knorn, F., 2020, *M-code LaTeX package*, MATLAB Central File Exchange, Version 2.7.0.0, https://www.mathworks.com/matlabcentral/fileexchange/8015-m-code-latex-package/.

Simmons, N. A., Myers, S. C., Johannesson, G. & Matzel, E., 2012. LLNL-G3Dv3: Global P wave tomography model for improved regional and teleseismic travel time prediction, *J. Geophys. Res.*, **117**, B10302, doi: 10.1029/2012JB009525.

Simon, J. D., Simons, F. J. & Nolet, G., 2020. Multiscale estimation of event arrival times and their uncertainties in hydroacoustic records from autonomous oceanic floats, *B. Seismol. Soc. Am.*, **100**(3), 970–997, 10.1785/0120190173.

Weatherall, P., Marks, K. M., Jakobsson, M., Schmitt, T., Tani, S., Arndt, J. E., Rovere, M., Chayes, D., Ferrini, V. & Wigley, R., 2015. A new digital bathymetric model of the world's oceans, *Earth Space Sci.*, **2**, 331–345, doi: 10.1002/2015EA000107.