



The Source-Specific Station Term and Waveform Cross-Correlation Earthquake Location Package and Its Applications to California and New Zealand

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ABSTRACT

In this article, I present a Fortran package (XCORLOC) that improves relative earthquake location accuracy based on compressional and/or shear-wave seismic data. The program can perform phase arrival (e.g., single event, static station term, and source-specific station term [SSST]) and waveform cross-correlation relocation sequentially or separately. It performs an iterative grid-search approach that allows application of more robust norms (L1 and hybrid L1–L2) than traditional least squares, which are less sensitive to gross timing errors. This package can be used for relocations in local, regional, and global scales. Specific topography information can be included to avoid artificial effects in the presence of significant topographic relief. In addition, the package can be used to compute station corrections in areas with strong velocity contrasts from a suite of well-constrained earthquake locations and then achieve similar location accuracies for a different set of events. As an illustration, I show location improvements of the SSST and the waveform cross-correlation locations relative to the typical seismic network locations for three regions, the Vallecitos Valley region in southern California, Parkfield in central California, and the North Island of New Zealand. Comparison with other location techniques is also provided for a case study. The XCORLOC package is available for free download (see [Data and Resources](#)).

INTRODUCTION

This article describes the programs included in the XCORLOC location package, which are designed to improve earthquake locations using compressional (*P*)- and shear (*S*)-wave data and have been tested on synthetic and real (local and regional) seismic data.

The location process in this package consists of two parts, phase arrival-time location and waveform cross-correlation location. In the phase arrival-time location section, there are options to apply the single event, the static station term, and the source-specific station term (SSST) methods ([Lin and](#)

[Shearer, 2005](#)). The corresponding programs are directly adopted from and explained in detail in the COMPLOC location package ([Lin and Shearer, 2006](#)). The details of the waveform cross-correlation location approach are described in [Lin et al. \(2007\)](#). Different versions of the relocation algorithm have been applied with slight variations in numerous location studies (e.g., [Lin et al., 2007, 2014](#); [Lin and Thurber, 2012](#); [Lin, 2013a,b, 2015](#); [Zhang and Lin, 2014](#); [Lin and Okubo, 2016](#); [Lin and Wu, 2017](#)). The package provides relative location results comparable to the hypoDD program by [Waldhauser and Ellsworth \(2000\)](#) and the GrowClust program by [Trugman and Shearer \(2017\)](#), shown by previous studies (e.g., [Hauksson and Shearer, 2005](#); [Shearer et al., 2005](#); [Matoza et al., 2013](#); [Lin et al., 2014](#); [Lin, 2015](#)).

XCORLOC is a Fortran computer program package that performs a number of iterations of earthquake location based on first arrivals and/or waveform cross-correlation data. The program has been tested on both MAC and LINUX systems, but is made available without warranty. The initial and future releases of the XCORLOC package are available for free download (see [Data and Resources](#)).

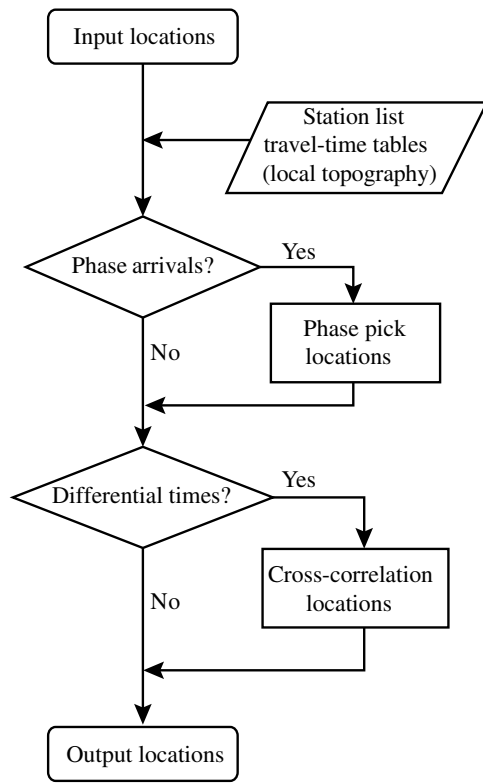
REQUIRED FILES

Figure 1 shows a work flowchart of the relocation procedures. The input file formats can be easily modified for each user's own purpose. Before beginning the location process, it is necessary to have the following:

1. *P*- and/or *S*-travel-time tables calculated from a given velocity model
2. a list of station names, their locations, and station corrections if available
3. initial locations for the events to be located
4. *P*- and/or *S*-phase pick data and/or differential times from waveform cross correlation
5. local topography file (optional)

PROGRAM DESCRIPTIONS

The travel-time tables can be calculated for a given 1D velocity model for the study area using the `deptable.f` program in the



▲ **Figure 1.** A work flowchart of the location procedures.

COMPLOC package (Lin and Shearer, 2006). It is recommended to run the `vzfillin.f` subroutine by Lin and Shearer (2006) first to resample to 1 km (or 0.5 km) depth intervals to create a 1D gradient velocity model. In addition, 3D ray-tracing can be carried out in XCORLOC by modifying the `get_tts.f` subroutine.

The station list should include each station's name, latitude, longitude, elevation, and P - and/or S -wavepath corrections if available. The station elevations are not used in the current relocation process, therefore they can be set as 0.0. However, if the user decides to modify the `get_tts.f` subroutine to perform 3D raytracing, they should be specified. Station corrections for P - and S waves should be listed in two separate columns. The travel-time residual t_r is defined as $t_r = t_o - (t_p + T + t_c)$, in which t_o is the observed arrival time, t_p is the predicted time from the travel-time table, T is the event origin time, and t_c is the station correction (either static or source specific). A positive t_c means that the predicted travel time from the 1D velocity model is faster than the observed one.

Similar to the COMPLOC package, the locations can be fixed to their starting locations with varying origin times to achieve the best fit (set `ilocfix = 1`). This option is only recommended for static station term computation from a given set of locations with respect to a particular 1D velocity model. This set of locations can be obtained from other sources (e.g., controlled sources or events relocated by a 3D velocity model) with well-constrained absolute locations. The calculated

station terms and the corresponding 1D model can then be used to relocate a different group of events in the same area to accomplish similar absolute location accuracy.

The user can select the L1, L2, or hybrid L1–L2 norm for the residual misfit function. The hybrid L1–L2 norm was proposed by Huber (1973) and is referred to as the L3 norm throughout this article and in the released package for simplicity. Synthetic data tests with Gaussian distributed noises show that all the three error measure methods work equally well with the L2 norm slightly better. However, for real data, the L1 and L3 norms give better results and are recommended because of their robustness with respect to outliers and possible presence of non-Gaussian noise in real data.

When Lin *et al.* (2007) relocated the southern California seismicity, they shifted the entire cluster after waveform cross-correlation relocation so that the new centroid of each cluster is the same as the centroid of the starting locations to maintain the absolute cluster location and stabilize the inversion. This option is also available in the package and is only recommended when the input absolute locations are well constrained.

A latitude/longitude/depth window option permits locating a geographic subset of the dataset. The program can also read in specific local topography information to avoid air quakes, which is helpful in areas with the presence of significant topographic relief (e.g., volcanoes). The topography file simply provides elevation values for a series of grid points. The elevations are given in meters, and positive indicates above sea level. If unavailable, then the topography file name can be put as “none”.

The program offers different starting locations for the waveform cross-correlation relocation process, with (1) for initial (e.g., catalog) location and (2) for phase arrival location, including the single event, the static station term, and the SSST locations (Lin and Shearer, 2005, 2006). The single event location means each event is located separately with no information from any other events. For a compact cluster of events, the ray paths to each station pass through approximately the same velocity structure and a single travel-time correction term at each station can account for the biasing effects of the 3D structure, which is defined as static station term. For distributed seismicity, the travel-time corrections at each station vary as a function of source position but are highly correlated among nearby events, which are referred to as the SSSTs.

The distance cutoff permits rejection of seismic data (both absolute and differential times) from stations beyond a maximum distance (km) from the event. If location option (2) is selected, then absolute times are required for phase data relocation before performing waveform cross-correlation relocation. The phase data should include an event identification number for each event and station name, phase identification, source–receiver distance, and observed travel time for each pick. Each event must have a unique identification number. The location and origin time for each event can be different in the initial location and phase arrival files. In this case, the location in the event file will be used in the following relocation process and the phase arrivals will be corrected for the difference between the origin times in the event and phase files.

The programs for phase arrival location are adopted from the COMPLOC package (Lin and Shearer, 2006) and the parameters are also described in that package. If location option (1) is chosen, then phase file name can be simply put as “none”.

The differential times can be stored in a series of files. The directory and a list of these files where the differential times are stored are required by the program. Each file with differential times consists of lines of event pairs and their corresponding differential times. The event pair line includes event identification numbers that match those in the event and phase files. Each station line includes station name, phase identification, differential time, correlation coefficient, and average epicentral distance for the event pair.

The differential time is defined as the relative time of the second event with respect to the first one. They are used in the relocation process based on a few criteria:

1. minimum correlation coefficient to use a given differential time; if above 1.0, it means no correlation data will be used in the relocation
2. minimum correlation coefficient for a given differential time to be considered as good
3. minimum number of good differential times to include event pair in relocation

If all the available differential times need to be included, the user can simply put all the correlation coefficients as 1.0. The current program allows output of the starting location for the waveform cross correlation (either the input initial or phase arrival location). Relocation after each iteration is also outputted. The relocation process can be stopped after the given number of iterations is reached or when the root mean square of the differential times is smaller than a given threshold. The relative location uncertainty in x , y , z , and T for each event is estimated by applying the bootstrap resampling approach (Efron and Gong, 1983; Efron and Tibshirani, 1991) and outputted in the final iteration. Because this process can be time consuming, it is recommended to first run the package without estimating location uncertainties to find optimal parameters. The last column of the relocation file indicates the final location type with 1 for initial input location, 2 for phase arrival relocation (e.g., SSST), and 3 for waveform cross-correlation location.

EXAMPLES

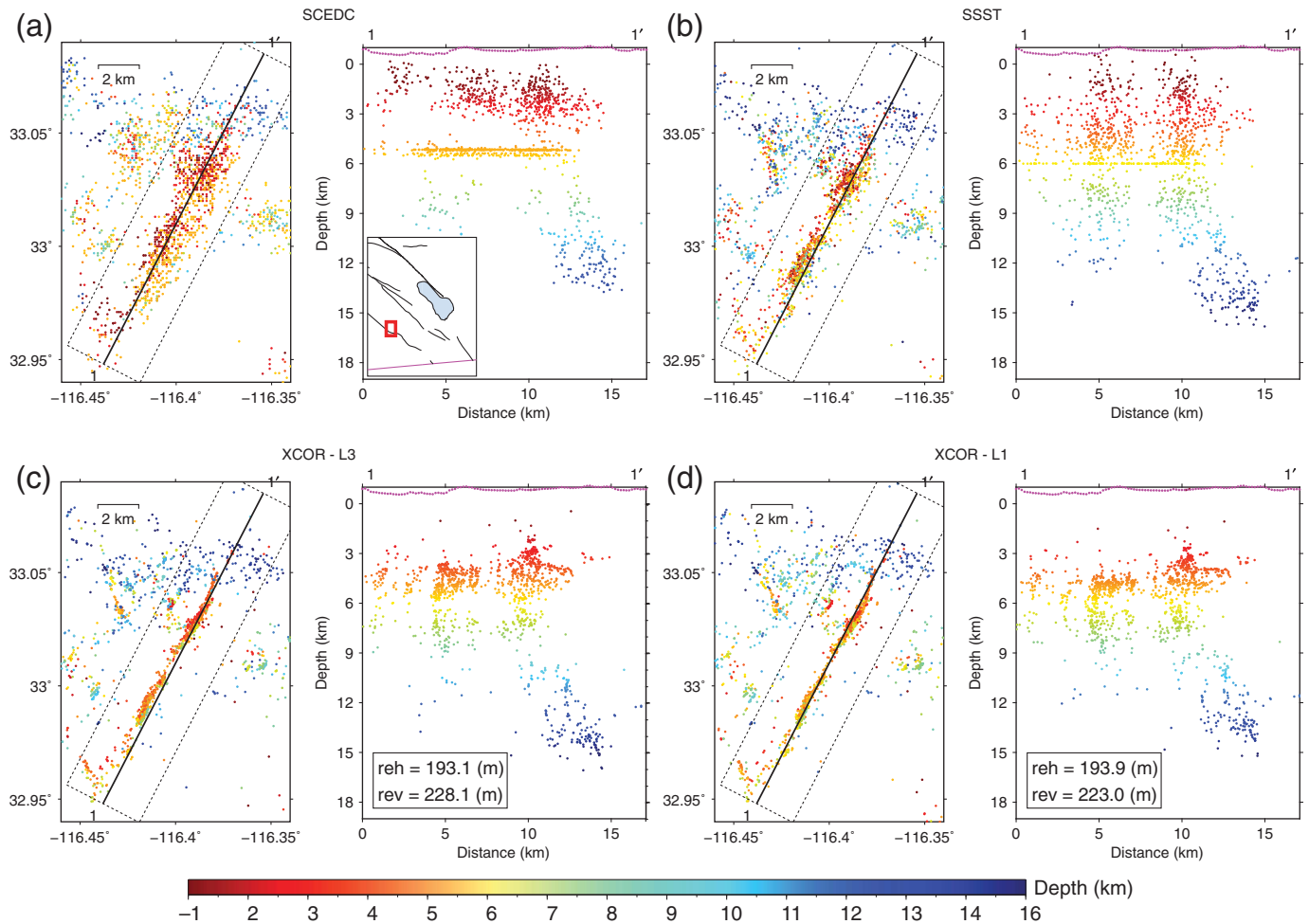
Three examples are provided in this article as a demonstration of the package including the Vallecitos Valley in southern California, Parkfield in central California, and the North Island of New Zealand. Details of the cross-correlation process are beyond the scope of the XCORLOC package and may be available in a future release. Users should feel free to apply their own approaches to obtain differential times and the corresponding correlation coefficients. All the location results shown in this article are generated using the default parameters in the package, although careful selections could produce better results.

Vallecitos Valley, Southern California

Relocation results for the Vallecitos Valley region, southern California, are shown in Figure 2 as the first example. The corresponding scripts to run XCORLOC are also included in the released package. The seismic data were obtained for events between 1981 and June 2005 from the Southern California Earthquake Data Center (SCEDC) (2013). These events are the same as those used in the example by Lin and Shearer (2006). It appears that the SCEDC has adjusted locations for some shallow events since the data download by Lin and Shearer (2006). Therefore, the SCEDC locations in this study are slightly different for a small number of events than those used by Lin and Shearer (2006). However, these differences do not have significant effects on the relocation results. To prepare for the differential time relocation, I carried out the waveform cross-correlation computation as described by previous studies (e.g., Lin *et al.*, 2007, 2014; Lin, 2015; Lin and Okubo, 2016; Lin and Wu, 2017). In Figure 2, location comparisons are presented for the 2282 events that satisfy the differential time relocation criteria out of all the 3233 events. Figure 2a–c shows the results using the L3 norm and location option (2). I first start with the SCEDC catalog locations (Fig. 2a) to obtain the SSST location based on P - and S -phase arrivals (Fig. 2b) and then perform the waveform cross-correlation location (Fig. 2c). The SSST locations are similar to those presented by Lin and Shearer (2006). To show the effect of different error measure methods, the waveform cross-correlation relocations using the L1 norm are also presented in Figure 2d. The final locations in Figure 2c,d are very similar to each other and also to the results in Shearer *et al.* (2005), illustrating great sharpening relative to the initial SCEDC catalog locations. The estimated relative location uncertainties from bootstrap resampling are about 190 m for horizontal and 220 m for vertical.

Parkfield, Central California

Relocation results for Parkfield, central California, are shown in Figure 3 as the second example. The seismic data were obtained for events between 2000 and 2018 from the Northern California Earthquake Data Center (NCEDC) (2014). Relocations are obtained for the 12,159 out of all the 14,376 events, which fulfill the correlation coefficient requirements. In Figure 3, location results are presented for the 10,778 events whose double-difference locations are available for comparison (Schaff and Waldhauser, 2005; Waldhauser and Schaff, 2008; Waldhauser, 2009). The relocation results in this study are obtained starting from the NCEDC catalog locations (Fig. 3a,b1,c1,d1) based on the L3 norm and location option (2). To constrain the absolute locations, I first calculate the static station terms using a group of 3D relocated events by Zhang and Thurber (2005) and include these terms in the SSST location process (Fig. 3b2,c2,d2). I then apply the waveform cross-correlation location based on these SSST locations with the *a priori* static station terms (Fig. 3b3,c3,d3) and the L3 norm. For comparison, I also plot the waveform cross-correlation locations without using the *a priori* static station



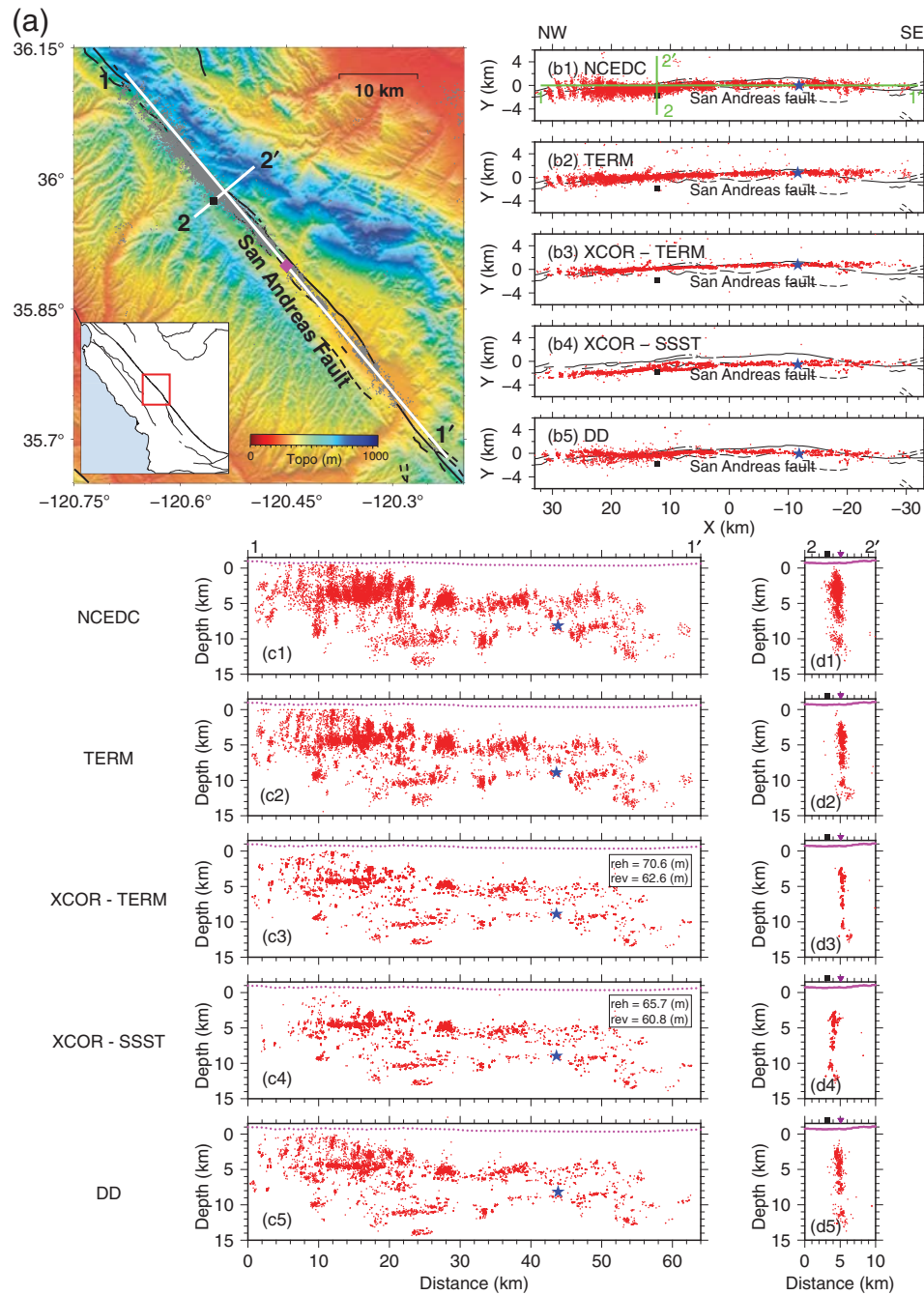
▲ **Figure 2.** Location comparison of the Southern California Earthquake Data Center (SCEDC), the source-specific station term (SSST), and the waveform cross-correlation (XCOR) location catalogs in the Vallecitos Valley region, southern California. (a) SCEDC location. (Inset) The location of the study area (red box) near the Salton Sea region in southern California. (b) SSST location using the L3 norm. (c) Waveform cross-correlation relocation starting with (b) using the L3 norm. (d) Similar to (c) but based on the L1 norm. Note that only common events in all catalogs are presented here. Depth distributions are shown for seismicity enclosed by the dotted black boxes along the solid straight lines. Dotted pink curves at the top of the cross sections illustrate the local topography. Relative location uncertainties estimated from bootstrap resampling after waveform cross-correlation location are provided for both horizontal (reh) and vertical (rev) directions.

terms (Fig. 3b4,c4,d4), and they show slight offset from the San Andreas fault. Although the true absolute locations of these earthquakes are arguable, the purpose of this example is to show the capability of the XCORLOC package to improve absolute location accuracy given well-constrained static station terms. The 2004 M 6.0 Parkfield mainshock is also plotted in both map views and cross sections for each catalog. The waveform cross-correlation relocation for this earthquake is not available given our criteria in the example. Therefore, the mainshock location in Figure 3b3,b4,c3,c4 is the phase arrival location, instead of the waveform cross-correlation location. Although the two types of waveform cross-correlation locations show slightly different absolute locations, they both illustrate great sharpening relative to the initial NCEDC catalog locations. The estimated relative location uncertainties from

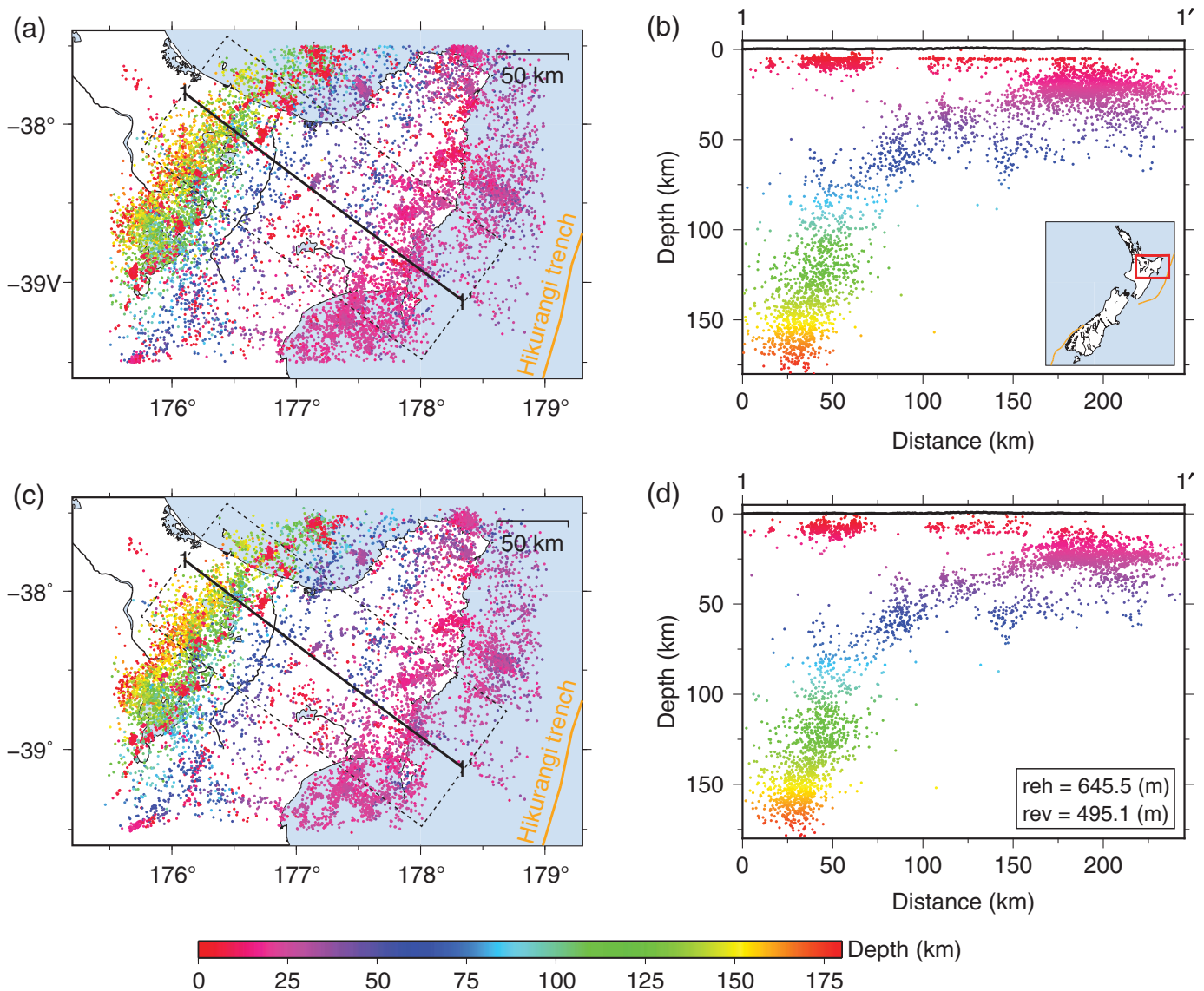
bootstrap resampling are about 65 m for both horizontal and vertical directions. The double-difference locations for all the common events are shown in Figure 3b5,c5,d5 for comparison. The location difference could be caused by a combination of the different location algorithm, velocity model, and all the parameters used during the location process. The waveform cross-correlation relocations using the L1 norm are very similar to those from the L3 norm, and therefore are not shown here.

North Island, New Zealand

The XCORLOC package can also be used to locate regional and global scale earthquakes. The last example is shown for the North Island of New Zealand near the Hikurangi trench (Fig. 4). The seismic data were obtained for 18,654 events with magnitudes between 2 and 5 recorded by local and regional



▲ **Figure 3.** Location comparison of the Northern California Earthquake Data Center (NCEDC), the SSST with the *a priori* static station terms (TERM), the waveform cross-correlation with (XCOR-TERM) and without station terms (XCOR-SSST), and the double-difference (DD) location catalogs in Parkfield, central California. (a) Map view of the NCEDC location (gray dots) near the San Andreas fault (black lines) with the topography as the background. (Inset) The location of the study area (red box) in northern California. The two white straight lines 1–1' and 2–2' are profiles for the cross sections along the northwest–southeast and southwest–northeast directions, respectively. The black square and also those in b1–b5 and d1–d5 show the location of the SAFOD (San Andreas Fault Observatory at Depth). The purple diamond in the middle of the map is the origin of the Cartesian coordinate. (b1–b5) Map views of the seismicity in the Cartesian coordinate. Profiles 1–1' and 2–2' are parallel to the X axis and Y axis, respectively. (c1–c5) Cross sections of the seismicity along profile 1–1'. The blue stars in b1–b5 and c1–c5 denote the location of the 2004 M 6.0 Parkfield mainshock. (d1–d5) Cross sections of the seismicity along profile 2–2'. The pink triangles show the location of the San Andreas fault. Both the SSST and waveform cross-correlation locations are based on the L3 norm. Note that only common events in all catalogs are presented here. Depth distributions are shown for seismicity within ± 0.5 km distance of the profiles. Dotted pink curves at the top of the cross sections illustrate the local topography. Relative location uncertainties estimated from bootstrap resampling after waveform cross-correlation location are provided for both horizontal (reh) and vertical (rev) directions.



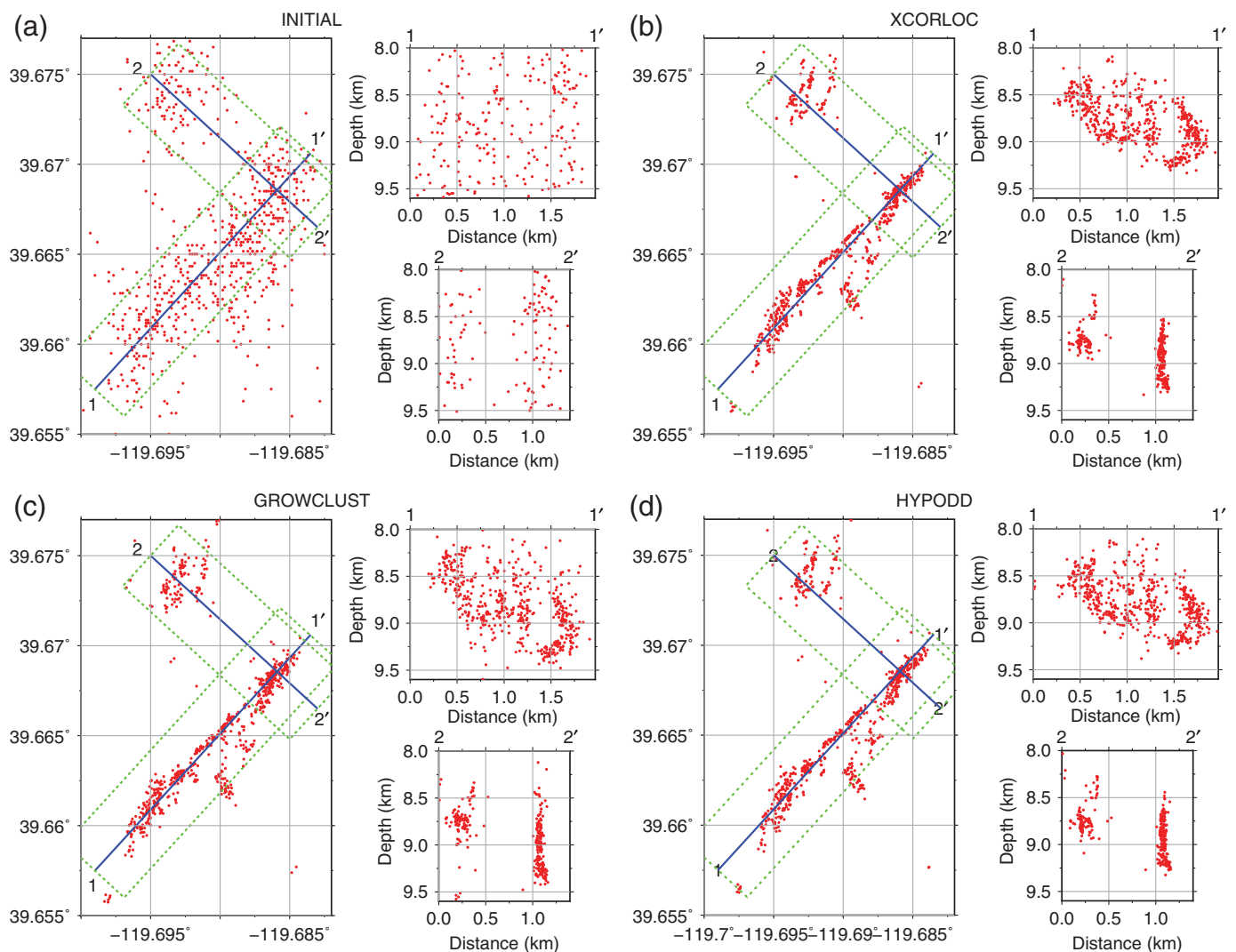
▲ **Figure 4.** Location comparison of the GeoNet and waveform cross-correlation locations in the North Island, New Zealand. (a,b) GeoNet location. (c,d) Waveform cross-correlation relocation starting from the GeoNet location using the L3 norm. Inset map in (b) shows the location of the study area (red box) in New Zealand. Note that only common events in both catalogs are presented here. Depth distributions are shown for seismicity, enclosed by the dotted black boxes along the solid straight lines. Dotted black curves at the top illustrate the local topography. Note topography is not included in the relocation process in this example because of the large depth range. Relative location uncertainties estimated from bootstrap resampling after waveform cross-correlation location are provided for both horizontal (reh) and vertical (rev) directions.

seismic stations at the GeoNet between 2012 and July 2017. Because these locations are carefully determined by the GeoNet using a 3D seismic velocity model for New Zealand (Eberhart-Phillips *et al.*, 2010), I start with the GeoNet location (location option 1) to relocate 12,508 events that satisfy the correlation coefficient requirements using waveform cross-correlation data. Figure 4 shows both map views and cross sections of the starting GeoNet and waveform cross-correlation locations. The bootstrap estimated location uncertainty is 0.65 km for horizontal and 0.50 km for vertical. The improvement in locations is seen clearly in the depth distribution. In addition to the more

condensed spatial resolution, a double seismic layer between 25 and 75 km depth is more clearly viewed in the relocation catalog, which is also observed in other areas of New Zealand (e.g., Zhang and Thurber, 2006).

COMPARISON WITH OTHER METHODS

The XCORLOC algorithm provides relative location improvements similar to the hypoDD program by Waldhauser and Ellsworth (2000) and the GrowClust program by Trugman and Shearer (2017). To compare the three location algorithms, I



▲ **Figure 5.** Location comparison for the 2012–2015 Spanish Springs sequence. (a) Initial location; (b) Waveform cross-correlation relocation resulted from the XCORLOC package, starting with (a) using the L3 norm; (c) GrowClust relocation; (d) double-difference relocation. Depth distributions are shown for seismicity enclosed by the dotted green boxes along the blue straight lines. Note that only common events in all catalogs are presented here.

took advantage of the example data for the 2012–2015 Spanish Springs sequence available in the GrowClust package. Given the same location parameters, the three techniques produce similar relocation results. The number of relocated earthquakes is 759, 793, and 753 for the XCORLOC, the GrowClust, and the double-difference catalogs, respectively. In Figure 5, I show location comparison of the different location catalogs for the 720 common events.

The XCORLOC algorithm uses all available differential times that satisfy the user-specified criteria for each event in the relocation process, therefore, it does not have computational advantage compared with the GrowClust approach by Trugman and Shearer (2017), which was motivated for computation efficiency. The computation time strongly depends on the dataset (e.g., numbers of events, stations, phase arrivals, and differential times), specific details of program construction (e.g., grid size, iteration number for grid search, and

number of bootstrap resampling for location uncertainty estimate), and type of computers used to conduct the job. For the 2012–2015 Spanish Springs sequence, it takes 83.4 s and 173.8 s on a MacBook Pro for the GrowClust and XCORLOC algorithms, respectively.

SUMMARY

The XCORLOC package represents an expansion of the COMLOC relocation package by Lin and Shearer (2006) with the inclusion of the differential time relocation. The following features are available.

1. Phase arrival-time location and waveform cross-correlation location are combined and can also be carried out separately.
2. Both the SSST method and differential-time relocation approach greatly improve the relative location accuracy among nearby events.

3. Static station terms can be computed for a particular 1D velocity model from a given group of well-constrained earthquakes, which can be used to achieve similar absolute location accuracy for a different set of events.
4. The grid-search approach allows application of more robust norms than least-squares. The availability of the L1 and hybrid L1–L2 norms in addition to the traditional L2 norm enables more robust relocation results.
5. The location program can be used for other types of phases as long as the corresponding travel-time tables are available.
6. The subroutine that reads in travel times can be modified to perform 3D raytracing.
7. Specific topography information can be included to avoid artificial effects in the presence of significant topographic relief and shallow earthquakes.
8. This package can be used for relocations in local, regional, and global scales because an earth-flattening transformation is applied to the velocity model prior to the raytracing.

DATA AND RESOURCES

Seismic data used in this study were accessed through the Southern California Earthquake Data Center (SCEDC), the Northern California Earthquake Data Center (NCEDC), the New Zealand GeoNet data centers, and published work. The topography data are downloaded from the U. S. Geological Survey. The XCORLOC package is available for free download at <http://www.rsmas.miami.edu/users/glin/XCORLOC> (last accessed May 2018). ☒

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