REAL

0. Author

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1. References

Zhang, M., W.L. Ellsworth, and G.C. Beroza. Rapid Earthquake Association and Location, Seismol. Res. Lett., 90.6, 2276-2284, 2019.

Kissling, E., W.L. Ellsworth, D. Eberhart-Phillips, and U. Kradolfer: Initial reference models in local earthquake tomography, J. Geophys. Res., 99, 19635-19646, 1994.

Waldhauser F. and W.L. Ellsworth, A double-difference earthquake location algorithm: Method and application to the northern Hayward fault, Bull. Seismol. Soc. Am., 90, 1353-1368, 2000.

2. Introduction

REAL (Rapid Earthquake Association and Location) associates arrivals of different seismic phases and locates seismic events primarily through counting the number of P and S picks and secondarily from traveltime residuals. A group of picks are associated with a particular earthquake if there are enough picks within the theoretical traveltime windows. The location is determined to be at the grid point with most picks (Fig. 1a). If multiple locations have the same maximum number of picks, the grid point with smallest traveltime residual is selected (Fig. 1b). We refine seismic locations using a least-squares location method (VELEST) and a high-precision relative location method (HypoDD).

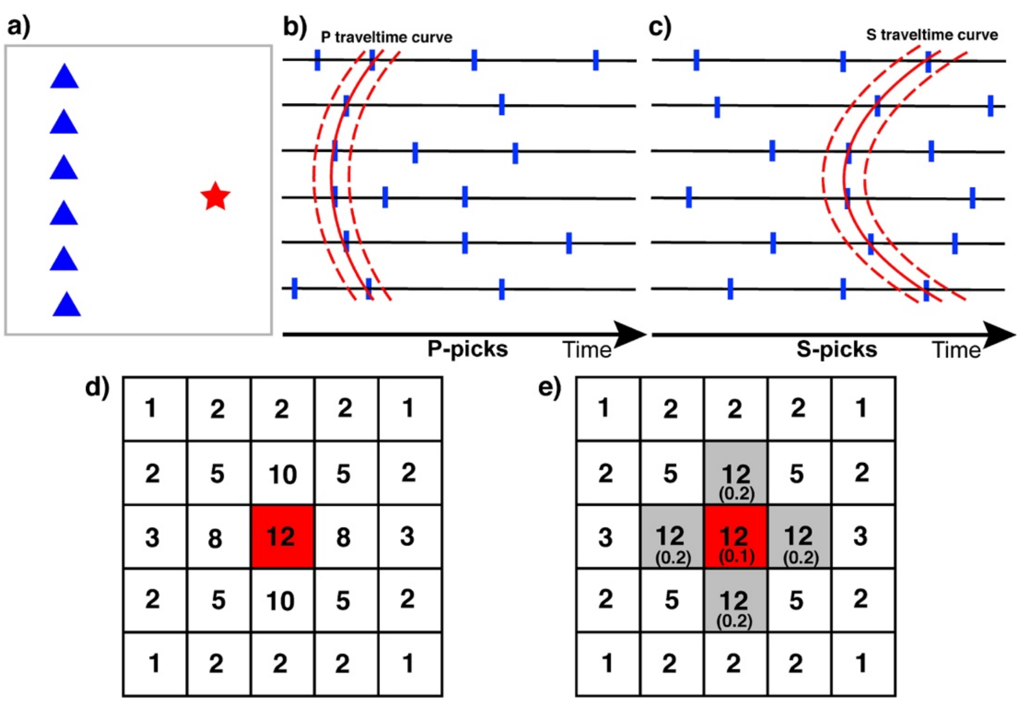

Figure 1. Cartoon illustrating the concept of REAL. a) The distributions of seismic event (red star) and seismic stations (blue triangles). b) *P* arrival time curve (red) with its uncertainty range (red dashed), associated *P* picks and other false *P* picks (blue bars). c) same as b) but for *S* picks. d) The optimal location is determined to be at the grid point with most picks or e) the grid point with smallest traveltime residual (shown in bottom parentheses, unit: second) among multiple locations with the same maximum number of picks.

3. Requirements
VELEST (http://www.seg.ethz.ch/software/velest.html, for further location, already provided)
hypoDD (https://www.ldeo.columbia.edu/~felixw/hypoDD.html, for DD relocation)
ObsPy (https://github.com/obspy/obspy, for data downloading, processing and picking only)
SAC (http://ds.iris.edu/ds/nodes/dmc/software/downloads/sac, for data processing only)
GMT (https://www.soest.hawaii.edu/gmt/, for figure plotting only)
Matlab (https://www.mathworks.com/products/matlab.html, for figure plotting only)

4. Usage (Type "REAL")
-D (nyear/nmon/nday/lat_center)
-R (rx/rh/tdx/tdh/tint[/gap/GCarc0/latref0/lonref0]])
-V (vp0/vs0[/s_vp0/s_vs0/ielev])
-S (np0/ns0/nps0/nppp/std0/dtps/nrt[/rsel/rsel])
[-G (trx/trh/tdx/tdh)]
station
pickdir
[ttime]

------------------------------------explanation---
"[]" denotes optional parameters.

-D:
(nyear/nmon/nday/lat_center)
(year/month/day/lat_center)
e.g., 2016/10/01/42.75
date of the day (year/month/day) and latitude center of the target region (deg., so that lat and lon have consistent distance in km)
[REAL can process seismic picks recorded in one day (or a few days but only up to 31 days, e.g., 2016/10/01 – 2016/10/31 but not eligible for 2016/10/02 – 2016/11/01). All picks are relative to ZERO of the day (e.g., 60.00 corresponds to 2016/10/14 00:01:00.00 and 864060 corresponds to 2016/10/02 00:01:00.00)]

-R:
(rx/rh/tdx/tdh/tint[/gap/GCarc0/latref0/lonref0])
(degree/km/degree/km/sec[degree/degree/degree/degree])
e.g., 0.2/30/0.02/2/5.0 or 0.2/30/0.02/2/5.0/360 or 0.2/30/0.02/2/5.0/360/180 or 0.2/30/0.02/2/5.0/360/180/42.75/13.25
rx: search range in horizontal centered at the station recorded the initiating phase (degree)
[e.g., > twice of average station interval]
rh: search range in depth (km)
[e.g., 30 km for crustal earthquakes, will search depth from 0 to 30 km]
tdx: search grid size for epicenter (degree)
tdh: search grid size for depth (km)
tint: two events cannot appear within tint sec, otherwise only keep the most reliable one (tint sec)
[The code will use the S travel time within one grid instead if your tint is too small]

gap: only keep events with reasonable station gap (e.g., default is 360°). It is strongly recommended to use this constraint when station coverage is poor.
GCarc0: only keep events with distance of < GCarc0 (e.g., default is 180°)
latref0: reference latitude (degree)
lonref0: reference longitude (degree)
[latref0 and lonref0 are optional; if not provided, the location of the station recording the initiating phases will be used]

-V:
(vp0/vs0/[s_vp0/s_vs0/ielev])
(km/s|km/s|[km/s|km/s|int])
e.g., 6.2/3.3 or 6.2/3.3/5.5/2.7/1
vp0: average P velocity (homogenous model) (km/s)
vs0: average S velocity (homogenous model) (km/s)
[vp0 and vs0 will be used to automatically calculate the default time window (time window between two dashed lines in Fig. 1), i.e., sqrt(tdx**2+tdh**2)/vp0 for P time window, sqrt(tdx**2+tdh**2)/vs0 for S time window]
s_vp0: shallow P velocity (km/s)
s_vs0: shallow S velocity (km/s)
ielev: station elevation correction (optional; default is 0; if 1, then s_vp0 and s_vs0 must be given for elevation correction. Note this assumes vertical ray path and corrects by elevation/s_vp0 for P phase and elevation/s_vs0 for S phase)

-S:
(np0/ns0/nps0/nppp/std0/dtps/nrt[/rsel/ires])
(int/int/int/int/double/double/double/[double/int])
e.g., 5/0/18/1/0.5/0.5/1.3, 5/0/18/1/0.5/0.5/1.3/5.0, or 5/0/18/1/0.5/0.5/1.3/5.0/1
np0: threshold for number of P picks
np0: threshold for number of S picks
nps0: threshold for total number of picks (P&S)
nppp: effective number of grids that meet the thresholds (np0, ns0 and nps0)
[The recommend value is 1. nppp>1 means more critical threshold (eligible for fine grid size)]
std0: standard deviation threshold (residual)
[Here residual is defined as the deviation of the origin times from different picks (for the same event). It is not the traditional RMS residual]
dtps: time threshold for S and P separation
[dtps is used to remove some false S picks. P picks may appear in S pick pool in real data when applying STA/LTA pickers. Set dtps = 0 to turn this constraint off]
nrt: nrt*default time window (>1)
[i.e., nrt*sqrt(tdx**2+tdh**2)/vp0 for P time window or nrt*sqrt(tdx**2+tdh**2)/vs0 for S time window. It accommodates the inaccuracy of velocity model (as well as pick uncertainty). Use larger nrt if velocity model is insufficient]
rsel: tolerance multiplier; keep picks in phase_sel.txt with residuals less than rsel*STD
[rsel is used to remove picks with large residuals. Default rsel is 5.0 (a large value, i.e., approximately turn this constraint off). For example, if your final standard deviation is 0.1 sec, REAL will automatically remove those suspicious picks with residuals > 0.5 sec]

ires: resolution_or_not
[optional; 1-output resolution file; 0-don't output. Note: only works for the first associated event when the first initiating pick is true. Thus, this is only recommended for synthetic resolution analysis]

[-G:]
[optional, no need for homogenous model case]
(trx/trh/tdx/tdh)
(degree/km/degree/km)
e.g., 1.4/20/0.01/1
trx: horizontal range in traveltime table (degree)
trh: vertical range in traveltime table (km)
tdx: grid size in traveltime table (degree)
tdh: grid size in traveltime table (km)

Dependent files:
station file
pick directory
[traveltime table] (optional, no need for homogenous model case)

Formats for input files:
pick file:
File name – net.station.phase.txt (e.g., YR.ED01.P.txt)
Phase pick (e.g., 13.977 1.0 0.0)
arrivaltime (sec), stalta_ratio or phase_probability, amplitude_in_micrometer
[If you don't have amplitude information, set amplitude_in_micrometer as ZERO and REAL will not estimate the magnitude. Using weight factors is highly recommended, which can be STA/LTA ratios (from STA/LTA picker) or phase probabilities (from machine-learning picker)]

station file:
e.g., 13.0929 42.5264 YR ED01 HHZ 0.739
lon., lat., network, station, component, elevation (km)

traveltime table:
e.g., 1.25 2 22.797 41.701 17.920 24.639 -0.0622 -0.2564 P S
distance (degree), depth (km), P traveltime (sec), S traveltime (sec), p_ray_parameter (sec/degree), s_ray parameter (sec/degree), p_vertical_slowness (sec/km), s_vertical_slowness (sec/km), P_or_p, S_or_s
[REAL accepts different search grids within the traveltime table. It will automatically look for the table and interpolate traveltimes using ray parameters. This file is not needed for homogenous velocity model case]

Formats for output files:
catalog_sel.txt:
e.g., 1 2016 10 14 00:00:08.158 8.1580 0.1076 42.8190 13.2305 10.0000 -inf nan 60 60 120 29.59
num, year, mon, day, time (hh:mm:ss), origin time (relative to ZERO, sec), residual (sec), lat., lon., dep., mag., mag var (uncertainty), number of P picks, number of S picks, total number of picks, station gap
[If you don't calculate magnitude, mag and mag_var would be "-inf" and "nan", respectively]

phase_sel.txt:
e.g., 1 2016 10 14 00:00:08.158 8.1580 0.1076 42.8190 13.2305 10.0000 -inf nan 60 60 120 29.59

```
  YR    ED06    P     14.7946      6.6365   0.0000e+00     -0.0762      1.0000      0.3290
  YR    ED06    S     20.4912     12.3332   0.0000e+00     -0.1038      1.0000      0.3290
```

Event line:
same as catalog.txt
Phase line:
network, station, phase name, absolute travetime (relative to ZERO, sec), traveltime relative to event origin time (sec), phase amplitude in micrometer, individual phase residual (sec), weight, azimuth

resolution.txt [optional for resolution test]:
e.g., 30.0047 42.7544 13.2483 10.0000 60 60 120 0.0871
origin time (sec), lat., lon., dep., number of P picks, number of S picks, number of total picks, residual (sec)

6. Updates
REAL 1.0
First release on Github on June 27, 2019

REAL 1.1 (Sept. 13, 2019)
1. Consider Earth's ellipticity when calculating distance (gcarc)
2. Calculate and output azimuth for each station/pick and station azimuth gap for one event
3. Exclude events with large station gap.
4. Fix a bug

REAL 1.2 (Nov. 14, 2019)
1. Utilize stations within a specified distance (see: GCarc0)
2. Update code only, didn't change the demo

REAL 1.3 (March 8, 2021)
1. Use cos(latcenter) to balance distance in km for lat. and lon.
2. Eliminate event splitting