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How Accurately Are MERMAID Seismograms Located?

Guust Nolet^{*1,2}, Joel D. Simon², and Sebastien Bonnieux¹

Abstract

Floating seismographs (Mobile Earthquake Recorder in Marine Areas by Independent Divers project “MERMAIDs”) record the data at depth at a location that is determined by linearly interpolating between the Global Positioning System positions when surfacing, assuming a constant drift velocity at depth. We study the influence of a changing drift velocity between surfacings and of a curvature of the drift trajectory. We separate localizations that directly follow a triggered ascent from those that are interpolated later. The first ones have on average a mislocation of 99 m due to curvature of the drift, against 685 m for interpolated localizations. Mislocations due to nonconstant velocity are somewhat smaller. Equivalent time errors have a distribution with heavier tails than Gaussian. The halfwidth of the 95% interval for equivalent arrival-time errors is smaller than 27 ms if the seismogram recording triggers an immediate ascent. If the recording is transmitted at a later surfacing, the interpolation is less precise with a 95% confidence interval halfwidth of 222 ms, but 67% of the errors are below 44 ms. We conclude that the localization errors have no significant impact on the accuracy of picked arrival times.

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Introduction

Mobile Earthquake Recorder in Marine Areas by Independent Divers project (MERMAIDs) are autonomous hydrophones, drifting passively with the ocean bathyal flow, usually at a depth of 1500 m (Simons *et al.*, 2009; Hello *et al.*, 2011; Sukhovich *et al.*, 2015; Hello and Nolet, 2020).

The arrival of a recognizable *P*-wave triggers a signal recording and, if it is strong enough, an immediate return to the surface where the float’s location is determined with Global Positioning System (GPS) and where data from memory are transmitted via satellite (Iridium). Since there is a gap of at least several hours between recording and the first geolocalization, the location of the MERMAID at the time of recording has to be reconstructed from its drift speed and direction. The standard localization procedure assumes a constant drift velocity at depth and a linear trajectory between two surfacings.

Joubert *et al.* (2016) describe the method and analyzed its accuracy using data from second-generation MERMAIDs in the Mediterranean. Second-generation MERMAIDs were successfully used in an experiment to image the Galápagos plume (Nolet *et al.*, 2019).

Currently, 49 third-generation MERMAIDs are operating in the South Pacific ocean as part of project “South Pacific Plume Imaging with MERMAIDs” or SPPIM (Simon *et al.*, 2020, 2022). These MERMAIDs are spherical in shape and take much longer to arrive at the surface (about 5 hr) than the earlier cylindrical design, calling for a renewed analysis of

the accuracy of localization and its equivalent timing error when the *P*-wave arrival times are used in seismic tomography or hypocenter determinations. We use 4826 surfacings from 18 MERMAIDs to study flow statistics and estimate the accuracy of localization by comparing the standard, linear, estimates with those that allow for changes in drift velocity and direction between two surfacings.

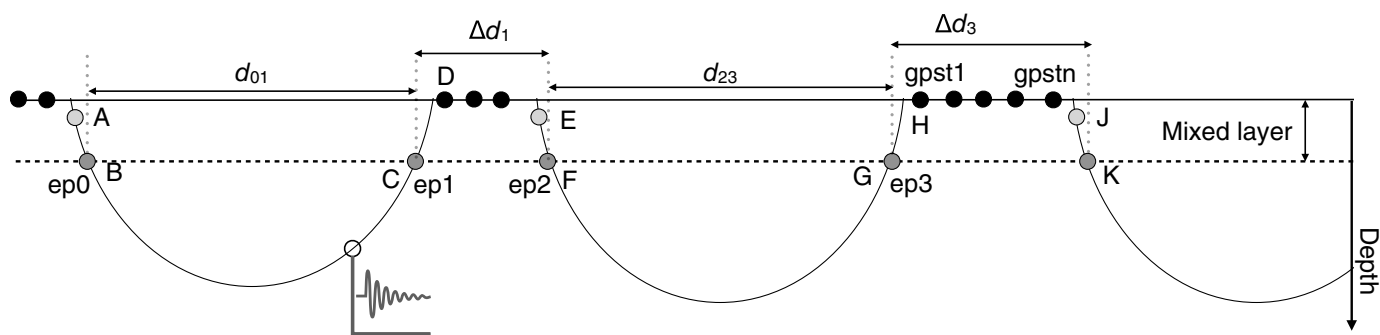
Geolocalization of MERMAID Recordings

Figure 1 shows the basic steps in a MERMAID deployment: after launch it starts to dive (A). During dives and ascents, pressure is recorded every few minutes, allowing us to time the crossing at B into the thermocline at the bottom of the “mixed layer” (time t_0 at extrapolated positioning ep_0 in the figure). It floats at a programmable constant depth (open circle) until a strong earthquake signal triggers a surfacing, or until a maximum deep float time (also programmable, usually to 7–10 days) has passed. It crosses the thermocline again at ep_1 (C) and starts GPS geolocalization at D. Once all relevant data have been transmitted (typically in less than one hour) the float dives again (E) and enters the deep ocean

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at ep2 (F). We refer to the drift between ep1 and ep2 as the “surface drift”. This sequence repeats itself many times (e.g., between G and K in the figure) until the float is picked up or its batteries are exhausted. Though the design called for at least 250 surfacings, the oldest MERMAID in the project (P0006) has already surfaced more than 300 times in 5 yr.

Each GPS geolocalization (black dots) includes the following steps: (1) waiting for a signal of a sufficient quality, (2) measuring the clock drift of the float with a microsecond precision, (3) measuring the frequency of the quartz oscillator which drives the clock, and (4) adjusting the clock date and the quartz frequency parameter. The clock drift measured on the floats is usually around 0.1 s per day. Knowing that the drift is null at the beginning of a dive, and assuming a constant drift with time, the clock drift for each record can be determined. The change in clock drift due to temperature change when the float is surfacing is negligible since the GPS synchronization is done within about 10 min, which contributes less than 1 ms to the drift (1% of the daily drift). The time stamps of recorded earthquake signals are automatically corrected for this drift.

With few exceptions, there are always at least two GPS fixes, which allows us to determine the local flow speed and direction at the surface, which we assume is identical and constant near the ascent in the mixed layer. Using this and the time difference between crossings of the thermocline and the first (gpst1) and last GPS localization (gpstn) allows us to extrapolate and determine the locations of the crossings such as ep0, ep1, etcetera. For the SPPIM project we adopt a generic depth of 50 m that separates the mixed layer from the deep ocean, which agrees well with the average depth to the thermocline. From this we determine the average bathyal speed of the float. Assuming a linear trajectory and a constant flow speed, we finally determine the locations at the depth where recordings were made.

For events that generate an ascent, a simple back-of-the-envelope calculation shows that we can expect the error in the extrapolation distance to be small: the distance travelled in the mixed layer until the first GPS is on average 0.3 km (only 19 out of 4826 surfacings showed a distance exceeding 1 km). With a rise time of 5.5 hr and an average deep flow of 2.24 km/day the ascent in the deep layer adds on average

Figure 1. A schematic showing the important stages in the reconstruction of the Mobile Earthquake Recorder in Marine Areas by Independent Divers project (MERMAID) trajectory at depth. The black dots indicate known Global Positioning System (GPS) locations. The dark gray dots ep0 to ep3 indicate reconstructed crossings of the bottom of the mixed layer at times t_0 to t_3 . The light gray dots indicate the first positive pressure measurements, indicating the start of the dive. The open circle indicates one position at the time of recording of a seismogram. We use a combination of bathyal flow speed and the flow in the mixed layer to determine the offset between D and that position (see text).

0.5 km, for a total average extrapolation of 0.8 km. For example, even if we allow for, say, a 30% error in the estimated drift speed we obtain a localization error of 0.24 km. If the P wave has a slowness of 0.08 s/km, the equivalent time error for a station in the direction of the drift is then only 0.02 s, which is well tolerated by both seismic tomography and earthquake location algorithms.

However, for smaller earthquakes that do not trigger a surfacing, the drift distance until the first GPS is larger and the estimate becomes more uncertain. 46% of the deep distances travelled (d_{01} and d_{23} in Fig. 1) were less than 10 km, 7% exceeded 30 km. Moreover, the validity of our constant velocity assumption, as well as the linearity of the trajectory, may be questionable. Figure 2 shows that MERMAID drift can become quite unpredictable, especially when the float gets trapped in an eddy current. Therefore, we must include an estimate of both path curvature and acceleration when reconstructing the MERMAID location at the time of seismogram recording.

The linearity of the leg is quantified by the angle α between a leg and the leg before it (see Fig. 3). If α differs much from 180° we can expect substantial errors in interpolated localizations. Although 49% of the trajectories studied in this article had $170^\circ < \alpha < 190^\circ$, no less than 22% had α deviating more than 45° from 180° , confirming our suspicion that the effects of changes in direction need to be investigated. In the following sections we describe our method for estimating the errors in interpolated MERMAID location due to nonzero acceleration and curvature of the bathyal drift trajectory.

$$\delta t_h = ph \sin(\eta - \beta + \phi). \quad (16)$$

Similarly, because \vec{b} is in the flow direction, its equivalent time error is as follows:

$$\delta t_b = pb \cos(\eta - \beta). \quad (17)$$

Experimental Results

We analyzed the recordings of 18 MERMAIDS, all contributed to the SPPIM experiment by Princeton and Geoazur and launched between June and September 2018. Until July 2023, this had yielded 1640 seismograms with a *P* wave strong enough to trigger an ascent, and 1491 that were transmitted later. The latter ones had localizations interpolated farther away from the triggered GPS location and are therefore expected to be less accurate. A summary of the results is shown in Table 1. The curvature error *h* is on average 685 m from the straight-line path if the localization is interpolated, compared with 430 m for the acceleration error *b*, almost an order of magnitude larger than in the triggered case. By summing the equations (16) and (17) we obtain the equivalent time error that remains small for teleseismic waves with $p \ll 1$ s/km, even for the interpolated case. The distribution for the equivalent error has a 95% confidence interval halfwidth of 27 and 222 ms for triggered and interpolated localizations, respectively. These widths are more than twice the 67% confidence interval of the residuals, which defines the robust standard deviation of the residuals (Motulsky and Brown, 2006), indicating a wider spread of errors than would be expected from a normal distribution.

The histograms for *b* and *h*, separated for triggered and for interpolated seismograms, are shown in Figure 5. The histograms for the resulting equivalent errors are in Figure 6.

Discussion and Conclusions

One shortcoming of our approach is the simplified division of ocean flow in two layers with a fixed depth of 50 m for the thermocline. In reality, this depth varies not only with location, but also with the seasons. Local variations may introduce changes in the calculated velocities—and thus the apparent accelerations—that do not reflect true variations of the bathyal flow. Similarly, rise times through the surface layer may vary from place to place and influence the velocity estimates (e.g., recent rainfall causes lower water density which slows the ascent). It is therefore not certain that the curvilinear positioning is better than the linear one, but we can adopt the difference between the two, and their equivalent time errors, as a first-order estimate of the errors introduced in the position calculations by the assumptions of linearity and zero acceleration.

To study the influence of the thickness of the mixed layer on the estimates presented in this article, we computed alternative equivalent errors assuming thicknesses of 25 and 75 m. For the

TABLE 1

Error Statistics

| | Triggered | Interpolated |
|---------------------------------------|--------------|--------------|
| Number of data | 1640 | 1491 |
| Mislocations | | |
| Average <i>b</i> (km) | 0.066 | 0.430 |
| 67% confidence interval <i>b</i> (km) | 0.001/0.11 | 0.08/0.72 |
| Average <i>h</i> (km) | 0.099 | 0.685 |
| 67% confidence interval <i>h</i> (km) | 0.01/0.17 | 0.06/1.20 |
| Equivalent time errors | | |
| Average (s) | 0.000 | 0.004 |
| RSDR (s) | 0.007 | 0.044 |
| 95% confidence interval (s) | −0.029/0.024 | −0.277/0.167 |
| Min and max error (s) | −0.115/0.095 | −2.132/0.942 |

Min and max, minimum and maximum; RSDR, robust standard deviation of the residuals

MERMAIDS of the SPPIM project, this covers most of the excursions from 50 m to be expected among different seasons and latitudes (Treguier *et al.*, 2023).

Figure 7 shows the errors for the two cases plotted against the errors for the average thickness of 50 m. It shows that the differences are small, ruling out that the choice of thickness of the mixed layer has an important influence on the error estimates.

Considering that the contribution of MERMAIDS to earthquake location is most effective for earthquakes in oceanic areas where land-based seismic stations are farther away, even the average mislocation of 685 m for interpolated localizations is small with respect to the hypocentral accuracy that is reached with surface stations only, which is 5 km if a local network is available (Bondár *et al.*, 2004). We conclude that MERMAID seismograms should be considered for the purpose of improving earthquake hypocenters, especially in the oceans.

In global tomography, we consider errors of 0.1 s in travel times to be negligible in view of picking errors in the presence of noise and uncertainties in crustal corrections that are generally larger. In the case of floating seismometers in the oceans, the crustal correction is dominated by the correction for bathymetry which may also be rather uncertain. As is clear from Table 1, the largest errors for triggered localizations are 0.1 s and errors larger than 0.2 s are rare even for interpolated localizations. For the latter, an error of 0.1 s is at the 85% confidence level. The largest interpolated error (−2.1 s) was found for P0006 when it was caught in an eddy with very high drift speeds (15.2 km/day) and rapidly changing directions (this eddy is visible near the bottom of Fig. 2 at 176° E). For global tomography, the MERMAID seismograms thus constitute a valuable addition to the recordings from ocean bottom and island stations, in

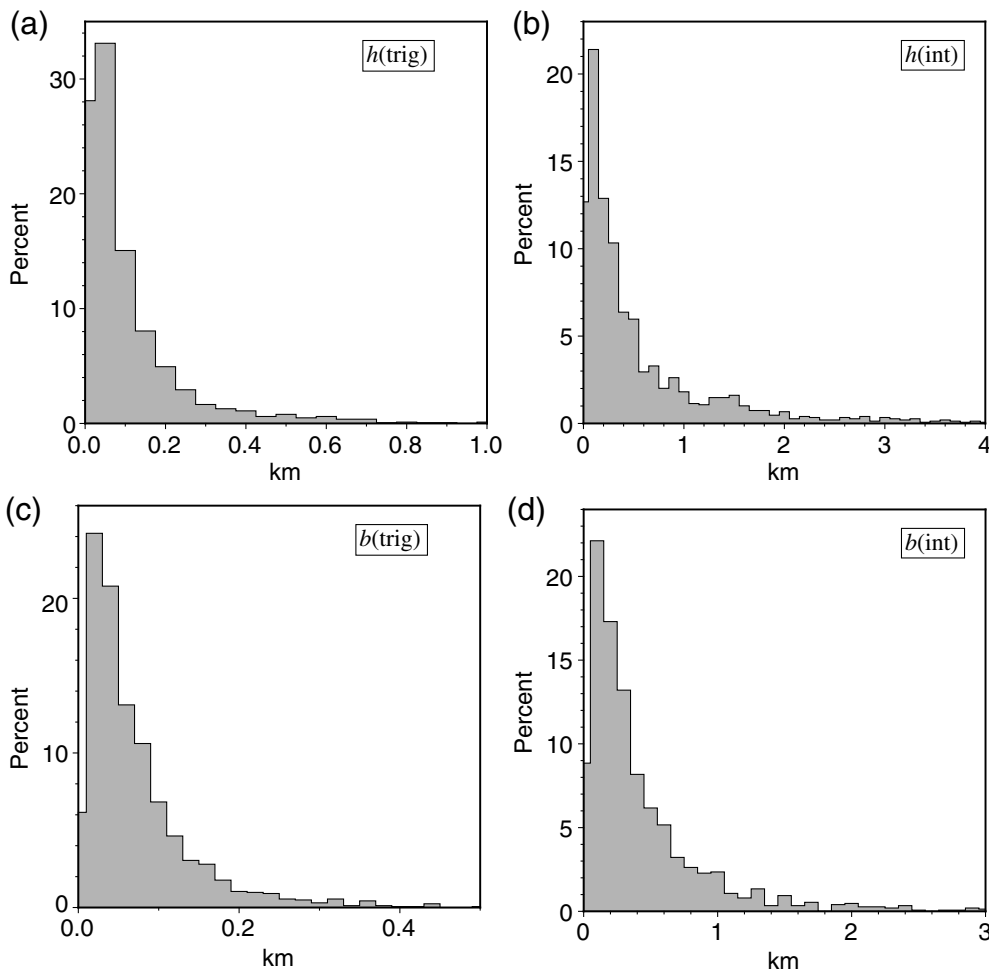


Figure 5. Histograms for the (a,b) off-path mislocations h and (c,d) on-path mislocations b . (a,c) The case where the P wave triggered an immediate ascent to the surface and subsequent GPS fixes, from which the localization was extrapolated. (b,d) The case that the seismogram was stored in memory and where the localization was interpolated between two surfacings.

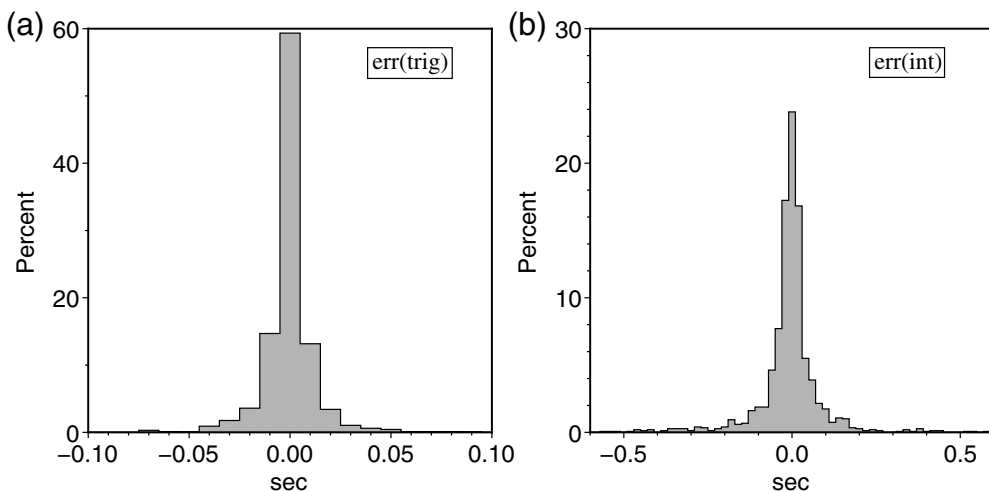


Figure 6. Histograms for the equivalent errors in travel time (using $\delta t = p\delta\Delta$). (a) The case where the P wave triggered an immediate ascent to the surface, with subsequent GPS fixes from which the localization was extrapolated. (b) The case that the seismogram was stored in memory and where the localization was interpolated between two surfacings, and farther away from a GPS geolocalization.

particular because they are able to cover large areas over time at low cost.

Of course, picking errors on MERMAID seismograms (Simon *et al.*, 2020) add to the uncertainty in the travel time and variances must be added to get the full error estimate. The bottom line is that the localization errors determined in this study do not appear to cause a significant deterioration of the accuracy by which arrival times can be determined from MERMAID seismograms.

Data and Resources

The Mobile Earthquake Recorder in Marine Areas by Independent Divers project (MERMAID) positional metadata used in this article are available at the EarthScope data center (<https://www.earthscope.org/>; formerly Incorporated Research Institutions for Seismology [IRIS]) under the network code “MH” (doi: [10.7914/SN/MH](https://doi.org/10.7914/SN/MH)). Positional metadata in the form of GeoCSV files is available for all floats at <https://ds.iris.edu/data/reports/MH>. The hydroacoustic data are also stored with EarthScope but were not used in this article. With a few exceptions (P0006, P0007, P0008, P0010, and P0016) these seismograms are embargoed for two years after acquisition. All websites were last accessed in March 2024.

Declaration of Competing Interests

The authors acknowledge that there are no conflicts of interest recorded. S. B. has been employed in the past by OSEAN SARL in Le Pradet, France, who produce the Mobile Earthquake Recorder in Marine Areas by Independent Divers project (MERMAIDS), but currently has no links with the firm.

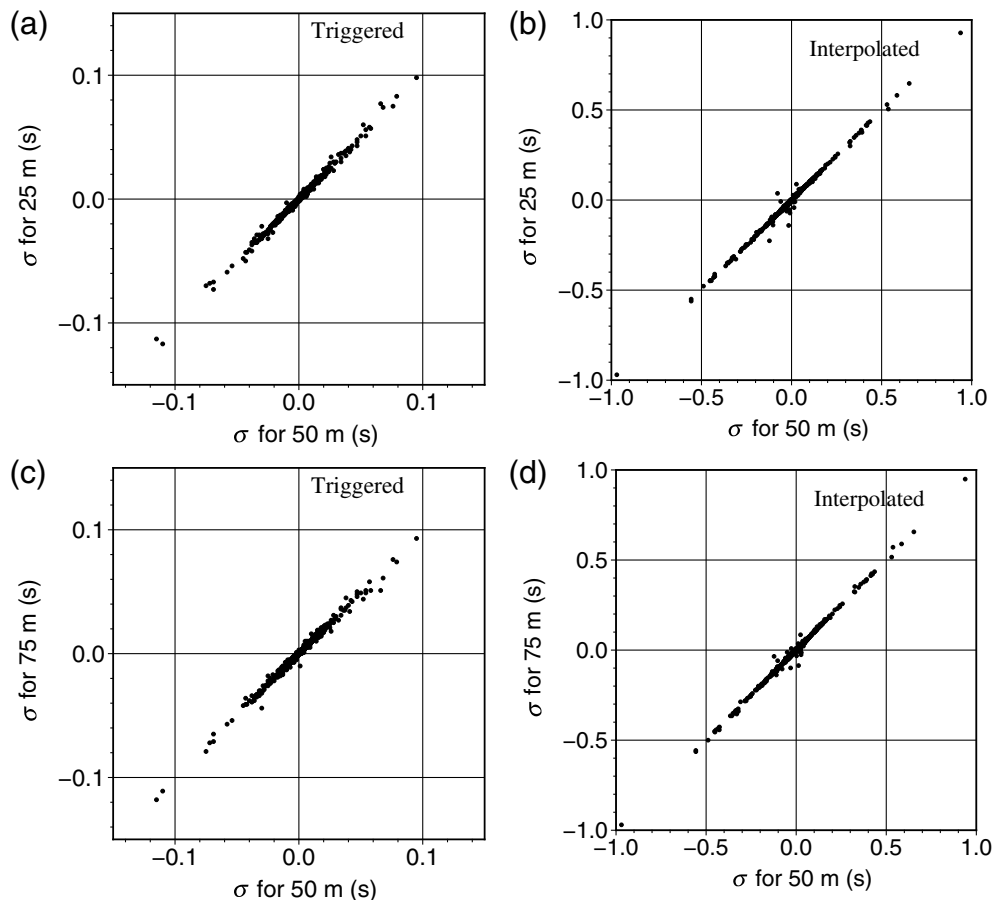


Figure 7. Equivalent time errors calculated assuming a mixed layer of (a,b) 25 m or (c,d) 75 m for (a, c) triggered seismogram localizations and (b,d) interpolated ones, plotted against the error assuming a 50 m thickness.

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