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MEMS Accelerometers Mini-Array (MAMA) Initial results and lessons learned

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1. Background

Most operational earthquake early warning systems (EEWS) consider earthquakes to be point-sources and have difficulty providing imminent and robust source locations and magnitudes, especially at the edge of the seismic network or where seismic stations are sparse.

Mini-arrays have the potential to reliably estimate hypocentral locations by beam-forming (FK-analysis) techniques. They can also characterize the rupture dimensions and account for finite-source effects, leading to more reliable estimates of ground motions for large magnitude earthquakes. In the past, the high price of multiple seismometers has made creating arrays cost-prohibitive.

Here, we present a setup of two mini-arrays of a new low-cost (<$150) seismic acquisition unit based on a high-performance MEMS accelerometers around conventional seismic stations deployed at UC Berkeley (UCB) and Humboldt State University (HSU) campuses. The expected benefits of using such **MEMS Accelerometer Mini-Arrays (MAMA)** include decreasing alert-times, improving real-time shaking predictions and mitigating false alarms (Nof et al., 2019).

2. The Challenge

A significant problem faced by EEWS is the correct characterization of earthquakes that occur at the edge of or outside of the seismic network. Due to poor azimuthal coverage, location estimate errors can be considerable.

3. The Solution

Combining multiple **MAMA** may make it possible to robustly estimate the epicenter of an earthquake based on just two arrays instead of the current requirement of 4 stations. This would decrease the time needed for point source EEWS to issue an alert, especially where the seismic network is sparse.

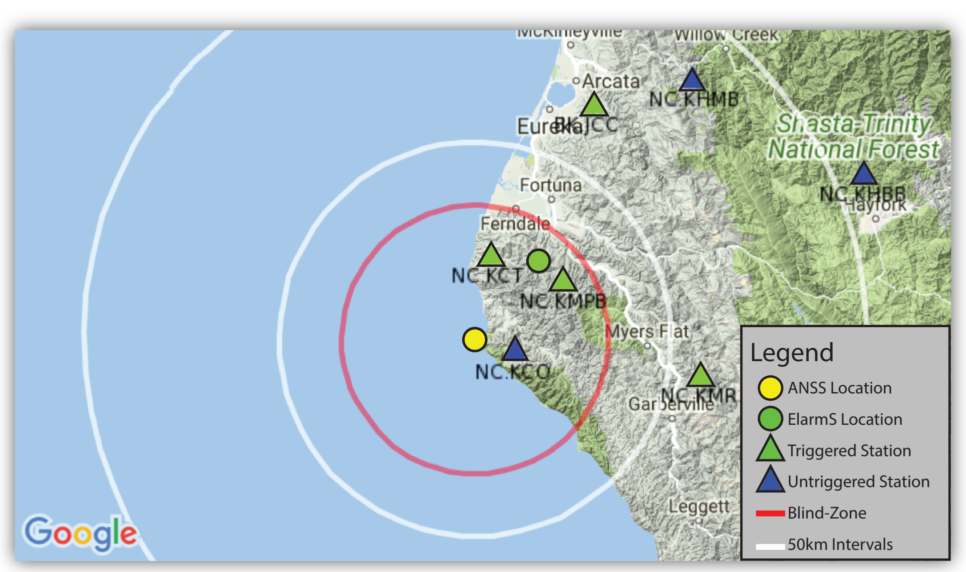


Figure 1: ElarmS review tool snapshot of the first (mislocated) alert of Mw 4.5 earthquake that occurred on December 5th, 2016 at 18:55. Yellow circle marks the ANSS catalog location; green circle marks ElarmS calculated location. Seismic stations used for solving the event parameters are marked as green triangles, while other stations are marked as blue triangles. The blind-zone is marked as a red circle and the white circles show 50km intervals. Had there been a MAMA around station NC.KMPB and assuming a 5 sec delay to process the data and calculate the BAZ, a better location might be achieved without delaying the alert time, which was sent 6 sec after P-wave arrival to the station. The large alert time delay is due to an ElarmS requirement that 4 stations must trigger before an alert can be sent out.

4. New MAMA Device

We have developed a new low-cost (<US$150) device. This unit consists of a printed circuit board (PCB) bearing four analog MEMS accelerometers (±2g range) and a 24-bit ADC, and which is combined with a RaspberryPi (RPi) single board computer. The RPi serves as a datalogger and is capable of providing online access to the 100 samples per second data streams via an onboard seedlink server. The device can be used as a single low-cost station or be a part of an array and is more sensitive than the avialable off-the-shelf sensors currently available (Figs 2 & 3).

5. MAMA Deployment

The first **MAMA** deployment, BRK **MAMA**, was at the UCB campus and the second, ARC **MAMA,** at the HSU campus (Fig 4). **MAMA** devices were placed in basement or ground floor rooms (Fig 5). We note that using this method the coupling to the ground is not ideal, but it is a very quick, low-cost and non-intrusive method, suitable for offices and occupied urban areas. Communication with the nodes is done via Wi-Fi or Ethernet.

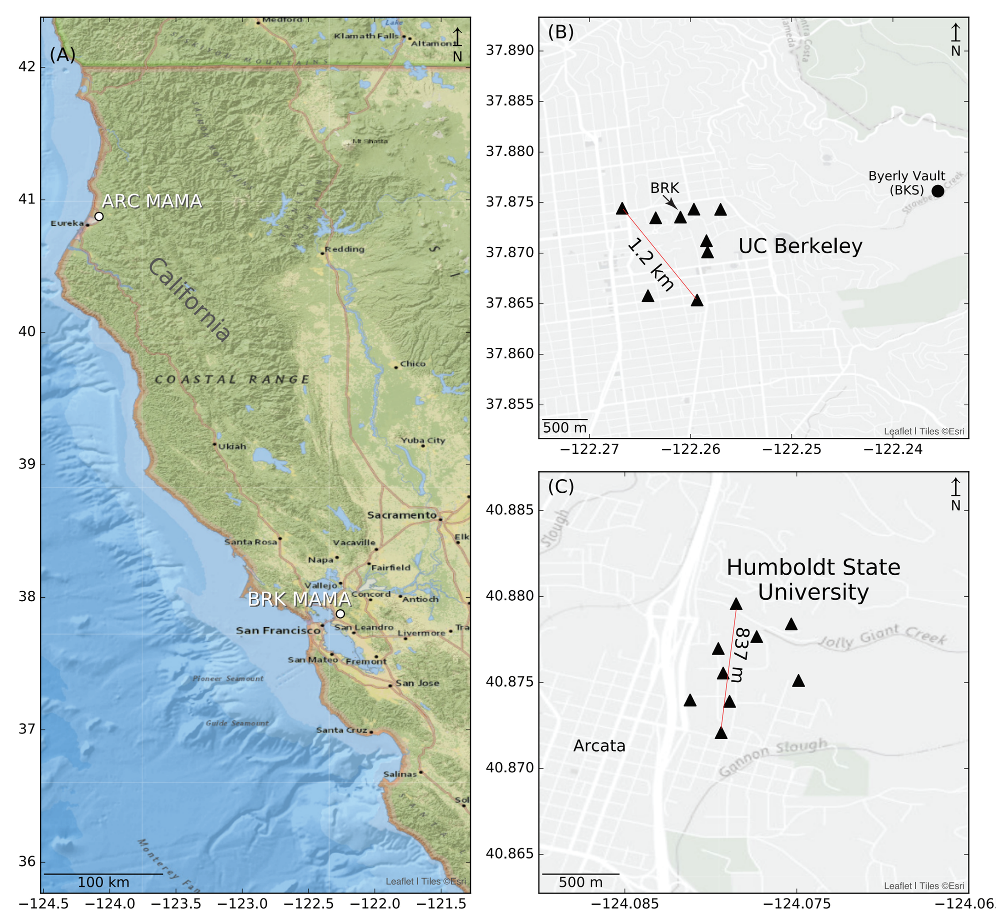


Figure 4: MAMA location map. (A) General Location Map. (B) BRK MAMA at UCB, Berkeley, CA. BRK marks the location of the conventional BK.BRK station at Haviland Hall; (C). ARC MAMA at HSU, Arcata, CA. MAMA nodes are marked as triangles.

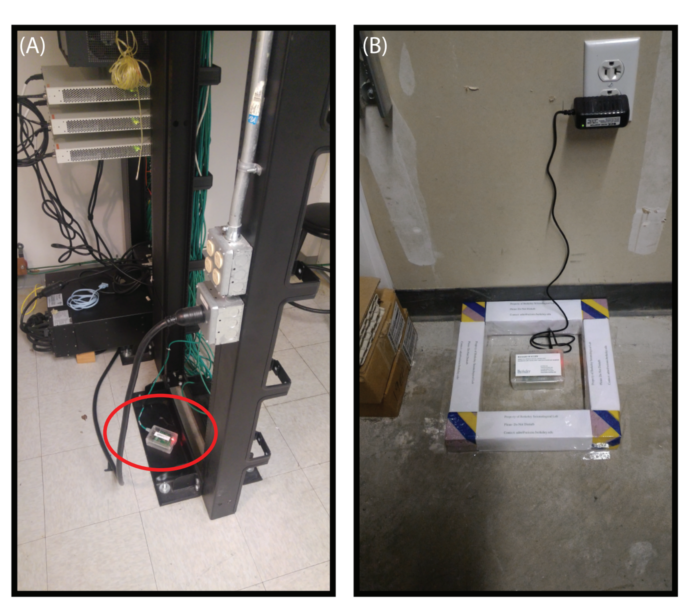


Figure 5: MAMA device deployment. (A) An example of ARC MAMA node ARC21 in a telecomunication room. (B) BRK MAMA node BRK12 in a utility room. Each node was connected to a wall outlet for power, aligned to magnetic north, and attached to the floor with a two-sided tape.

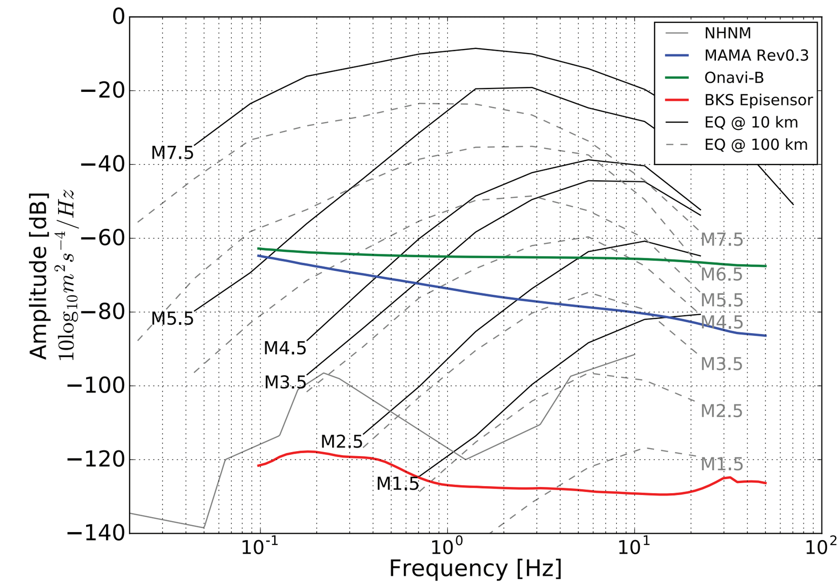


Figure 2: Comparison of mean horizontal trace PPSD (McNamara and Buland, 2004) of a MAMA device (blue), a QCN's ONAVI-B 16-bit MEMS sensor (green) and a conventional strong motion sensor of the BK network (red) installed at the Berkeley Byerly Vault, measured between 2016-09-01 and 2016-09-05. Earthquake representative spectra response (Clinton and Heaton, 2002) marked as dark solid and dashed gray lines for near and far fields, respectively. NHNM (Peterson, 1993) is marked as solid gray line.

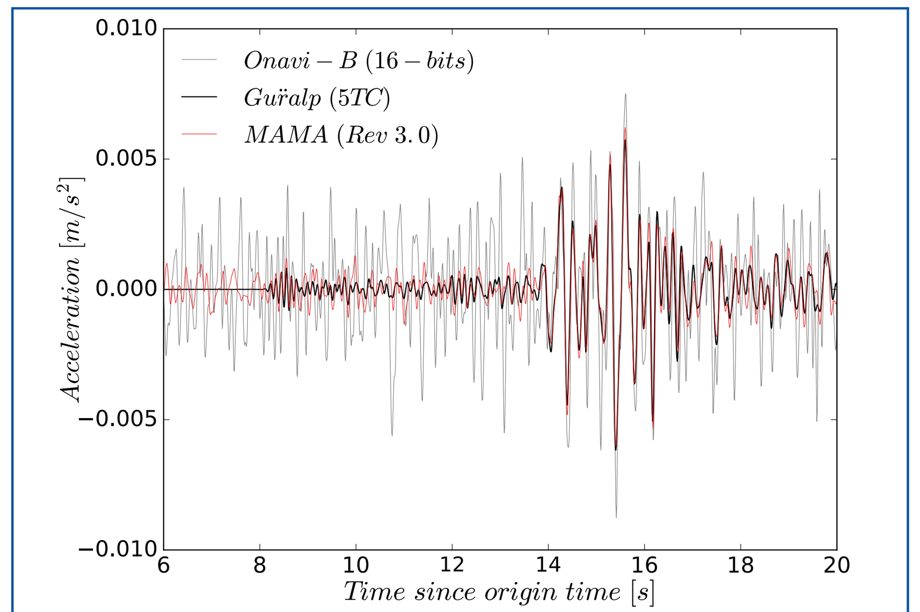


Figure 3: Comparison of north component from a MAMA device (red), a Güralp 5TC accelerometer (black), and an Onavi-B device (gray), for event nc72795746, Mw 3.78 located 40.2 km away. All devices were co-located at Berkeley Byerly Vault. Time is relative to origin time. Traces are bandpass filtered between 1 Hz and 10 Hz.

Figure 6: Examples of 3 earthquakes recorded by BRK or ARC MAMA. Each subfigure title details the event ANSS ID, date, magnitude, distance from MAMA center and observed BAZ. (A) BRK MAMA records of ANSS event nc72819101. Note the similar signal at co-located locations and between a conventional high-end Episensor accelerometer and MAMA devices. This is the closest event recorded. (B) ARC records of event nc72852151. This is the highest magnitude event recorded.

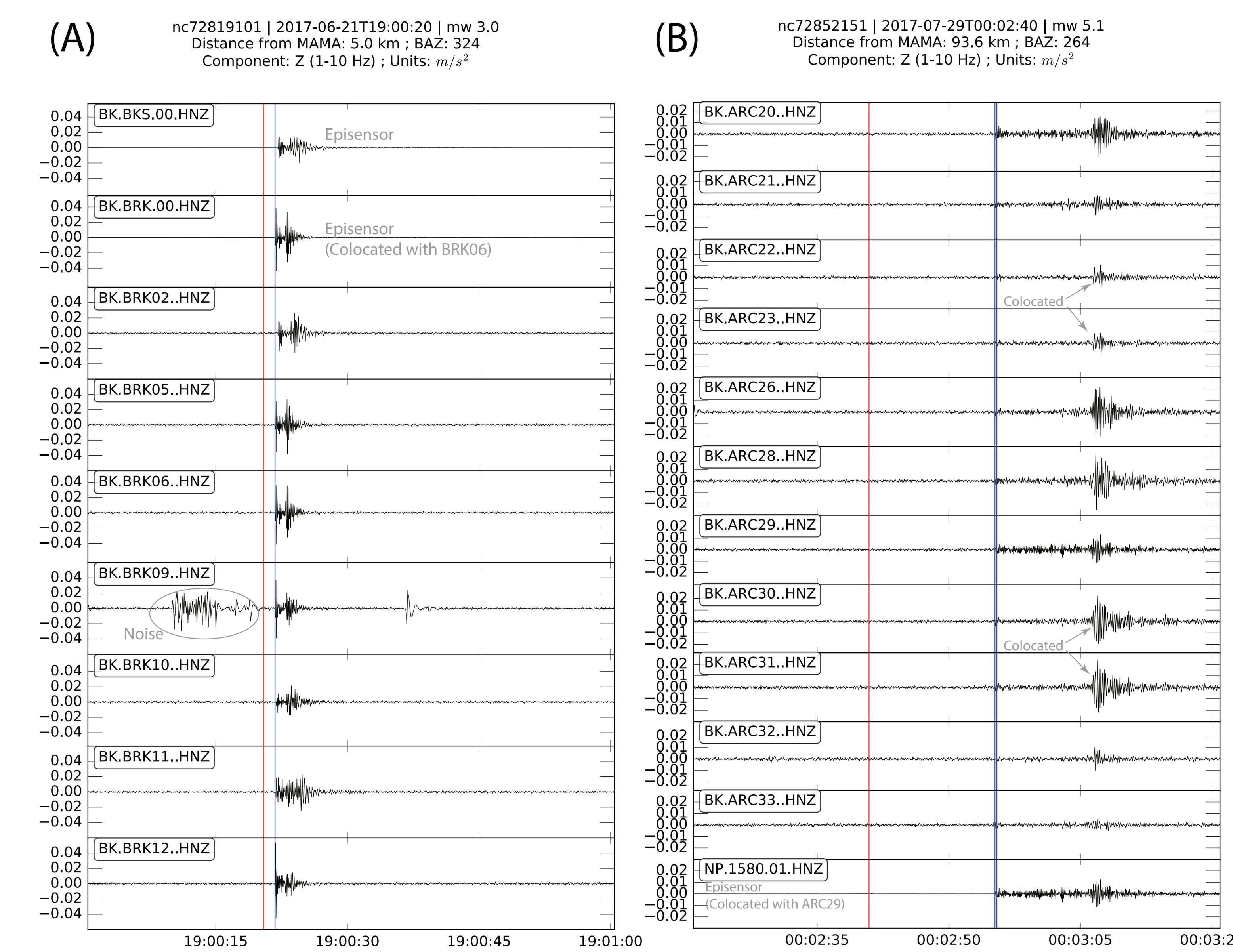
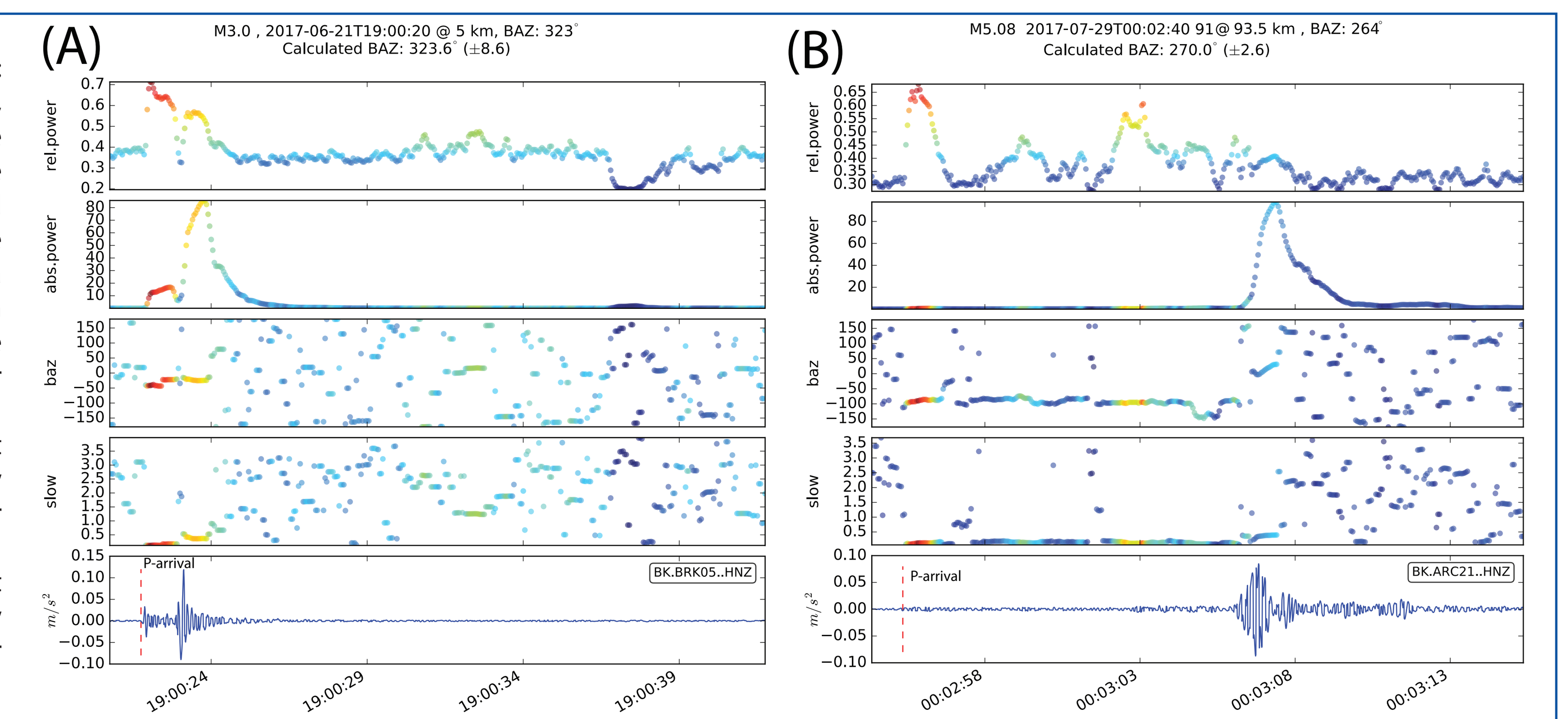


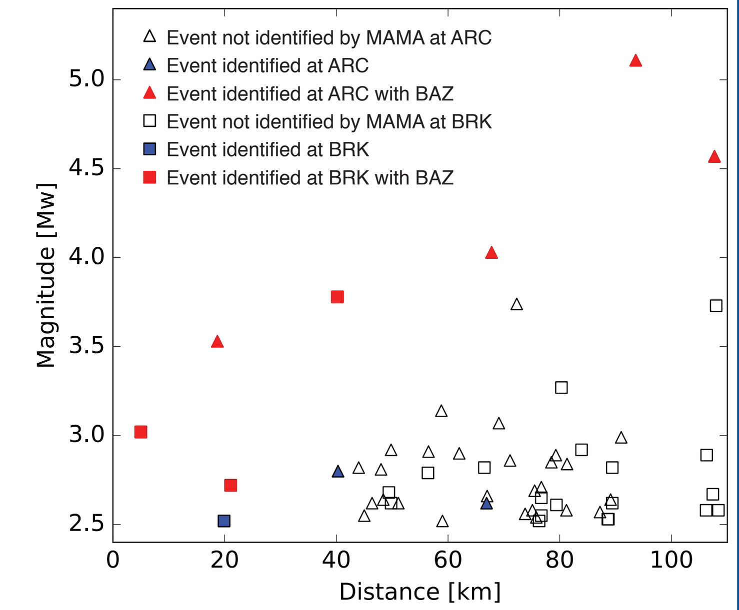
Figure 7: Subplots from the top are: relative power, absolute power, BAZ, slowness, and a typical MAMA device acceleration waveform with the trigger time marked by a dashed red line. Each point represents the calculations done for a 1 s data window ending at point position along x-axis. Colors represent the amplitude of the relative power values.
(A) BAZ calculation plot for event nc72819101 2017-06-21T19:00:20 Mw 3. This result was obtained 1.8 s after the trigger time.
(B) BAZ calculation plot for event nc72852151 2017-07-29T00:02:40 Mw 5.1, This result was obtained 1.5 s after the trigger time.



6. Results

Both ARC and BRK **MAMA** data were collected at BSL's data center. Using the USGS ANSS catalog, for events Mw > 2.5 within a 110-km radius from the **MAMA** center, we automatically process the waveforms from the **MAMA**s and calculate the BAZ to the event using F-K analysis (Figs 6 & 7). Using an automatic processing scheme, 4 out of 23 events were identified by the BRK **MAMA** and 6 out of 33 events were identified by the ARC **MAMA** between March 9th, 2017 and August 1st, 2017. Of the identified events, we successfully calculate BAZ for 3 and 4 events at the BRK and ARC **MAMA**s, respectively. Figure 8 shows the BAZ and event identification threshold with respect to magnitude and distance. We have been able to calculate BAZ for earthquakes with magnitudes as low as M 2.7 at 20 km distance.

Figure 8: MAMA detection and BAZ calculation performance. All events with M>2.5 and within 110 km from a MAMA are plotted as triangles and squares for ARC and BRK MAMAs, respectively. Red markers represent identified events with calculated BAZ within 30° of the observed BAZ. Blue markers represent identified events with calculated BAZ more than 30° different from the observed BAZ. Empty markers represent events not identified by MAMA.



7. Conclusions

Though still noisier than class-A strong-motion devices (e.g. Episensor), our low-cost device significantly improves our capability to obtain useful signals of small magnitude events and allows us to test our approach without needing significant events to occur in the **MAMA** vicinity.

As demonstrated, **MAMA** can be used to rapidly obtain the BAZ of an event. Combining multiple **MAMA** may make it possible to robustly estimate the epicenter of an earthquake based on just two station-arrays. This would decrease the time needed for point source EEWS to issue an alert. Implementing **MAMA** BAZ in real-time and incorporating it into EEWS will allow for the better estimation of earthquake magnitudes and shaking intensity distributions.

Acknowlegments

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