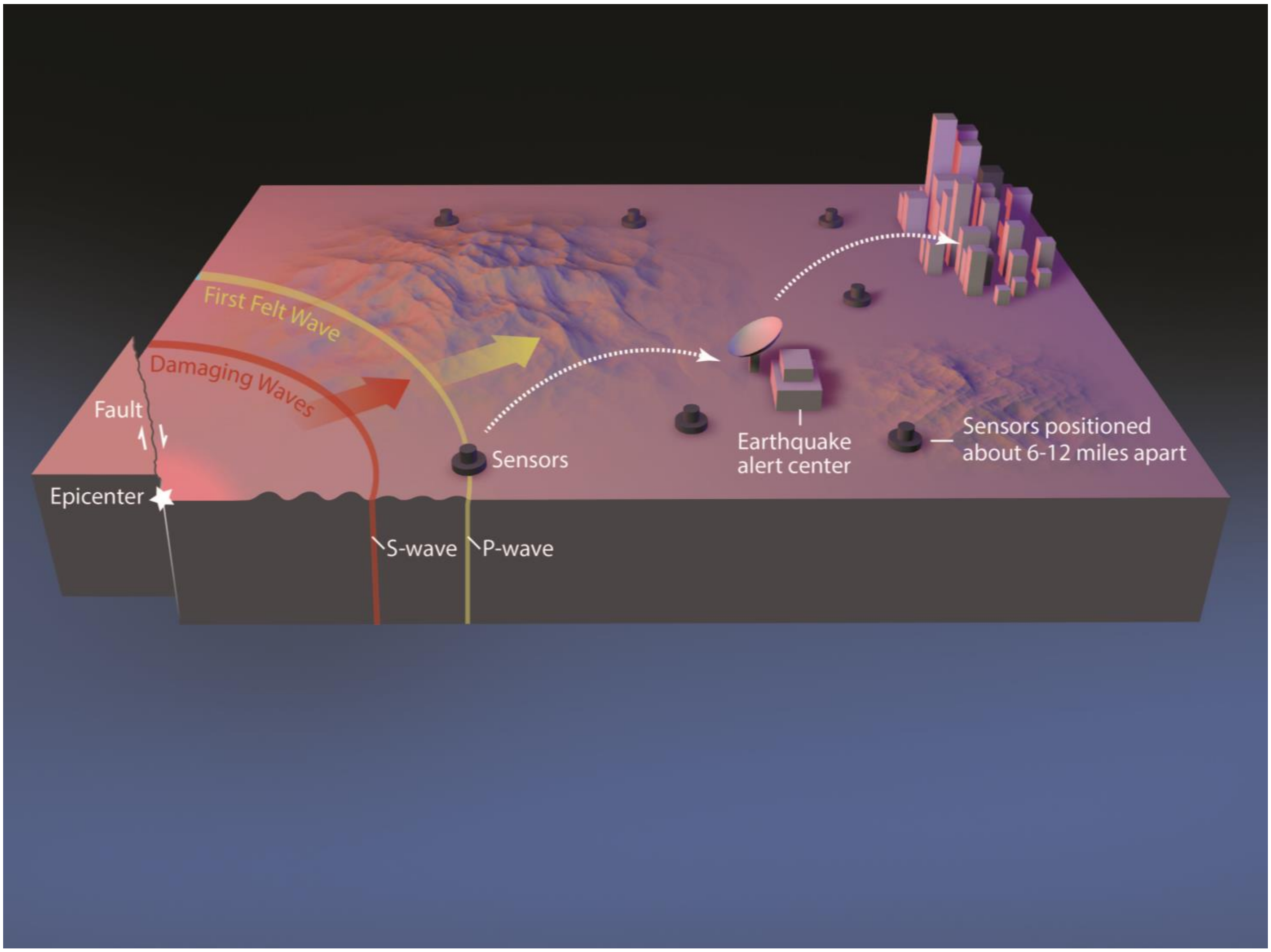
Feasibility Study of Earthquake Early Warning (EEW) in Hawaii



Open-File Report 2016–1172

U.S. Department of the Interior
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COVER: Earthquake early warning systems, like ShakeAlert, work because the warning message can be transmitted almost instantaneously, while shaking waves from the earthquake travel through the Earth at speeds of a few miles per second. When an earthquake occurs, seismic waves—including compressional (P) waves, transverse (S) waves, and surface waves—radiate outward from the epicenter. The faster but weaker P waves trip nearby sensors, causing alert signals to be sent out, giving people and automated electronic systems some time (seconds to minutes) to take protective actions before the arrival of the slower but stronger S waves and surface waves. Computers and mobile phones receiving the alert message can calculate the expected arrival time and intensity of shaking at your location. (From Burkett and others, 2014)

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By Weston A. Thelen, Alicia J. Hotovec-Ellis, and Paul Bodin

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Feasibility Study of Earthquake Early Warning (EEW) in Hawaii

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Executive Summary

The effects of earthquake shaking on the population and infrastructure across the State of Hawaii could be catastrophic, and the high seismic hazard in the region emphasizes the likelihood of such an event. Earthquake early warning (EEW) has the potential to give several seconds of warning before strong shaking starts, and thus reduce loss of life and damage to property. The two approaches to EEW are (1) a network approach (such as ShakeAlert or ElarmS) where the regional seismic network is used to detect the earthquake and distribute the alarm and (2) a local approach where a critical facility has a single seismometer (or small array) and a warning system on the premises.

The network approach, also referred to here as ShakeAlert or ElarmS, uses the closest stations within a regional seismic network to detect and characterize an earthquake. Most parameters used for a network approach require observations on multiple stations (typically 3 or 4), which slows down the alarm time slightly, but the alarms are generally more reliable than with single-station EEW approaches. The network approach also benefits from having stations closer to the source of any potentially damaging earthquake, so that alarms can be sent ahead to anyone who subscribes to receive the notification. Thus, a fully implemented ShakeAlert system can provide seconds of warning for both critical facilities and general populations ahead of damaging earthquake shaking. For example, using a fully implemented ShakeAlert system, a repeat of the shallow *M*7.9 1868 Kaʻū earthquake could send alarms with 12 to 14 seconds of warning for the communities of Hilo and Kailua-Kona, as well as for the Mauna Kea telescopes. The city of Honolulu would receive a full 70 seconds of warning before shaking began. If there were a repeat of the deeper *M*6.7 2006 Kīholo Bay earthquake, ShakeAlert could send alarms with 15, 3, and 6 seconds of warning for Hilo, Kailua-Kona, and the Mauna Kea telescopes, respectively, and Honolulu would receive an alarm 47 seconds ahead of shaking.

The cost to implement and maintain a fully operational ShakeAlert system is high compared to a local approach or single-station solution, but the benefits of a ShakeAlert system would be felt statewide—the warning times for strong shaking are potentially longer for most sources at most locations.

The local approach, referred to herein as "single station," uses measurements from a single seismometer to assess whether strong earthquake shaking can be expected. Because of the reliance on a single station, false alarms are more common than when using a regional network of seismometers. Given the current network, a single-station approach provides more warning for damaging earthquakes that occur close to the station, but it would have limited benefit compared to a fully implemented ShakeAlert system. For Honolulu, for example, the single-station approach provides an advantage over ShakeAlert only for earthquakes that occur in a narrow zone extending northeast and southwest of Oʻahu. Instrumentation and alarms associated with the single-station approach are typically maintained

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and assessed within the target facility, and thus no outside connectivity is required. A single-station approach, then, is unlikely to help broader populations beyond the individuals at the target facility, but they have the benefit of being commercially available for relatively little cost.

The USGS Hawaiian Volcano Observatory (HVO) is the Advanced National Seismic System (ANSS) regional seismic network responsible for locating and characterizing earthquakes across the State of Hawaii. During 2014 and 2015, HVO tested a network-based EEW algorithm within the current seismic network in order to assess the suitability for building a full EEW system. Using the current seismic instrumentation and processing setup at HVO, it is possible for a network approach to release an alarm a little more than 3 seconds after the earthquake is recorded on the fourth seismometer. Presently, earthquakes having $M \geq 3$ detected with the ElarmS algorithm have an average location error of approximately 4.5 km and an average magnitude error of -0.3 compared to the reviewed catalog locations from the HVO. Additional stations and upgrades to existing seismic stations would serve to improve solution precision and warning times and additional staffing would be required to provide support for a robust, network-based EEW system.

For a critical facility on the Island of Hawaiʻi, such as the telescopes atop Mauna Kea, one phased approach to mitigate losses could be to immediately install a single station system to establish some level of warning. Subsequently, supporting the implementation of a full network-based EEW system on the Island of Hawaiʻi would provide additional benefit in the form of improved warning times once the system is fully installed and operational, which may take several years.

Distributed populations across the Hawaiian Islands, including those outside the major cities and far from the likely earthquake source areas, would likely only benefit from a network approach such as ShakeAlert to provide warnings of strong shaking.

Introduction

Earthquakes are a well known phenomenon in the State of Hawaii, especially among residents of the Island of Hawaiʻi, who may feel tens of earthquakes each year. While some felt earthquakes occur directly in association with volcanic processes, most of the largest ($M \geq 6$) earthquakes occur within two source zones (figs. 1 and 2; Klein and others, 2001). Indirectly, many of the earthquakes are related to the presence and mass of the volcanic islands and magmatic activity at young volcanoes.

The first source zone for large earthquakes ($M \geq 6$) is at the nearly flat boundary between the erupted basalt of the volcanic islands and the old ocean floor upon which the islands are built (Crosson and Endo, 1982, Got and others, 1994). Called a “décollement,” this interface is about 6 mi (~10 km) beneath the coastline and was the source of the *M*7.0 and *M*7.9 earthquakes in Kaʻū in 1868 and the *M*7.2 and *M*6.2 earthquakes near Kalapana in 1975 and 1989, respectively (fig. 2; Swanson and others, 1976; Lipman and others, 1985; Wyss, 1988). Though a décollement is present under all of the Hawaiian Islands, damaging earthquakes are most likely to occur on the south and west sides of the Island of Hawaiʻi, where active rift zones are present (Klein and others, 2001).

The second main source of large earthquakes occurs deep beneath the island and ocean crust in the mantle below. Earthquakes in this zone generally occur 13 mi (21 km) or deeper and are thought to be a result of the stresses in the mantle arising from the weight of the volcanic islands above (for example, Wolfe and others, 2004). The most recent examples of this type of earthquake are the Kīholo Bay earthquake (*M*6.7) and Māhukona earthquake (*M*6.1), which both occurred in 2006 and caused significant damage on the Island of Hawaiʻi and disruptions on Oʻahu (fig. 2, Yamada and others, 2010). Large mantle earthquakes since 1868 are more widespread than décollement earthquakes and may have occurred as far north as Molokaʻi: it is believed that the *M*6.8 earthquake near Lānaʻi in 1871 and the *M*6.9 earthquake north of Maui in 1938 may have been mantle earthquakes (fig. 2; Wyss and Koyanagi, 1992; Klein and others, 2001).

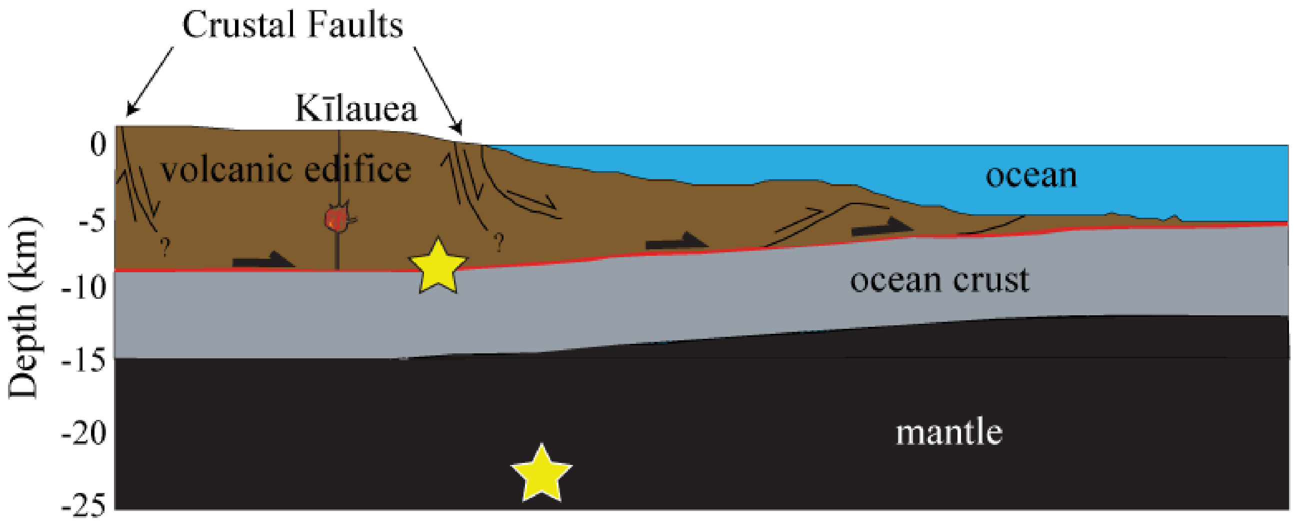


Figure 1. Schematic cross-section of the common sources of damaging earthquakes in the State of Hawaii. The décollement source (upper yellow star) occurs between the volcanic island (brown) and the underlying ocean crust (gray) along the ancient ocean floor (thin red line). Arrows indicate the direction of movement of the island over the ocean crust during décollement earthquakes. Décollement earthquakes are most common along the south and west coasts of the Island of Hawaiʻi. The mantle source (lower yellow star) occurs within the mantle (black). Mantle earthquakes can occur anywhere within the Hawaiian Islands, but are most common under the Island of Hawaiʻi. Other smaller earthquakes may occur on lesser crustal earthquakes (thin black lines) or along volcanic conduits (black vertical pipe and orange circular magma chamber).

Since 1868 there have been at least 51 earthquakes $M \geq 6$ across the State of Hawaii, with the overwhelming majority of the damaging earthquakes occurring near the Island of Hawaiʻi, where the volcanism is most active and the loads from overlying islands highest (Klein and others, 2001; Wyss and Koyanagi, 1992; fig. 2). The U.S. Geologic Survey (USGS) has calculated the seismic hazard for the whole State (fig. 3), and the results show that the areas of highest hazard are on the south part of the Island of Hawaiʻi, with decreasing hazard northwestward. On the south part of the Island of Hawaiʻi, the seismic hazard is similar to living on or in close proximity to the San Andreas Fault in California (Klein and others, 2001). Despite having a significantly lower hazard than the south part of the Island of Hawaiʻi, Oʻahu has a seismic hazard similar to many parts of the Intermountain West.

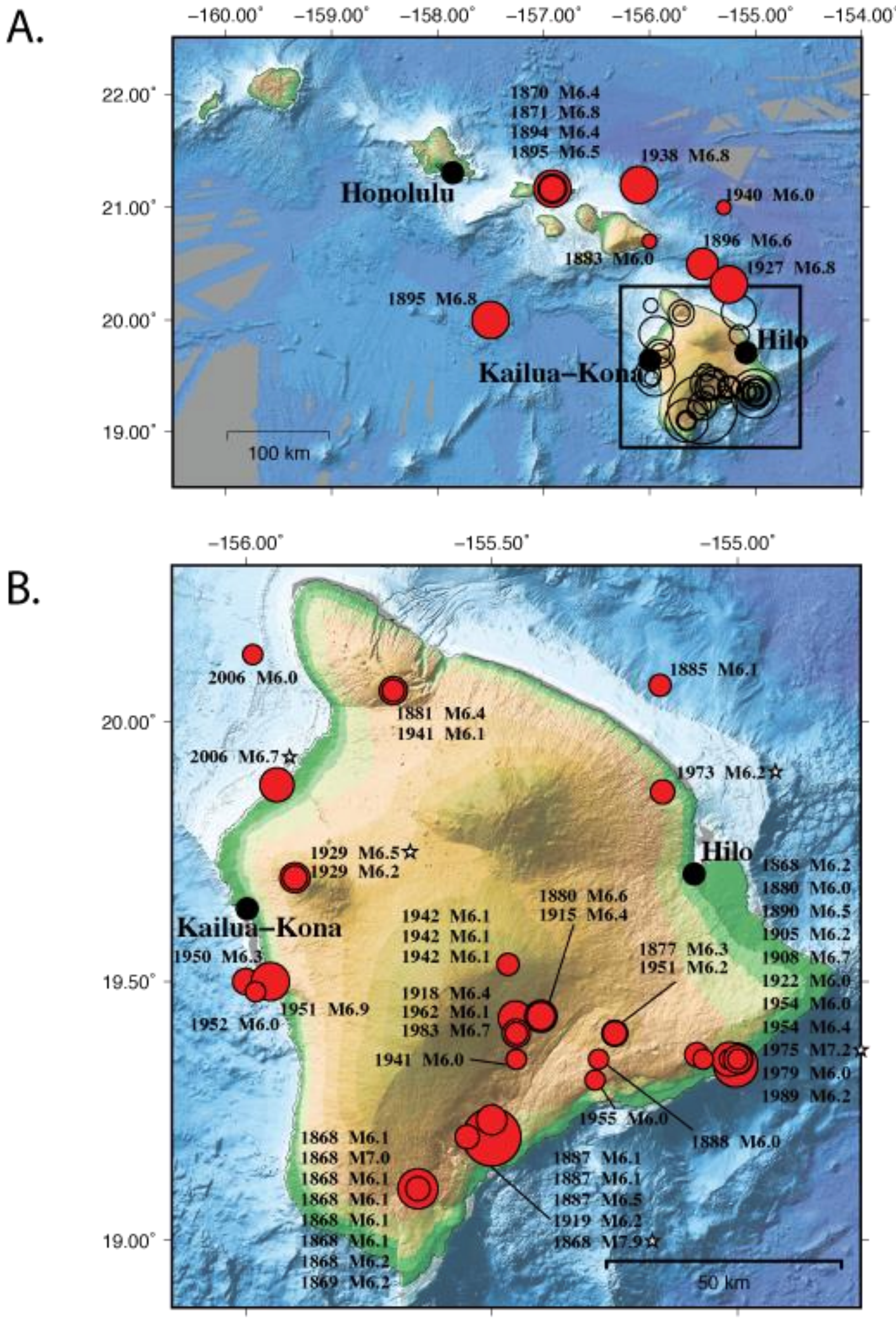


Figure 2. Map of $M \geq 6$ earthquakes in the State of Hawaii since 1868 (modified from Klein and others, 2001). *A*, Earthquakes, shown by red dots and open circles sized according to magnitude, annotated with the year of occurrence and magnitude. Black box shows extent of map in *B*. Large earthquakes are only denoted if they occur outside the box. *B*, Earthquakes on the Island of Hawai‘i, shown by red dots and sized according to magnitude, with year and magnitude denoted for each earthquake. Earthquake sizes in *A* and *B* are not scaled equivalently. Annotations with stars afterward refer to earthquakes in tables 2 and 3.

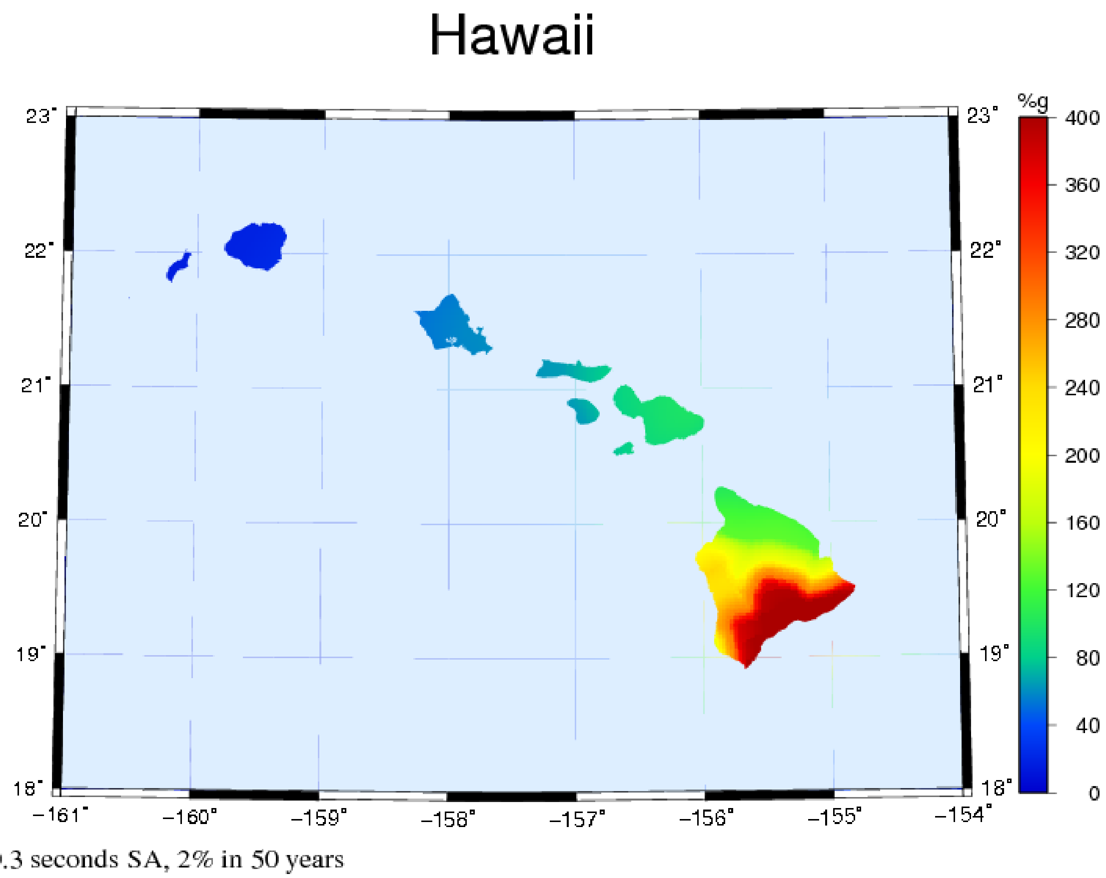


Figure 3. Seismic hazard map of the State of Hawaii. The percentage of the acceleration of gravity (percent g) is plotted that has a 2 percent chance of exceedance within 50 years at a seismic wave period of 0.3 s (3 Hz). Warm colors indicate a higher percent g, which can be used as a proxy for higher seismic hazard. Modified from Klein and others (2001).

The USGS Hawaiian Volcano Observatory (HVO) has been monitoring earthquakes since the inception of the observatory in 1912. A modern seismic network has been cataloging the occurrences of earthquakes since 1959. HVO has continuously incorporated new technologies and techniques to improve earthquake monitoring both for large and damaging earthquakes and for smaller earthquakes that assist in assessing volcanic hazard. The USGS Advanced National Seismic System (ANSS) recognizes HVO as the authoritative regional seismic network for the State of Hawaii and thus, HVO has the responsibility of calculating and reporting earthquake locations, magnitudes, and earthquake products to emergency managers and the public for preparedness and situational awareness. HVO also serves as the authoritative organization for assessing volcanic hazards in the State of Hawaii and issuing public notifications of volcanic activity.

Advances in instrumentation density, detection and calculation techniques, and data transmission technology now make it possible to detect a large earthquake and send notice prior to the onset of strong shaking. Called Earthquake Early Warning (EEW), the concept is to locate and characterize an earthquake using the instruments closest to the earthquake and to calculate the intensity of ground shaking, then send warning to affected groups and individuals at risk (fig. 4). EEW systems have already been established in the countries of Japan and Mexico. An EEW system on the West Coast of the United States is being developed, called ShakeAlert (Given and others, 2014); in this study, we assess the feasibility of portions of the ShakeAlert system for the State of Hawaii.

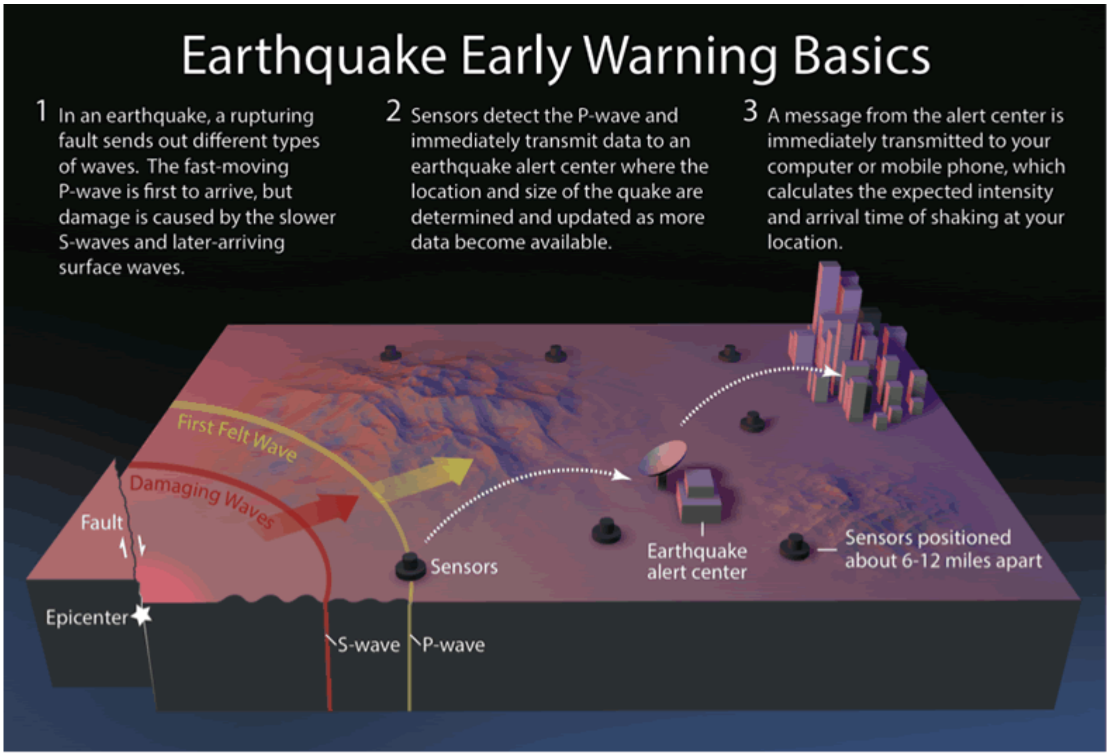


Figure 4. Schematic diagram of an earthquake early warning system. From Given and others (2014).

Despite having a very high seismic hazard (high likelihood of strong shaking), the seismic risk (exposure of population and infrastructure to the hazard) in the State of Hawaii is low compared to the West Coast of the United States, which has large population and complex infrastructure across a wide geographic area. However, there are critical structures and populations that would significantly benefit from the development of an EEW system in the State of Hawaii. The largest towns on the Island of Hawaiʻi include Hilo (population 43,263; United States Census Bureau, 2010) and Kailua-Kona (population 11,975; United States Census Bureau, 2010). Despite modest permanent populations, daily average visitors to Hilo and Kailua-Kona are 6,025 and 23,983, respectively (Hawaiʻi Tourism Authority, 2016). In addition, the State capital, Honolulu, has 337,256 people as of 2010 and nearly 1 million people reside on the Island of Oʻahu (United States Census Bureau, 2010). An additional daily average of 96,013 visitors on Oʻahu adds to that total (Hawaiʻi Tourism Authority, 2014). In terms of infrastructure, the telescopes on Mauna Kea and Haleakalā could benefit significantly by taking advantage of warning times of strong shaking from an EEW system to mitigate damage—some of them were damaged during the *M*6.7 Kīholo Bay earthquake in 2006. If given a short-term warning of strong shaking, elevators could be stopped, firehouse doors could be raised and delicate medical procedures stopped. Individuals with advance warning could drop, cover and hold on prior to the shaking or pull their cars over to the side of the road.

Earthquakes generate a variety of types of waves, however, for our purposes, we are only concerned with the fastest waves near the surface (primary waves or p-waves) and the slower waves that produce the strongest shaking (secondary waves or s-waves and surface waves). In EEW systems, the p-wave is typically analyzed to calculate both the location and magnitude of the earthquake; from those results, the intensity of shaking is estimated for the entire region. By using the first part of the p-wave recording on just a few of the stations closest to the earthquake, an EEW system can send a warning of ground shaking ahead of when the s-wave (and strong shaking) actually arrives at particular location. The amount of warning depends on several factors, but generally the farther away from the earthquake, the more warning an individual or structure would have. At the epicenter, or location, of the earthquake there may be a "blind zone" where no warning can be given because not enough observations have been gathered or the processing time is too great to send a warning before the shaking starts. The size of the blind zone can change depending on the depth of the earthquake, the density of stations around the earthquake, and the processing time needed to produce and transmit the alarm. The area of the blind zone can be reduced with denser station coverage and with faster transmit and processing times, but may never be zero—extremely shallow earthquakes that occur close to a population or facility of concern will experience shaking from shear waves before the alarm reaches them.

There are several approaches to EEW, which can be distilled into two categories: a single-station approach and a network approach. The single-station approach uses a single seismometer or small array of sensors at the same location, and thus can produce a very fast warning for earthquakes that occur close to the sensor; however, the quality of that warning may be lower as it is susceptible to noise on any given station (Böse and others, 2009). Typically, the single-station approach is favored for critical facilities because of its relatively low cost; alarms generated within a single-station system are generally used only to mitigate damage to that facility or immediate area.

The network approach uses a distributed array of seismometers, typically a regional seismic network, to detect and characterize a large earthquake. One network approach, called ElarmS, can trigger an alarm within less than 1 second of detecting a p-wave at a station and then continues to evaluate the first 4 seconds of the earthquake (Kuyuk and others, 2014). ElarmS is one of three algorithms embedded within the ShakeAlert software that is being implemented in the EEW-system on the West Coast of the United States. To reduce false alarms, triggers at four stations are required to determine the location and magnitude and to issue an alert (Kuyuk and others, 2014). As more observations of the earthquake are available, those observations are used to refine the solution and thus improve the estimate of shaking. Because algorithms using a network approach, like ElarmS, require multiple observations, the alarms produced may be slower than a single station algorithm for earthquakes very close to a critical facility or impacted population, but still faster than a single station algorithm for earthquakes farther away. Alarms are also more reliable as the algorithms using a network approach depend on several stations instead of one (Allen and others, 2009). In areas of high station density (10 km spacing) in California, ElarmS and ShakeAlert have issued warnings 4 seconds after an earthquake begins (Burkett and others, 2014). The network approach to EEW is more costly to implement, but has more potential benefit, as any public or private entity can sign up for shaking alerts and either design measures to reduce damage to infrastructure or educate themselves on what to do in the case of a shaking alarm (for example, Drop, Cover and Hold On!).

This paper details the feasibility of an EEW system in the State of Hawaii. First we discuss the current seismic network and the performance of the ElarmS algorithm of the ShakeAlert system within the current network. We explore the potential benefits and pitfalls of a single-station versus a network approach (such as ShakeAlert). Finally, we discuss what would be needed for a full implementation of the ShakeAlert system in Hawaii.

Current State of the Seismic Network

The current inventory of seismometers in the State of Hawaii is split between several operators, each with different priorities and goals for their instruments (fig. 5). Most EEW systems only use continuous broadband seismometers (sensitivity < 10 s period) and continuous strong motion accelerographs, and thus, only a subset of HVO's stations can be used (many stations are short-period seismometers). It is common practice, when resources exist, to install both a continuous broadband seismometer and a continuous strong motion accelerograph at the same site so as to be able to measure a range of amplitudes and frequencies (for example, low-amplitude long period waves, and s-waves from strong local earthquakes) with high fidelity. As of 2016, HVO operates 24 continuous broadband stations and 19 continuous strong motion accelerographs, nearly all on the Island of Hawaiʻi and densest around the summit and rift zones of Kīlauea and Mauna Loa (fig. 5). The placement of seismometers reflects the desire of the HVO to track small earthquakes associated with volcanic processes, though there are stations distributed across the Island of Hawaiʻi to track non-volcanic seismicity. The NOAA Pacific Tsunami Warning Center (PTWC) operates 19 real-time continuous stations that are distributed across the Hawaiian Islands in order to better characterize the tsunami hazard that arises from large Hawaiian earthquakes and to notify officials. All PTWC stations have strong-motion accelerographs, though only a subset have co-located broadband seismometers. The Global Seismograph Network (GSN) operates a real-time continuous station on the Island of Hawaiʻi and a real-time continuous station on the Island of Oʻahu, both of which bolster the ability of the GSN to track global seismicity. As of 2016, the only continuous data channels are from broadband seismometers, though triggered strong-motion accelerometers do exist at each site. Lastly, the National Strong Motion Program (NSMP) operates approximately 30 strong-motion accelerographs capable of recording very large ground motions. The stations are well distributed, however they are typically in buildings or structures that make the records noisy unless the ground motion is very large. Furthermore, the NSMP stations only produce data tens of seconds to a few minutes after a strong earthquake occurs and cannot, as of 2016, contribute to an EEW system. The number of unique sites available for EEW as of 2016, which either have a continuous broadband seismometer, a continuous strong motion accelerograph, or both is 56 across the State of Hawaii.

For the purposes of earthquake early warning, the closer an earthquake occurs to a single station (assuming a single station algorithm) or a set of stations (assuming a network approach like ElarmS/ShakeAlert), the faster an estimate of shaking can be produced and an alert sent to an end user. Therefore, earthquakes that occur in areas of higher station density will generally produce a faster alarm and have a relatively small or no blind zone. Considering the entirety of stations available for an EEW system in the State of Hawaii, the station density is highest around Kīlauea summit and East Rift Zone and the summit of Mauna Loa (fig. 6). Away from these areas, station density falls dramatically, especially to the north and northwest. Thus, given the current station configuration, earthquakes that occur on the south part of the Island of Hawaiʻi will generally have faster alert times than earthquakes that occur on other parts of the Island of Hawaiʻi. Within the 250 miles between Maui and Kauaʻi, there are only 10 continuous stations; 5 of those are on Oʻahu and there are none on Lānaʻi. Practically, this means that people within the vicinity of a large earthquake near Maui, Lānaʻi, or Molokaʻi are unlikely to benefit from an EEW system without additional instrumentation, although they could benefit from alerts for large events on the Island of Hawaiʻi.

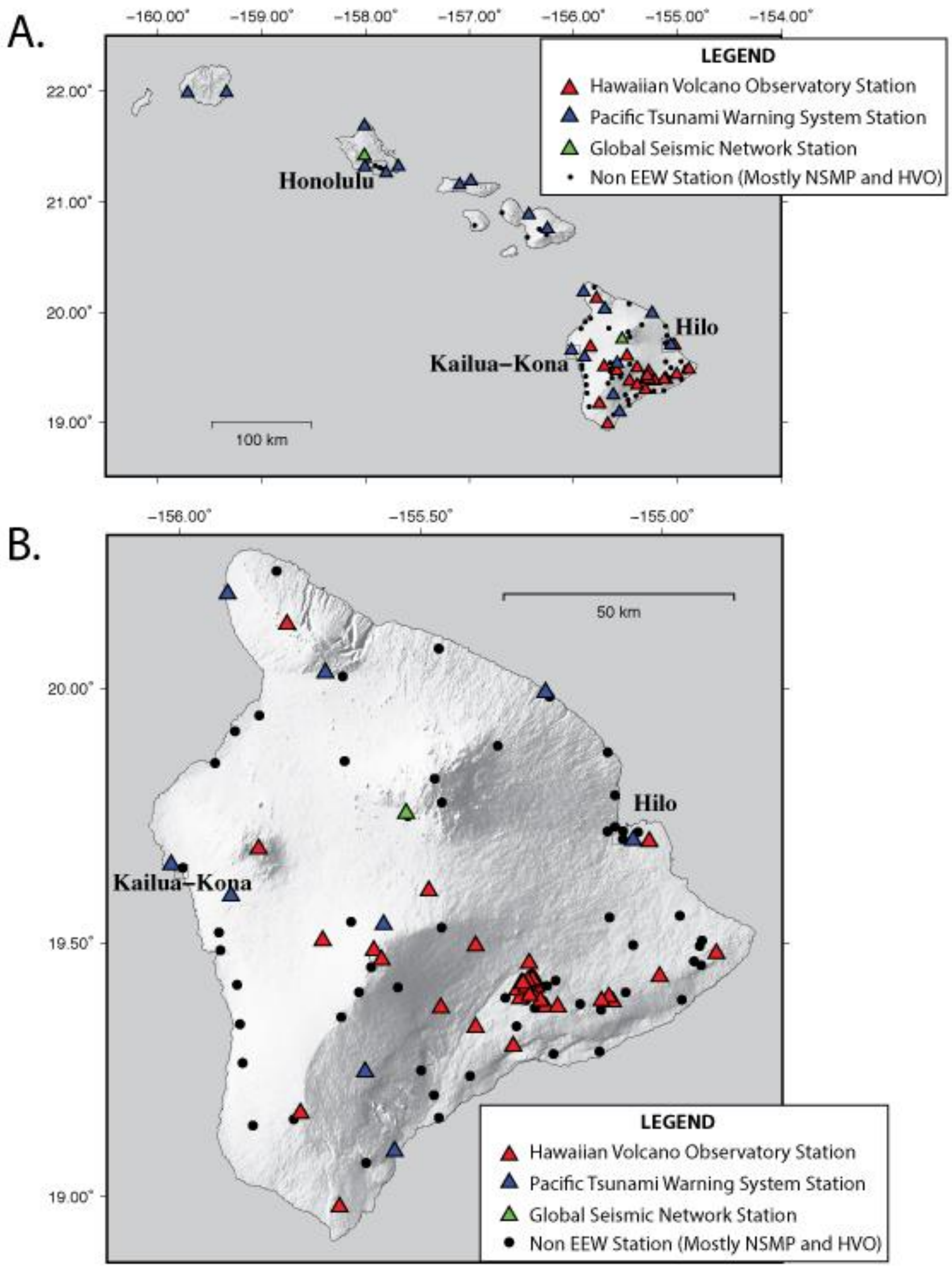


Figure 5. Current seismic station map within the State of Hawaii. Triangles are stations that could contribute to an earthquake early warning (EEW) system; colors indicate which agency operates the station. Black dots are existing stations that are not useful for earthquake early warning, either because of the instrumentation or type of recording. These stations could be upgraded to make them useful for earthquake early warning. *A*, Map of stations throughout the Hawaiian Islands. *B*, Stations on the Island of Hawaiʻi.

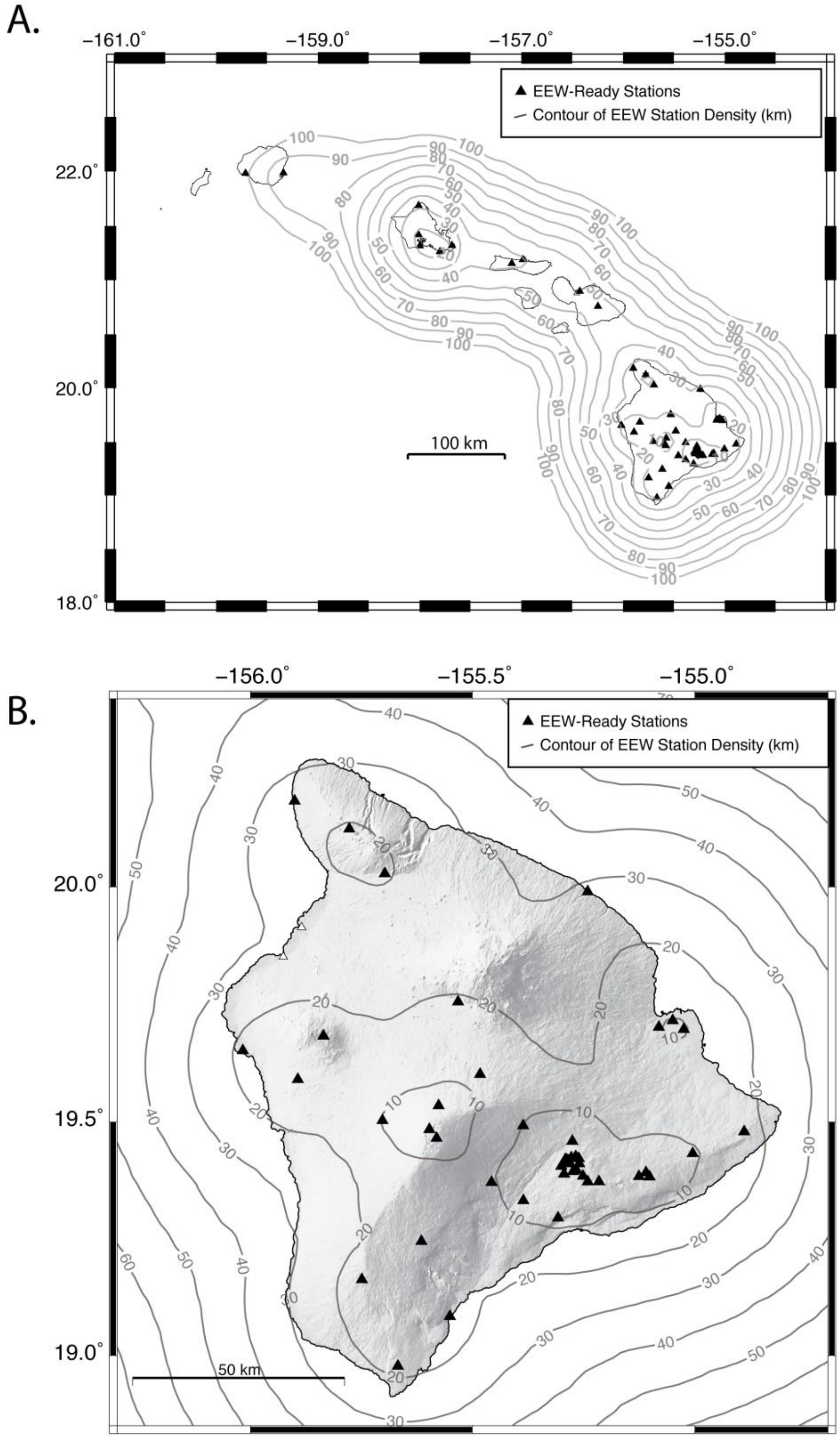


Figure 6. Station density plot (distance to nearest four stations) within the State of Hawaii. Black triangles are stations that could be used in an earthquake early warning (EEW) system. Contour lines represent the distance, in kilometers, to the nearest four stations. *A*, Station density across the State of Hawaii. *B*, Station density across the Island of Hawai‘i.

The reliability of an EEW system is dependent on the robustness of the facilities that receive the data and the links from those facilities to the remote instruments in the ground (telemetry). Currently, all seismic data for use in EEW is received at HVO. Located within Hawaiʻi Volcanoes National Park on the rim of Kīlauea Volcano, the HVO can be vulnerable to connection problems to the Internet because of weak communications infrastructure on the Island of Hawaiʻi. Without a reliable connection to the Internet, it is unlikely that EEW notifications could be released. To address this problem, HVO has recently completed a microwave link directly from HVO to the Daniel K. Inouye Regional Center on Ford Island, which lies within Pearl Harbor on the Island of Oʻahu. The link uses the ʻĀnuenue network, which is operated by the United States Coast Guard and relied upon for robust communications through a variety of natural disasters. HVO is in the process of building an offsite backup facility for the seismic network at Ford Island in a space that is shared by PTWC servers. Once completed, the presence of an offsite backup will allow seismic operations to be much more resilient in the wake of telecommunications failures and natural disasters on the Island of Hawaiʻi that affect the local operation of HVO. As part of any EEW buildout in Hawaii, a backup server would be co-located with the offsite facility on Ford Island and would benefit from the redundancy that comes with a full offsite backup facility. Current telemetry for stations used in EEW is naturally diverse because of the different agencies that operate the stations and their various approaches to data transmission. HVO's EEW-ready stations currently all use an internal telemetry network, which has demonstrated reliability during hurricanes and tropical storms. However, this internal telemetry network is maintained by HVO, which is not currently staffed during nights and weekends. PTWC stations transmit most of their data over cell modems, which can be susceptible to Internet outages, but their network has also successfully withstood hurricanes and tropical storms. Further, the PTWC facility on Ford Island is staffed 24 hours a day and has robust power and communications infrastructure.

The effectiveness of an EEW system relies on very rapid messaging, which, in turn, depends both on the time it takes to receive the data from the remote station and the time to process that data. Different agencies collect and transmit their data differently, and so some considerations arise for a network approach that uses data from HVO, PTWC, and GSN, as EEW in Hawaii would. The difference in time between when the earthquake occurs and when the data arrives at the datacenter is called station latency. Lower latencies allow for faster EEW notifications for end users. The station latency can be further divided into the time it takes for the digitizer at the station to collect and assemble the data from the seismometer (the length of the time packet), and the time it takes to transmit the data. In 2009, HVO upgraded all of their stations to use the Reftek RT130 digitizer, which waits for a buffer to fill up to a certain size before sending it to the datacenter. This results in a packet size of about 5 seconds for broadband stations and 9 seconds for strong motion accelerographs (fig. 7). The latency associated with the telemetry is between 1.8 and 3.8 seconds, depending on the strength of the link (fig. 7). All HVO stations that would be used in an EEW system traverse the observatory's own telemetry network. Stations operated by PTWC use a different kind of digitizer, which sends packets every second, reducing the latency but increasing the bandwidth requirements of the telemetry. Telemetry of stations operated by PTWC is largely over cell modem and has to be exported to HVO for EEW processing, producing latencies of 2.2 to 4 seconds (fig. 7). Some of the latency in HVO data is due to the large packet sizes, which must be fully transmitted before proceeding. There are two instances of PTWC stations with 1-second packet length transmitting data over HVO's telemetry network. In both cases, the 1-second packets have telemetry latencies around 0.95 seconds. The situation of digitizers producing 1-second packets and with telemetry latencies of 0.95 seconds represents the minimum latency that we may expect from all stations if the current seismic network was optimized for an EEW system. The two stations contributed by the GSN have packet lengths of 10 to 12 seconds and telemetry latencies of around 5 seconds, mostly because of the large packet sizes.

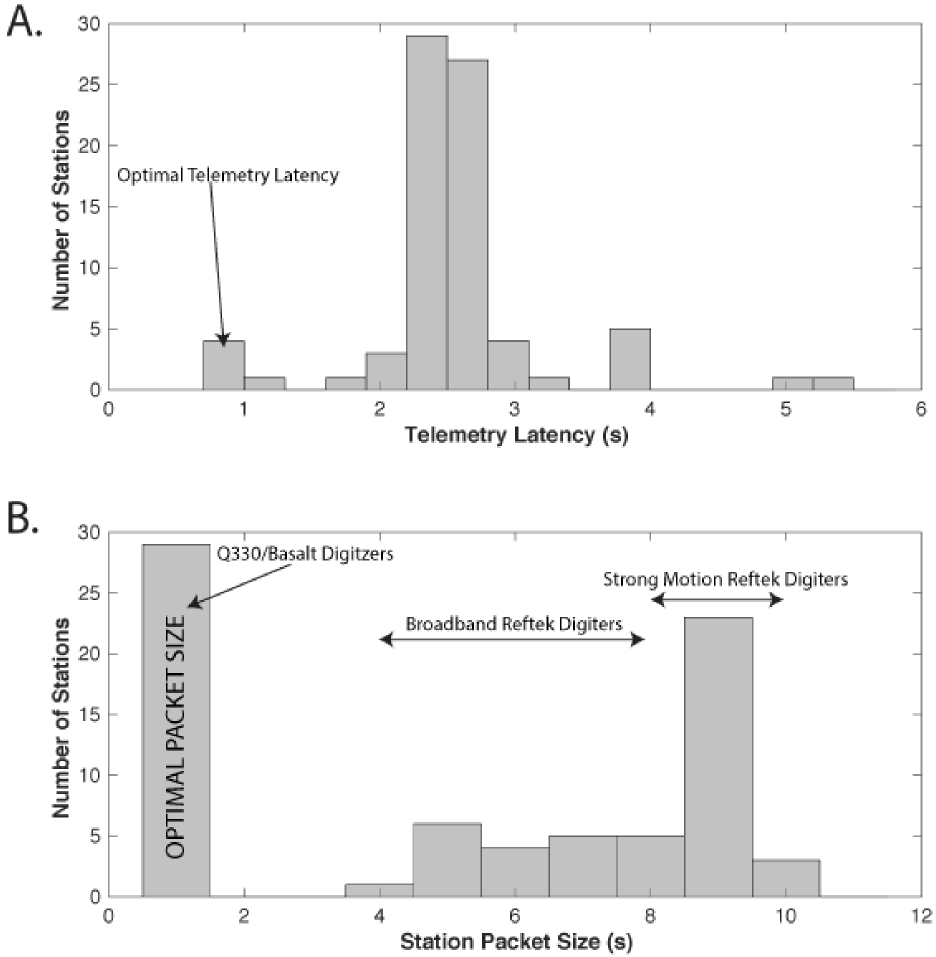


Figure 7. Histograms of latency and packet size of existing stations as measured on the earthquake early warning processing server. *A*, Histogram of telemetry latency in seconds. Most stations have telemetry latency between 2 and 3 seconds. Under optimal circumstances, telemetry latency could be reduced to less than 1 second. *B*, Histogram of packet size. Some digitizers have packets with a length of 1 second (Kinemetrics Q330 and Basalt digitizers); however, most stations have packet sizes that are larger (RefTek RT130 digitizers). Packet sizes of 1 second are the shortest packet that we can expect for an optimally configured EEW system.

Theoretical Performance of ElarmS and a Single Station Within the Current Network

Given the current inventory of seismometers on the Island of Hawaiʻi and current infrastructure latencies, we can estimate the theoretical warning times of the ElarmS algorithm and compare it to having a single-station algorithm implemented at a critical facility. As a reminder, ElarmS requires a minimum of four stations to detect an earthquake, while the single-station algorithm only requires one station at the critical site (an array may also be deployed at the site). We consider two source depths, a shallow source (approximately 6 mi [10 km] below surface) to simulate the décollement responsible for the 1868 *M*7.9 and 1975 *M*7.7 earthquakes and a deep source (approximately 25 mi [40 km] below surface) to simulate mantle earthquakes similar to the 2006 *M*6.7 Kīholo Bay earthquake. The calculation of the single-station warning time assumes that there is one station located at the critical facility that triggers an alarm without need of telemetry and with no contribution from the existing network. All theoretical ElarmS warning times assume the current inventory of installed stations and that those stations are fully operational with data delayed by current telemetry latency and half of the current packet length. We assume a processing time of 0.5 seconds for both methods and that the single-station algorithm requires a minimum of three seconds of seismic data to issue an alert. Here, we define the warning time as the difference between the arrival of the s-wave and the time of detection. For the two source depths we will consider theoretical warning times to Hilo, Kailua-Kona, Honolulu, and the observatories at the summit of Mauna Kea.

Hilo is the county seat of Hawaiʻi County and the Island of Hawaiʻi's most densely populated area. Hilo possesses a critical seaport, an airport, a hospital, a Civil Defense facility, and telecommunications and power infrastructure for the entire island. ElarmS theoretical warning times to Hilo from shallow sources range from zero seconds on Kīlauea's lower East Rift Zone at Cape Kumukahi, to 15 seconds for shallow sources located near South Point (fig. 8). Damaging shallow earthquakes are most likely to occur under the south flanks of Kīlauea and Mauna Loa and the west flanks of Mauna Loa and Hualālai so other areas are not discussed, though they are included in the maps. The blind zone for a shallow earthquake source with the current network configuration and latencies is geographically large. A critical facility in Hilo with a single-station algorithm implemented on one station located at the facility would potentially receive as much as 2 seconds of additional warning time for a shallow earthquake offshore to the north or east, but a single station system has similar warning times as a network system for shallow sources elsewhere on the Island of Hawaiʻi. ElarmS theoretical warning times to Hilo for deep earthquakes range from 10–14 seconds for earthquakes on the west side of the Island of Hawaiʻi to less than 2 seconds for deep earthquakes near Laupāhoehoe and Glenwood. The blind zone for deep earthquake sources is a large area extending radially up to 30 km from downtown Hilo. For deep earthquakes sources on the east side of the Island of Hawaiʻi, a single station implementation at a critical facility would see less than 2 additional seconds of warning, with more warning for deep earthquakes occurring offshore of Hilo to the northeast.

Kailua-Kona is the second-most-populous area on the Island of Hawaiʻi and a hub for tourism. Critical facilities include an international airport and many large hotels. ElarmS warning times in Kailua-Kona are relatively large for shallow earthquakes on the south flanks of Mauna Loa and Kīlauea and deep earthquake sources on the east side of the Island of Hawaiʻi (fig. 8). There could also be up to 3 seconds of additional warning for earthquake sources of all depths at critical facilities in Kailua-Kona that implement a single-station approach. For shallow sources on the south flank of Mauna Loa and Kīlauea, ElarmS warning times range from 11 seconds near South Point to 20 seconds at the east end of Kīlauea's East Rift Zone. For deep earthquake sources on the east side of the Island of Hawaiʻi, ElarmS warning times for Kailua-Kona are between 6 and 20 seconds. There is a large blind zone that encompasses nearly all of Hualālai Volcano and Kailua-Kona, including the epicenter of the 1929 *M*6.1 earthquake and the 2006 *M*6.7 Kīholo Bay earthquake. Critical facilities using a single-station approach in Kailua-Kona may gain less than 2–3 seconds of additional warning time for deep earthquake sources that occur to the west of the summit of Hualālai. There is no significant difference in warning times between a single station approach and a network approach for deep earthquake sources on the east part of the Island of Hawaiʻi.

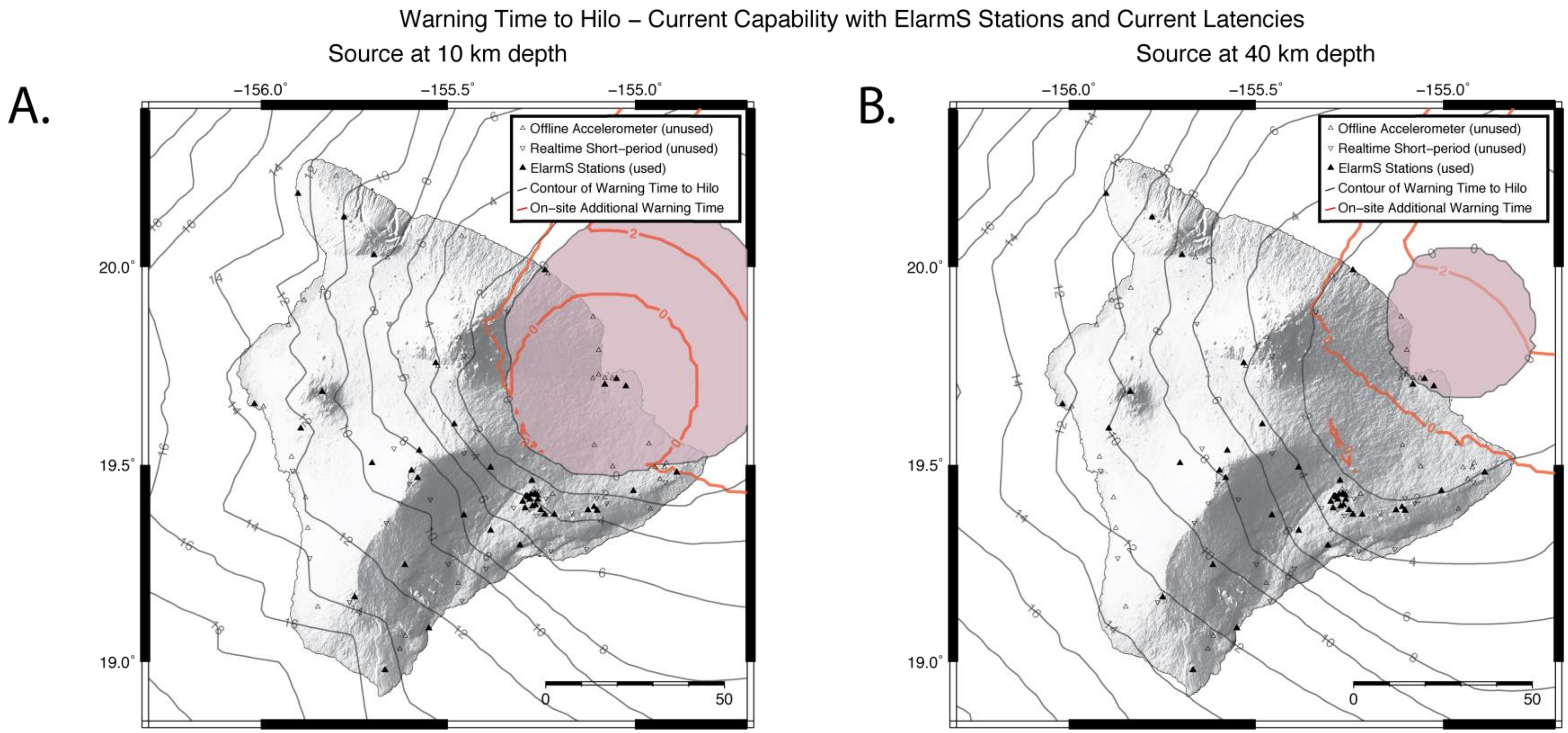


Figure 8. Warning time to Hilo, Kailua-Kona and the summit of Mauna Kea from different source areas considering the existing earthquake early warning stations and latency. Black triangles are existing earthquake early warning stations. Clear triangles represent non-realtime accelerometers or short period instruments, neither of which can be used for earthquake early warning. Black contours are warning times in seconds using an ElarmS algorithm that requires four stations for earthquake detection. Red contours are the additional warning time of a single-station system assuming a single station placed at a critical facility at the target area. Shaded pink area is the ElarmS blind zone. *A*, Warning times to Hilo from sources at a depth of 6 mi (10 km) to simulate a décollement source. *B*, Warning times to Hilo from sources at a depth of 25 mi (40 km) to simulate a mantle source. *C*, Warning times to Kailua-Kona from sources at a depth of 6 mi (10 km) to simulate a décollement source. *D*, Warning times to Kailua-Kona from sources at a depth of 25 mi (40 km) to simulate a mantle source. *E*, Warning times to the summit of Mauna Kea from sources at a depth of 6 mi (10 km) to simulate a décollement source. *F*, Warning times to the summit of Mauna Kea (MKO) from sources at a depth of 25 mi (40 km) to simulate a mantle source.

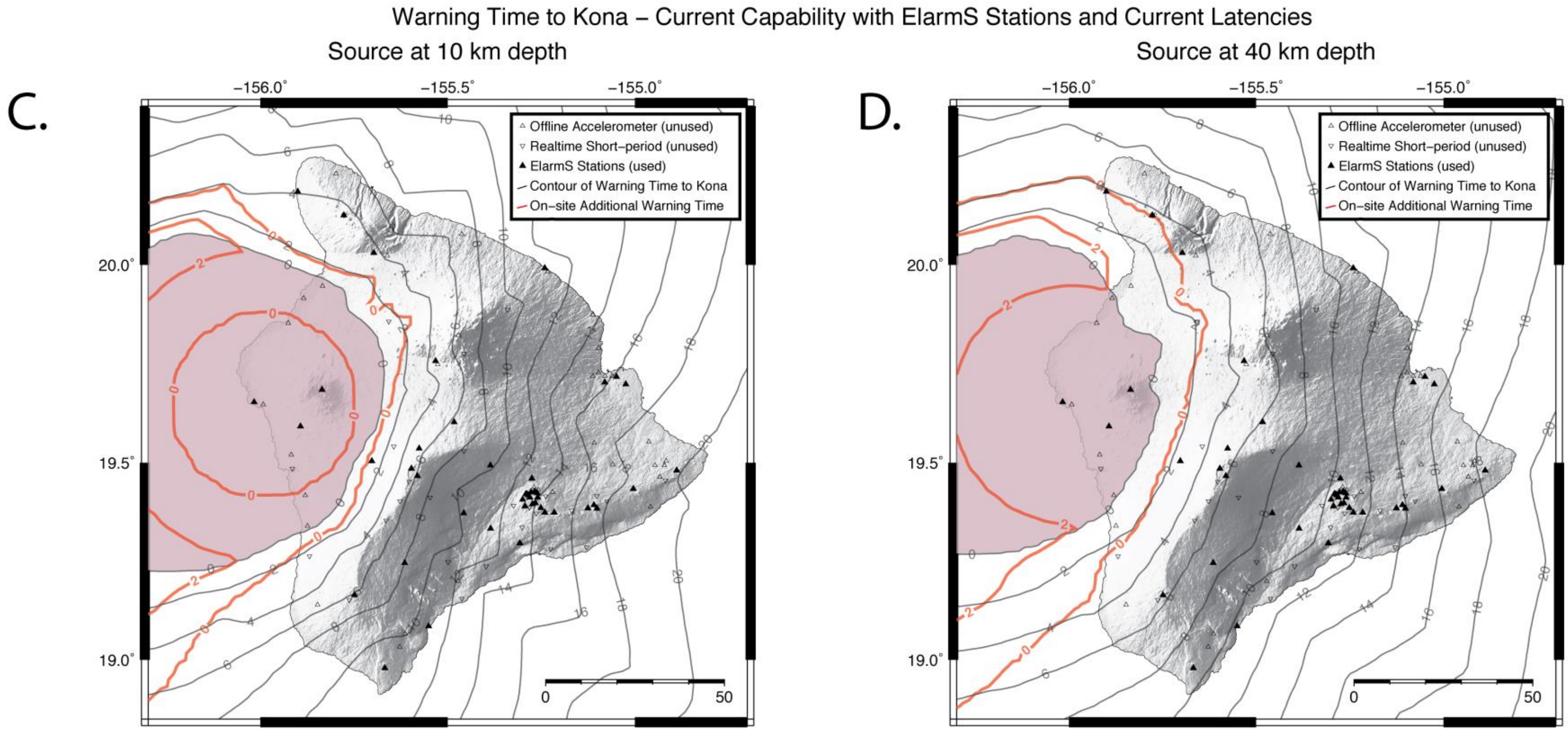
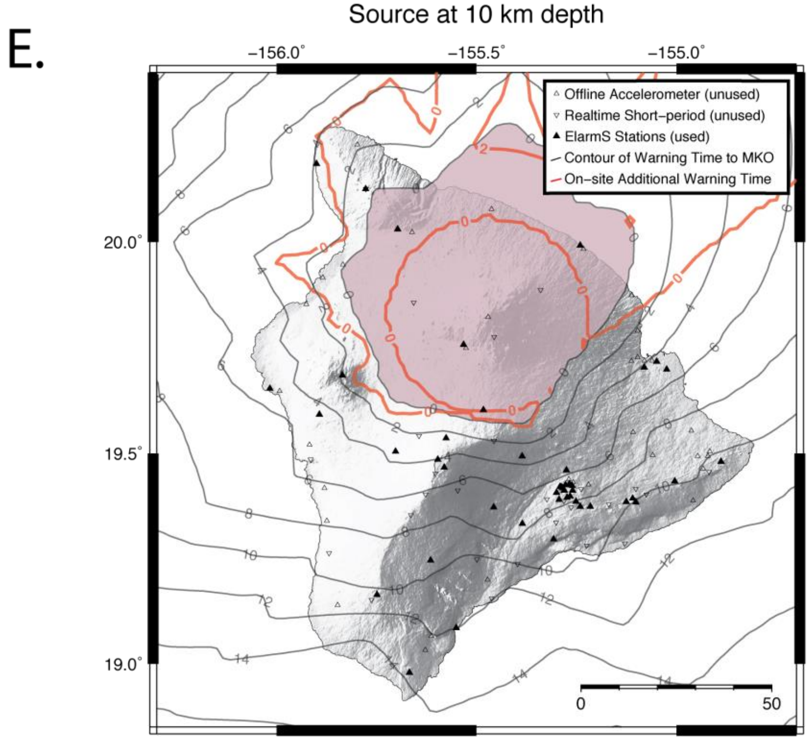


Figure 8. —Continued

Warning Time to MKO – Current Capability with ElarmS Stations and Current Latencies



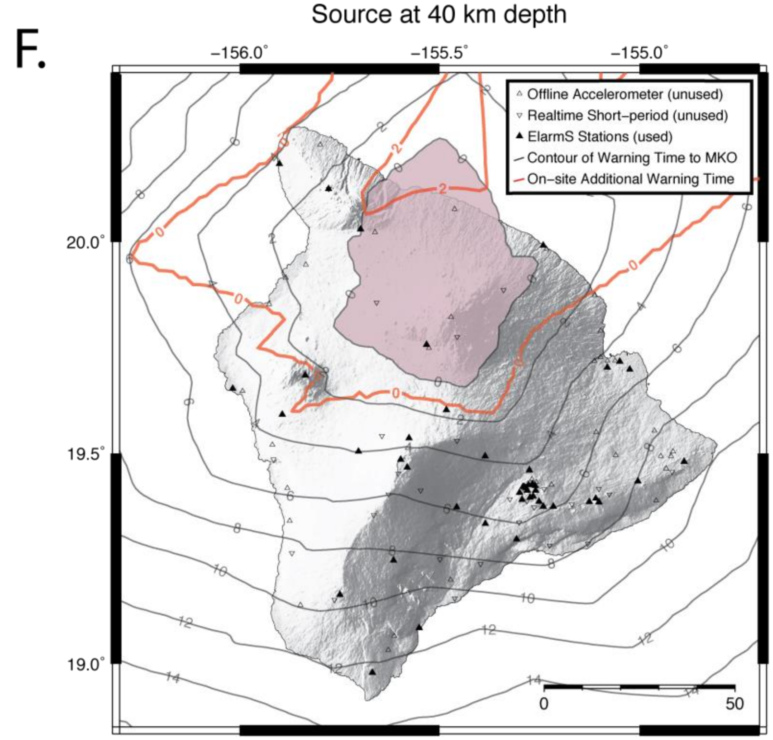


Figure 8. —Continued

The observatories at the top of Mauna Kea have instrumentation that is highly susceptible to shaking, as shown by damage caused during the 2006 Kīholo Bay earthquake (McAvoy, 2006). The current station coverage around Mauna Kea is relatively sparse, which leads to relatively short warning times and a large blind zone. For shallow earthquake sources on the south flanks of Kīlauea and Mauna Loa, ElarmS warning times to Mauna Kea range from 4 seconds near the summit of Mauna Loa to 14 seconds at South Point (fig. 8). For shallow earthquake sources to the west of Hualālai, warning times to the observatories range from 2 to 6 seconds. The blind zone for shallow sources is large; however, it encompasses an area unlikely to have damaging shallow earthquakes (Klein and others, 2001). A critical facility with a single-station algorithm implemented upon Mauna Kea stands to gain less than 2 seconds for shallow sources within the ElarmS blind zone, so there is no benefit for shallow sources under Kīlauea or Mauna Loa. For deep earthquake sources on the north part of the Island of Hawai‘i, ElarmS has the potential for warning times of up to 4 seconds for a facility at the top of Mauna Kea. The blind zone for deep earthquake sources is a geographic area extending radially from Mauna Kea for 30 to 50 km. There have been 11 deep earthquakes between *M*4 and *M*5 that have occurred within the blind zone since 1960 and 3 $M \geq 6$ earthquakes since 1881 (fig. 2; fig. 8). A critical facility on Mauna Kea using a single-station system will receive up to 2 seconds of additional warning time for earthquakes that occur within the ElarmS blind zone. A single-station algorithm could also give between 0 and 2 seconds of additional warning for most deep earthquake sources on the west part of the Island of Hawai‘i. For most of the earthquakes occurring on the south flanks of Kīlauea and Mauna Loa, a single-station algorithm would provide no more warning than ElarmS for deep earthquake sources when considering critical facilities atop Mauna Kea.

Honolulu is the final locale that we consider because of its critical infrastructure and large population. The seismic hazard on O‘ahu due to large earthquakes on the Island of Hawai‘i is severe enough to consider potential warning times to Honolulu, especially considering the disruption caused in Honolulu by the 2006 *M*6.7 Kīholo Bay earthquake, which included widespread power outages (Reyes, 2006). Theoretical ElarmS warning times for Honolulu are similar between shallow and deep earthquake sources and range from 40 seconds for earthquakes on the north part of the Island of Hawai‘i and 75 seconds for damaging earthquakes occurring on the most distal parts of Kīlauea’s East Rift Zone (fig. 9). For critical facilities in Honolulu, a single-station algorithm may provide up to 2 seconds of additional warning for earthquakes occurring within the ElarmS blind zone, but there is no benefit to using a single-station algorithm to warn against shaking from earthquakes on the Island of Hawai‘i (fig. 9).

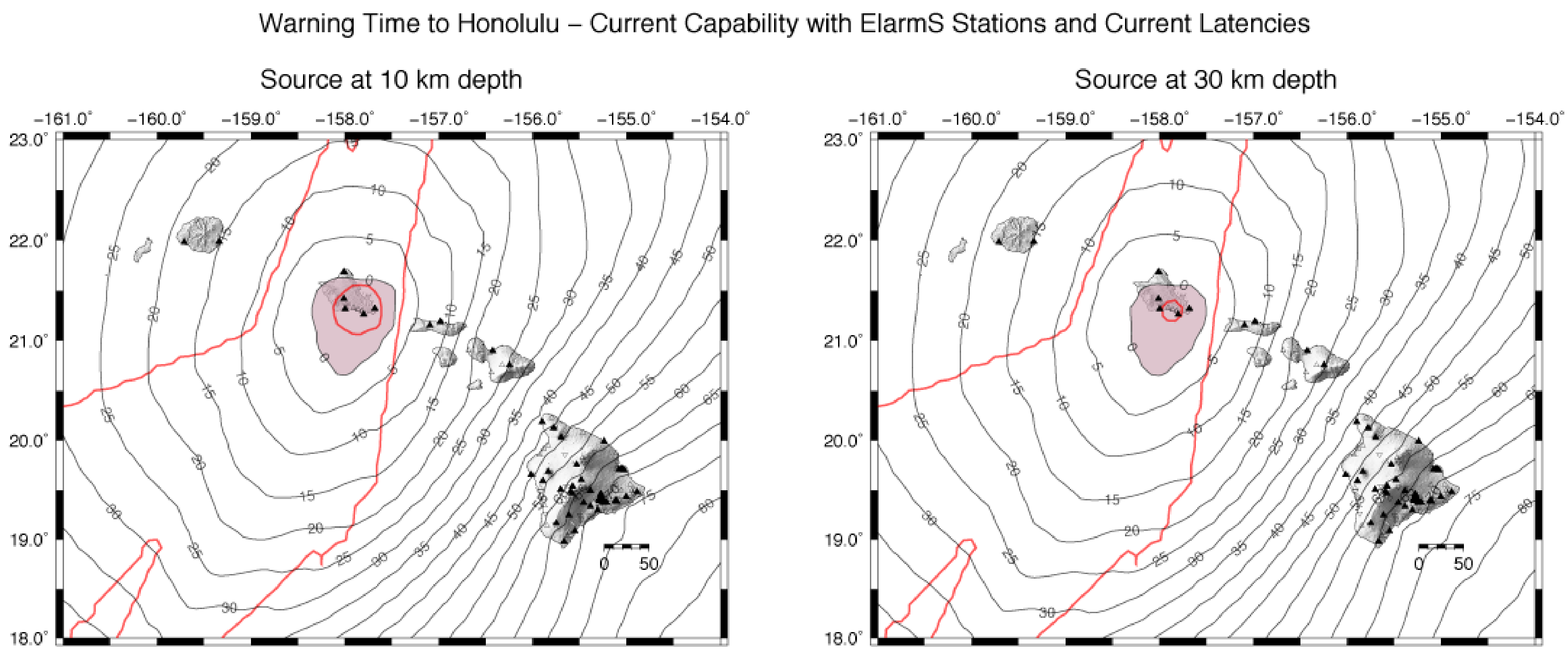


Figure 9. Warning times to Honolulu from different source areas considering the existing earthquake early warning stations and data latency. Black triangles are existing earthquake early warning stations. Clear triangles represent non-real-time accelerometers or short-period instruments, neither of which can be used for earthquake early warning. Black contours show warning times, in seconds, using an ElarmS algorithm that requires four stations for an earthquake detection. Red contours are the additional warning times of a single-station system assuming one station installed at a critical facility in Honolulu. Shaded pink area is the ElarmS blind zone. *A*, Warning times to Honolulu from sources at a depth of 6 mi (10 km) to simulate a décollement source. *B*, Warning times to Honolulu from sources at a depth of 25 mi (40 km) to simulate a mantle source.

Testing of ElarmS Within the Current Network

To better understand how an EEW system might work within the State of Hawaii, we implemented the ElarmS portion of the ShakeAlert system for a 10-month test of performance. We used configurations adopted from the Pacific Northwest Seismic Network (PNSN) with little tuning. There were three main goals for the test:

1. To understand the performance of the ElarmS system given the current seismic network and diverse seismicity on the Island of Hawaiʻi.
2. To test the processing times and alarm times for ElarmS.
3. To understand what needs to be tuned, adjusted, or added to decrease alarm times and minimize false triggers.

The performance of the ElarmS component of ShakeAlert is highly dependent on the magnitude cutoffs that we consider. Here we consider only earthquakes over magnitude 3 as defined by the ANSS earthquake catalog generated by HVO. During the test, there were 35 ElarmS alerts for earthquakes greater than *M*3. The events were mostly on the southern half of the Island of Hawaiʻi, with four earthquakes occurring near Mauna Kea and one earthquake significantly offshore to the northeast. No earthquakes greater than *M*3 occurred on the west coast of the Island of Hawaiʻi during our test. There were also seven false alarms from ElarmS that had no associated earthquake in the earthquake catalog. Two of the false alarms suggested earthquakes well off the Island of Hawaiʻi to the south and did not forecast strong ground shaking. The five other false alarms were each related to a rockfall into the active lava lake at the summit of Kīlauea. Though not a source of shaking hazard, the false alarms did forecast strong shaking in some regions because of artificially high magnitudes. There were no teleseisms (distant earthquakes) that triggered a false alarm during this testing period.

Processing times between the last contributing trigger and the ElarmS alarm ranged from 2 to 6 seconds for earthquakes equal to or greater than *M*3. The median time was 3.3 seconds, which includes latencies in digitizer processing and telemetry, so the actual ElarmS processing time is much less. Locations of earthquakes calculated by ElarmS have a median error of 4.6 km compared to the reviewed earthquake catalog locations. The magnitude calculated by ElarmS has a median error of -0.3 magnitude units compared to the actual value calculated in the HVO earthquake catalog.

The location and magnitude calculations made by ElarmS during the testing period are reasonably accurate for the Island of Hawaiʻi, but the number of false alarms was too high and could be reduced. One way to do so is to reduce the geographical area in which an EEW system detects large earthquakes. For instance, by only distributing alarms for earthquakes that are within approximately 20 km or so of the south and east coasts, we could cut down on the number of false triggers, some of which occurred off the coast and outside of the seismic network. The actual distance cutoff could be a topic of future research. There must also be a provision to exclude rockfalls in the Kīlauea summit area. The rockfalls tend to have imprecise locations in ElarmS that cover a broad region of Kīlauea's summit caldera and south flank so a simple geographic exception is probably not sufficient. Future work could to be done to better understand how to quickly distinguish the rockfall events from regular earthquakes.

Steps Toward Full EEW Implementation

While the implementation of a single-station EEW system is relatively straightforward, as ready commercial kits are available, the full implementation of a network-based EEW system is more complicated because it would involve the purchase and installation of new equipment and additional staffing to install, develop, and maintain the EEW system. The following discussion assumes that we will use ShakeAlert as the network-based EEW system of choice. We rely heavily on the experience of the consortium of organizations that are currently implementing ShakeAlert on the West Coast of the United States to guide our estimate of what would be required to implement an EEW system in Hawaiʻi.

One way to improve warning time is to increase the density of stations. Kuyuk and Allen (2013) suggest that average station spacing of stations on the order of 10–20 km is optimal, because spacing more dense than this offers negligible increases in warning time. The current station spacing for the Island of Hawaiʻi is <40 km, with three pockets of <10 km spacing around Kīlauea, Mauna Loa, and Hilo (fig. 6). The north and west sides of the island are clear targets for additional stations.

Alicia Hotovec-Ellis and coworkers (unpub. data) have developed a methodology to objectively target optimal locations to add stations based on improvement in warning time, seismic hazard, and station density. Specifically, it identifies sparse areas in the network with high seismic hazard that would experience the greatest increases to warning time. Hotovec-Ellis assigns such places a high “upgrade score,” and the highest scores are centered on the west coast of Hawaiʻi, north and south of Kailua-Kona (fig. 10). High scores coincide with several existing stations that have either triggered records or short-period seismometers (sensitivity >10s); those stations are not appropriate for EEW systems, but could be upgraded to include EEW-ready instrumentation. Such HVO-owned stations are favored for upgrades because the costs are less than establishing a station from scratch. The three best candidates for upgrades are two USGS NSMP stations on the northwest coast and an HVO station on the west coast near Captain Cook (table 1).

Assuming those three stations are added to the EEW network, the next best candidates are an HVO station on the southwest coast, a former NetQuakes site on the north coast, and three new stations (table1). Two more upgrades to NSMP sites and three upgrades to HVO sites round out the recommended improvements to the seismic network, which total 10 station upgrades and 3 new station installations (fig. 10).

Further upgrades beyond these 13 sites would not significantly affect warning time, assuming four stations are required for an initial warning. However, additional stations would improve the resilience of the network to station outages. Hotovec-Ellis and others (unpub. data) simulated a single station outage by increasing the number of stations required to render a warning to 5. The results show that the areas most susceptible to outages: north of Mauna Kea where there are no existing stations, and south of Hilo in the vicinity of a NSMP station. If all of the stations noted in figure 10 and table 1 are upgraded or installed, the new average station spacing is reduced to <20 km for nearly the entire island, with exceptions on the north, south, and east tips (fig. 10). This new station spacing would be on par with EEW networks in Japan and California. The State of Hawaii is geographically limited, as real-time broadband seismometers and accelerometers only exist on land and thus it is unlikely, given current technology, that an offshore earthquake could be optimally detected by an EEW system without resorting to extremely expensive surface-tethered ocean bottom seismometers.

Improvements to the seismic network around the volcanoes is ongoing, especially along the rift zones of Mauna Loa and Kīlauea as part of the National Volcanic Early Warning System (NVEWS; Ewert and others, 2005; Thelen, 2014). New stations installed as part of NVEWS stand to improve the density of stations and robustness of alarms to station outages in certain regions, but does not directly change the priority of the station upgrades noted here because none of the sites proposed in this study are near enough to the active volcanoes.

Beyond improving the station distribution of the network, major improvements to warning times may be realized by decreasing the latency of the data that is received at the datacenter. One simple change that could be made is to reduce the size of packets that are digitized on site. The current digitizers used in most of the HVO-operated seismic network have packet sizes between 5 and 9 seconds. By replacing the existing digitizers with ones that use 1-second packets, we can quickly cut overall latency. Such an improvement will require an upgrade of 30 existing stations (strong motion or broadband sites) within the HVO network. New or proposed upgrades should also include the short-packet digitizers.

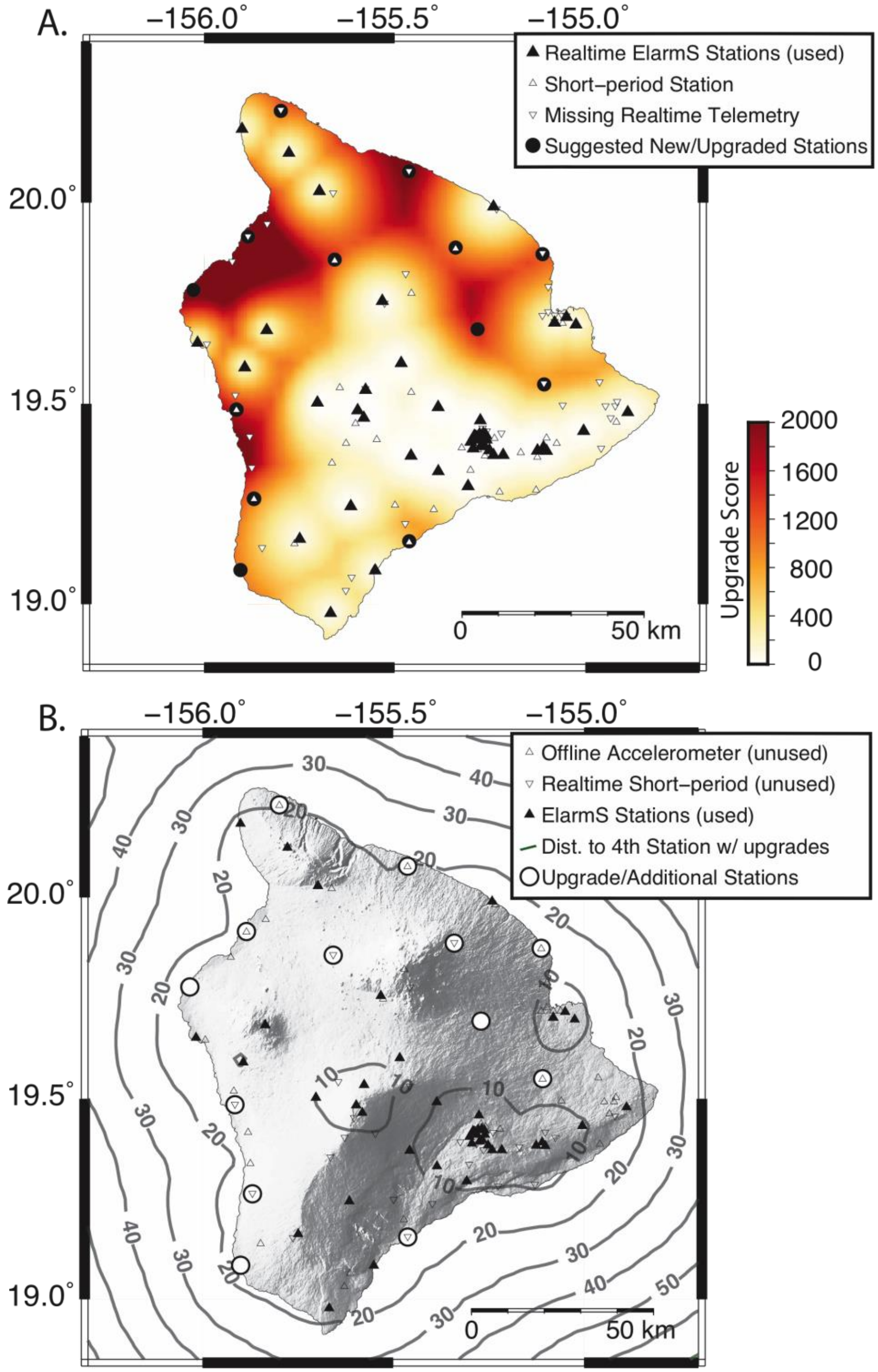


Figure 10. *A*, Map of proposed station upgrades. Warm colors indicate an upgrade score determined using methodology from Hotovec-Ellis and others (unpub. data). Higher upgrade scores indicate areas where upgrading stations would provide the most additional warning time to areas of high seismic hazard. *B*, Contour map of station density (distance to the nearest four stations) with new stations included based on the method of Kuyuk and Allen (2013). Clear triangles represent existing stations that are not sufficient for use in earthquake early warning. Black triangles represent existing earthquake-early-warning-ready stations. Circles indicate stations identified for upgrades in instrumentation and telemetry or entirely new station locations.

Table 1. List of instrument sites that could be upgraded to contribute to an earthquake early warning network, listed by descending upgrade score (Modified from Hotovec-Ellis and others, unpub. data).

[The locations are shown as black circles in figure 10. In the first column, Name refers to the name of the station, while the Net refers to the operator: NP, National Strong Motion Program; HV, Hawaiian Volcano Observatory]

Name.Net	Latitude	Longitude	Locale
2847.NP	19.91	-155.88	Waikoloa
2832.NP	20.08	-155.46	Honokaʻa
CACD.HV	19.48	-155.11	Captain Cook
KAAD.HV	19.26	-155.87	Kaʻapuna
HGC.HV	19.87	-155.11	Honomū
New Install	19.69	-155.27	Upper Waiakea
New Install	19.78	-156.03	Kona Airport
New Install	19.08	-155.90	Miloliʻi
2846.NP	19.55	-155.11	Mountain View
KKUD.HV	19.89	-155.34	Keanakolu
WAID.HV	19.86	-155.66	Waikiʻi Ranch
PPLD.HV	19.15	-155.46	Puʻu Pili
2826.NP	20.23	-155.80	Kapaaʻu
Total: 13 (3 new installs, 10 station upgrades)			

The speed and reliability of telemetry may also be considered. Upgrading digitizers will also reduce the time it takes to transmit the data across the existing telemetry network. Based on current telemetry performance, we may see telemetry latencies reduced to around 1 second, compared to the current range of 1.8 to 3.8 seconds. All of the EEW-eligible stations operated by HVO traverse the same telemetry network, which has been extremely robust. Even so, diversifying the telemetry used by a subset of the HVO-operated sites with cell modems would add communication capability in the case of a catastrophic failure of the HVO telemetry network. Stations that transmit data over cell modems should be geographically distributed relative to each other and to existing PTWC sites, which already receives data via cell modem. We have not specified which sites might be the best candidates for this telemetry upgrade, as the cell phone signal strength is not well characterized on the Island of Hawaiʻi.

Assuming the entirety of station upgrades are completed, new stations are installed, and latencies are ideally minimized, a best-case scenario for ElarmS performance can be calculated (figs. 11 and 12, table 2). The overall effects for critical facilities in Hilo, Kailua-Kona, and telescopes at the top of Mauna Kea would be a reduction or elimination of the ElarmS blind zone and improvement of ElarmS warning times of shallow earthquakes to about 2–4 seconds (fig. 11). Deep earthquake ElarmS warning times would also be improved, especially near the edges of the idealized blind zone. Additional warning times provided by a single-station system, as compared to an idealized ElarmS system, would also be reduced significantly if not eliminated (fig. 11). For critical sites in Honolulu, there would be a 2–5 second increase in ElarmS warning times for sources on the Island of Hawaiʻi (fig. 12). Overall reduced latencies reduce the ElarmS blind zone in the vicinity of Honolulu.

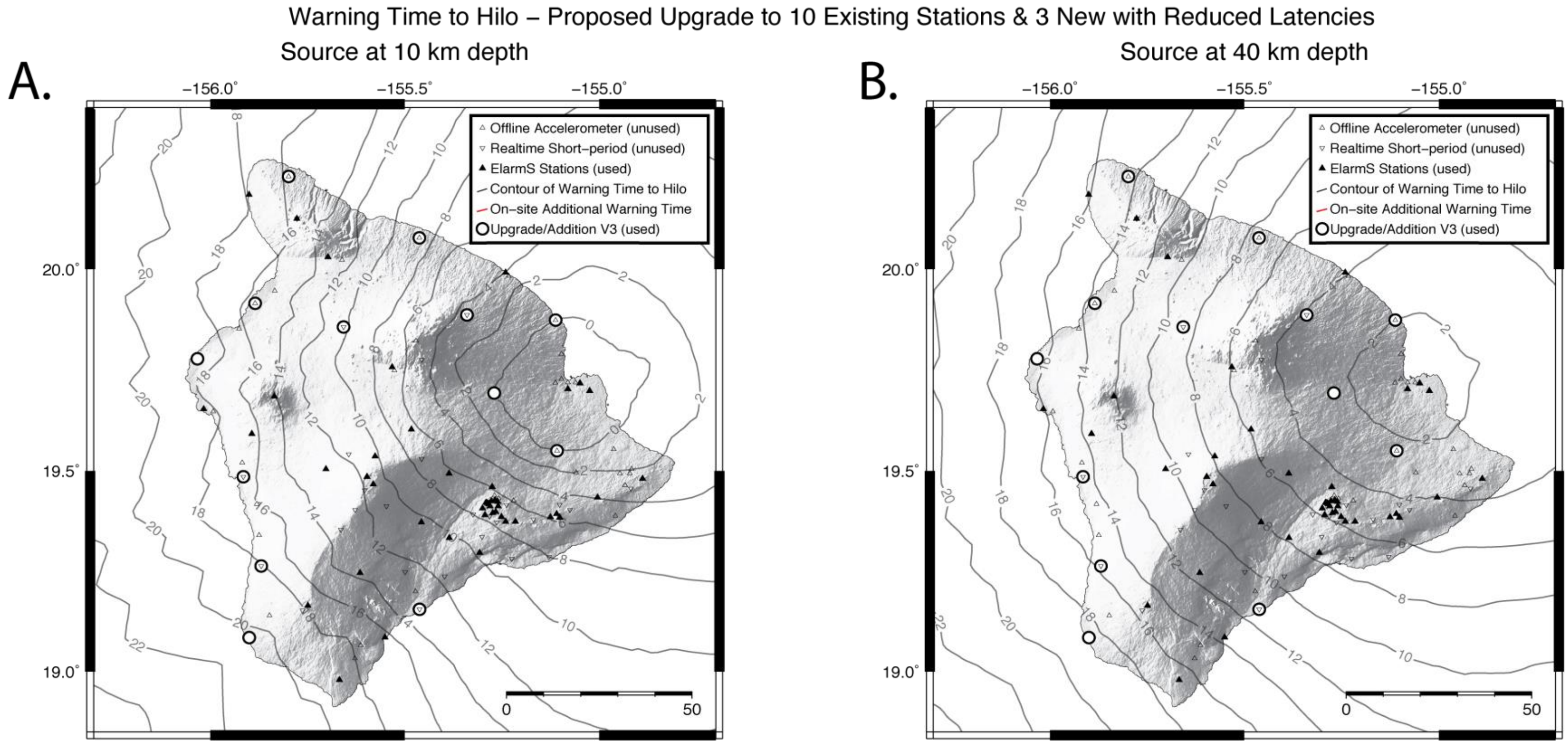
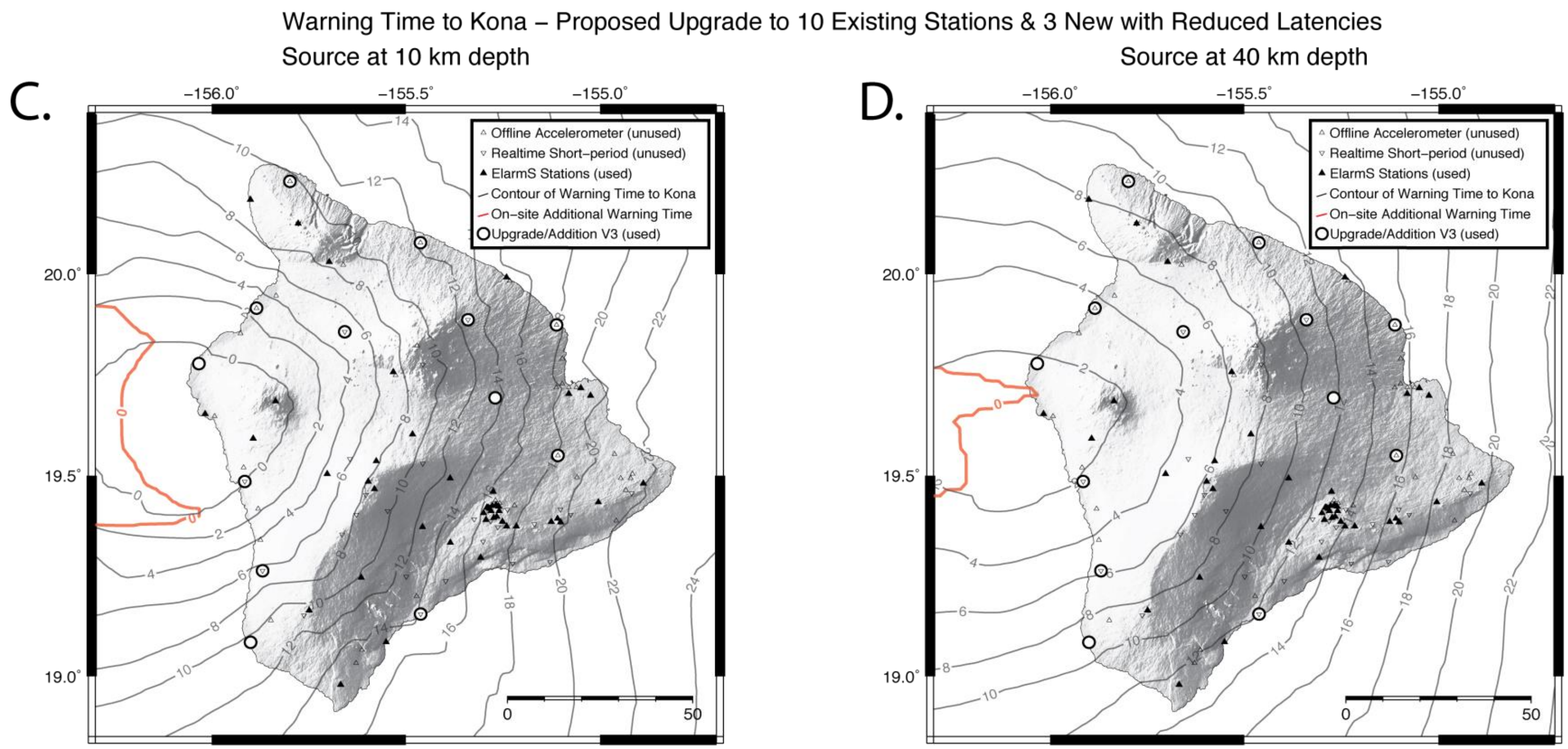


Figure 11. Warning time to Hilo, Kailua-Kona, and the summit of Mauna Kea from different source areas, assuming incorporation of all the proposed upgrades to stations and telemetry. Black triangles are existing earthquake early warning stations. Clear triangles represent non-real time accelerometers or short period instruments, neither of which can be used for earthquake early warning. Numbers on black contours are warning times, in seconds, using an ElarmS algorithm that requires four stations for an earthquake detection. Red contours are the additional warning time received by a single-station system, assuming one station placed at a critical facility at the target area. Shaded pink area is the ElarmS blind zone. *A*, Warning times to Hilo from sources at a depth of 6 mi (10 km) to simulate a décollement source. *B*, Warning times to Hilo from sources at a depth of 25 mi (40 km) to simulate a mantle source. *C*, Warning times to Kailua-Kona from sources at a depth of 6 mi (10 km) to simulate a décollement source. *D*, Warning times to Kailua-Kona from sources at a depth of 25 mi (40 km) to simulate a mantle source. *E*, Warning times to the summit of Mauna Kea from sources at a depth of 6 mi (10 km) to simulate a décollement source. *F*, Warning times to the summit of Mauna Kea from sources at a depth of 25 mi (40 km) to simulate a mantle source.



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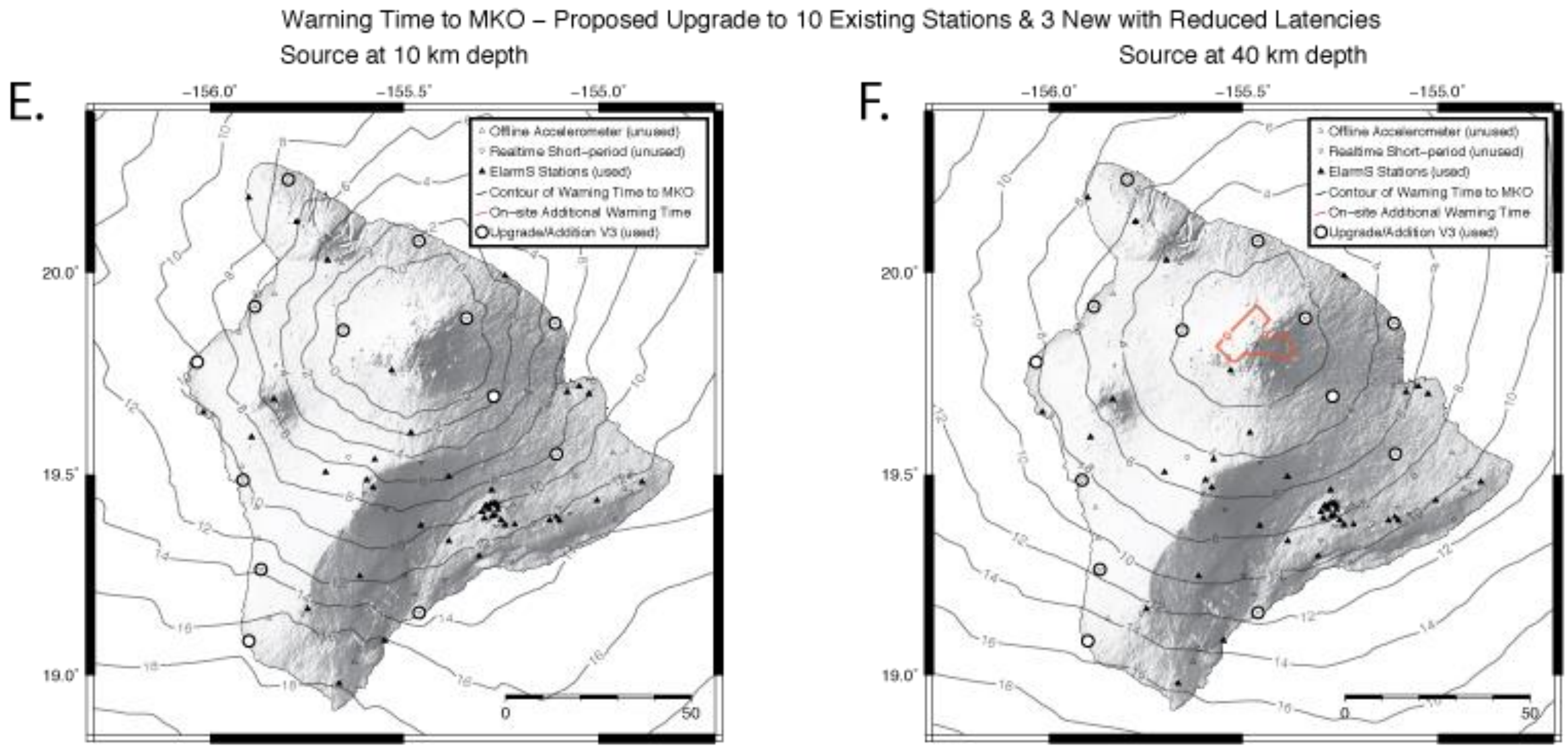

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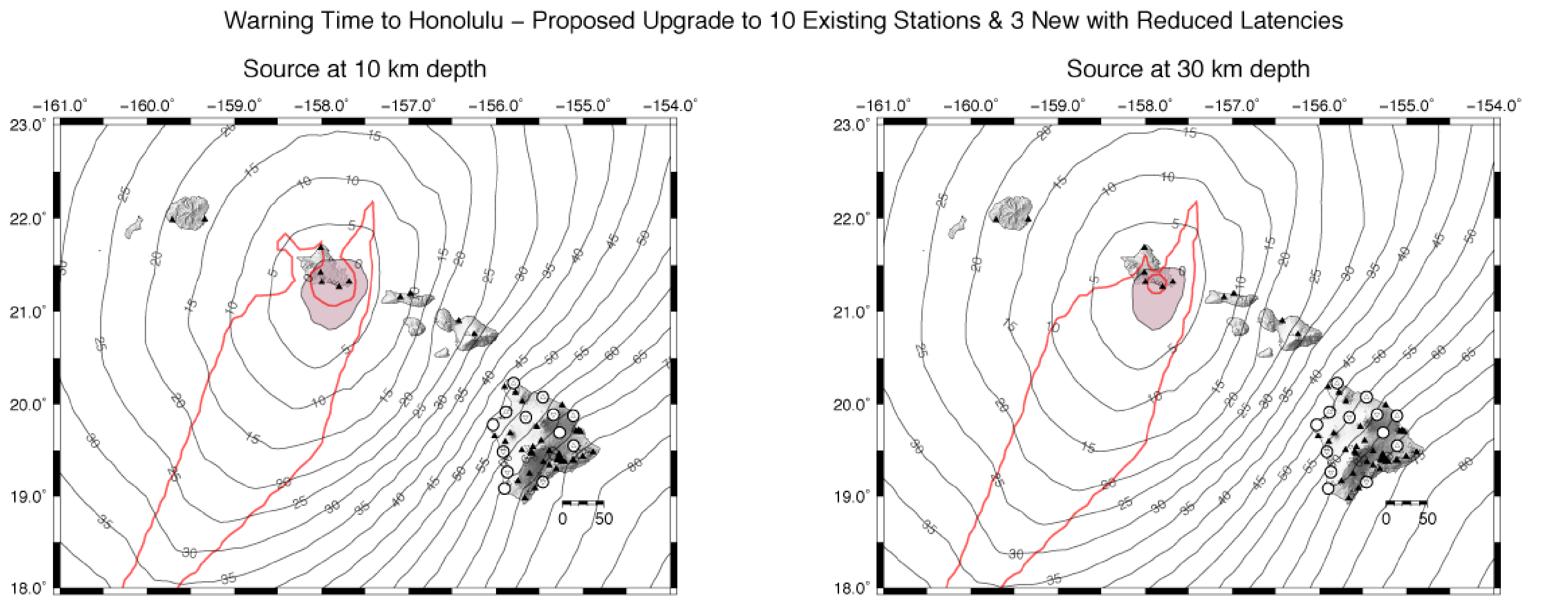

Figure 12. Warning time to Honolulu from different source areas, assuming incorporation of all the proposed upgrades to stations and telemetry. Black triangles are existing earthquake early warning stations. Clear triangles represent non-real time accelerometers or short period instruments, neither of which can be used for earthquake early warning. Numbers on black contours are warning times, in seconds, using an ElarmS algorithm that requires four stations for an earthquake detection. Red contours are the additional warning time received by a single-station system, assuming one station placed at a critical facility in Honolulu. Shaded pink area is the ElarmS blind zone. *A*, Warning times to Honolulu from sources at a depth of 6 mi (10 km) to simulate a décollement source. *B*, Warning times to Honolulu from sources at a depth of 25 mi (40 km) to simulate a mantle source.

Table 2. Current and idealized theoretical ElarmS warning times to areas of high population or critical infrastructure on the Island of Hawai‘i for some notable historical earthquakes. See the earthquakes with stars after the annotations in figure 2 for the earthquake.

	Warning times (in seconds)									
	1868 *M*7.9 Ka‘ū		1929 *M*6.5 Hualālai		1973 *M*6.2 Honomū		1975 *M*7.2 Kalapana		2006 *M*6.7 Kīholo Bay	
Target	**Current**	**Ideal**	**Current**	**Ideal**	**Current**	**Ideal**	**Current**	**Ideal**	**Current**	**Ideal**
Hilo	12	14	11	14	0	2	5	7	11	15
Kailua-Kona	10	12	0	0	13	15	18	20	0	4
Mauna Kea summit	11	14	2	6	2	5	11	14	2	6
Honolulu	67	70	51	55	60	62	71	74	45	47

The robustness of the datacenter is also an important consideration for an EEW system. Currently, all data are received and analyzed at the U.S. Geological Survey’s Hawaiian Volcano Observatory. While there are redundancies in place at HVO that protect against some failure modes, having a single location to analyze and distribute data is not ideal for a system that requires high availability. Recently, HVO completed a direct connection to infrastructure co-located with the Pacific Tsunami Warning Center at Ford Island on the Island of O‘ahu, using the U.S. Coast Guard’s ‘Ānuenue network. This new connection provides HVO with a redundant, independent, and extremely reliable connection to O‘ahu in the case of a local communications failure at HVO. In addition, HVO is currently testing hardware to establish a redundant offsite backup for the HVO seismic network data processing and dissemination at Ford Island. To make both datacenters more reliable for the operation and distribution of an EEW system, existing servers may need to be upgraded and networking components (radios, switches, routers) be upgraded, and spare parts could be purchased so that downtime is minimized.

An effective EEW system also requires a level of maintenance that cannot be met with the current staff at HVO. Addressing this deficiency involves two steps: first, the hiring of operational staff to meet the needs of the current real-time acquisition and analysis software; and, second, the hiring of operational staff to support the high-availability requirements, development, and maintenance of the new EEW system. The first step, supporting the current real-time network operations that feed data into the EEW system, is a critical piece that would strengthen the foundation of the entire EEW system; we estimate that HVO will need an additional two IT positions and part of a data analyst position. The second step, properly staffing HVO for the maintenance, tuning, and development of an EEW system to ensure that alarms have both low latency and high accuracy, will likely require at least six additional positions. These six new hires would include a program manager, an EEW-dedicated research scientist, a field technician, two IT support personnel, an outreach coordinator, and part of a data analyst position. With this staffing profile in place, HVO would have the best opportunity to provide accurate and timely warnings of earthquake shaking with an absolute minimum of system downtime.

ElarmS Compared to a Single-Station Approach

In general, a networked approach to EEW (for example, ShakeAlert/ElarmS) has the advantage of a more reliable and accurate warning than a single station, but comes at the cost of a potentially large blind zone unless the network and telemetry are optimized. A single station (or small array) co-located with processing at a site of interest may provide a few seconds of warning within the blind zone by bypassing the delay from p-wave travel time to multiple stations plus telemetry and processing. However, single-station approaches are more susceptible to noise and, therefore, false alarms. Sophisticated single-station algorithms (for example, PreSEIS OnSite; Böse and others, 2012) can utilize artificial neural networks with training datasets to discriminate noise from earthquakes, and provide estimates of magnitude, epicentral distance, and peak ground velocity (PGV). The pool of earthquakes that could be used for a training dataset for Hawaiʻi would be biased heavily by earthquakes on the southern side of the island, and would have limited observations at short epicentral distances from infrastructure at Hilo, Kailua-Kona, and Mauna Kea, where the single-station approach would give the most additional warning. A simpler approach could be to use a threshold of peak ground displacement in the p-wave (Pd). Wu and Kanamori [2008] suggest that "if Pd exceeds 0.5 cm, the PGV at the site most likely exceeds the damaging level, i.e., 20 cm/s."

In both cases, data following the initial p-wave trigger must be analyzed, and the amount of additional warning time from a single station compared to the networked approach is heavily dependent on this analysis window. For the threshold approach, a shorter, expanding window may lead to a faster warning, but perhaps only by a few seconds at best. The blind zone for the single-station approach is therefore never zero for shallow earthquakes, and is only slightly smaller than what the current network can provide with these conservative estimates of single-station warning time. With a fully optimized ShakeAlert system, such as proposed here, warning times are typically longer than a single-station approach for most sources to most population centers (figs. 11 and 12, table 3).

Table 3. Theoretical warning times to areas of high population or critical infrastructure on the Island of Hawaiʻi, comparing an idealized ElarmS system and a single-station approach (called "local" below) for some damaging earthquakes of note.

[See the earthquakes with stars after the annotations in figure 2 for the earthquake location. A value of zero indicates that the earthquake is within the blind zone for that particular locale]

	Warning times (in seconds)									
	1868 *M*7.9 Kaʻū		1929 *M*6.5 Hualālai		1973 *M*6.2 Honomū		1975 *M*7.2 Kalapana		2006 *M*6.7 Kīholo Bay	
Target	**ElarmS**	**Local**	**ElarmS**	**Local**	**ElarmS**	**Local**	**ElarmS**	**Local**	**ElarmS**	**Local**
Hilo	14	5	14	5	2	1	7	2	15	7
Kailua-Kona	12	5	0	0	15	7	20	7	4	2
Mauna Kea summit	14	5	6	2	5	2	14	5	6	3
Honolulu	70	28	55	23	61	27	74	30	47	21

Summary

Earthquake early warning has the potential to give seconds of warning of strong shaking to individuals, private companies, utilities, and municipalities. In the State of Hawaii, the implementation of a network approach to EEW, such as ShakeAlert, has significant potential benefit to the general population and critical infrastructure. The most appropriate approach to an EEW system (single-station or network) depends on the goals and available funds for such a project. A company eager to provide some level of warning of strong shaking to a critical facility (like a telescope) could implement a single-station system for low cost but may have to tolerate false alarms. If the goal is to warn a larger population (including critical facilities) or to provide as much warning as possible, then a network approach such as ShakeAlert may be most appropriate. The costs of a fully implemented network

solution such as ShakeAlert is higher, but the number of false alarms are reduced, the warning longer, and the impact broader. Given HVO's current role in statewide earthquake monitoring, its existing infrastructure and continued efforts toward improving redundancy, HVO could be an appropriate facility to implement a network-based EEW system. One hybrid or phased approach for critical facilities would be to implement a single-station system initially to provide some level of protection while a network-based EEW system is built.

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