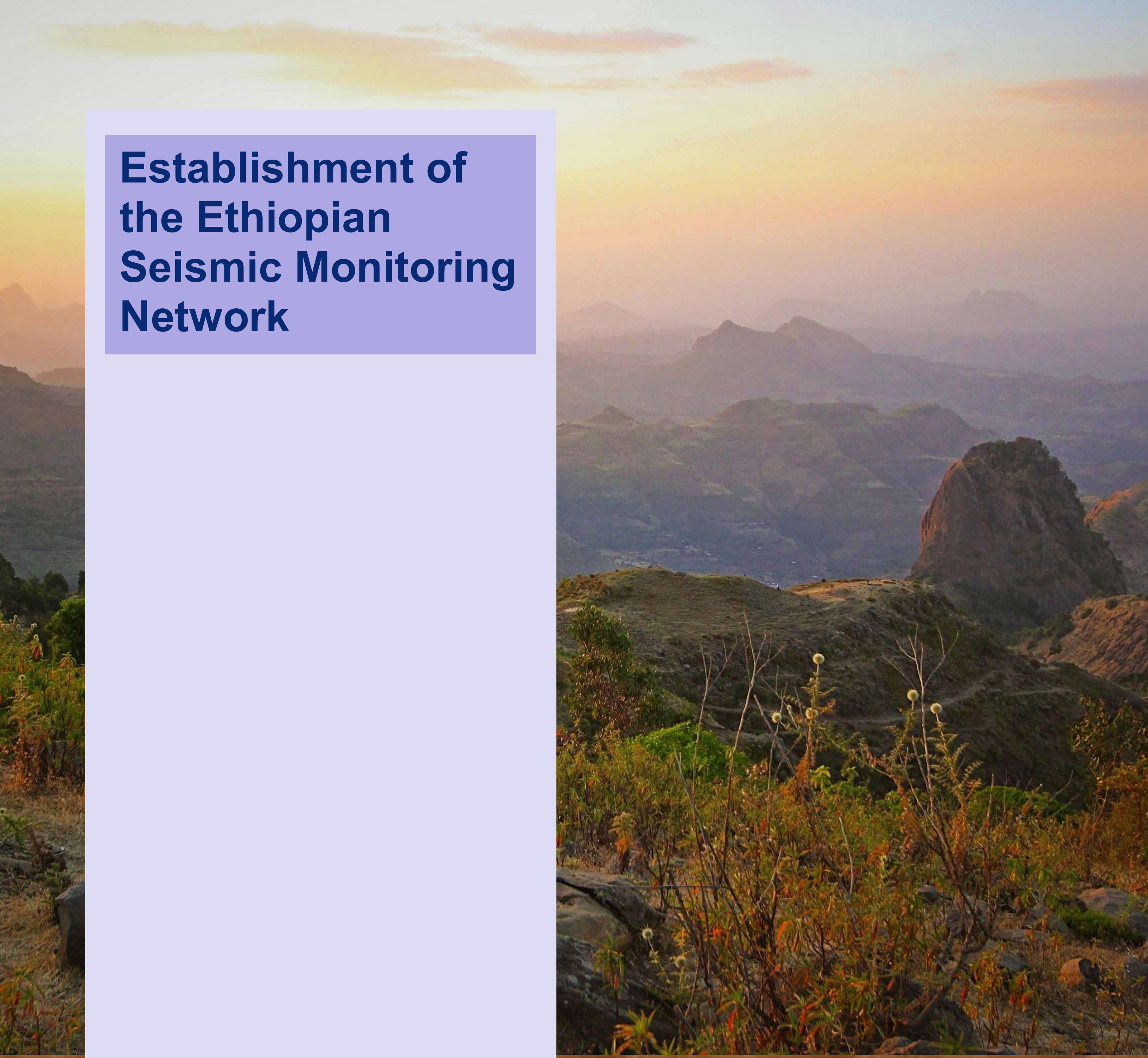

Establishment of the Ethiopian Seismic Monitoring Network

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0. Objective

The objective of this proposal is to contribute to the safeguarding of the Grand Ethiopian Renaissance Dam (GERD) through the establishment of an early seismic monitoring system. The early seismic monitoring system would create a network of sensors in the Horn of Africa at minimal cost, with the ultimate goal of implementing an earthquake early warning system and collecting data where there currently are no collection capabilities. Implementation of a seismic early warning network would be one of the many important tools governments can implement to ensure environmental risks are mitigated while simultaneously establishing a knowledge base of seismic research in Ethiopia and the African Horn at large.

Substantial infrastructure investments, like GERD, have long (years) time horizons before the investments break even. Safety and monitoring tools must be implemented to ensure investments like GERD, operate beyond their breakeven point. A seismic network would provide realtime information to ensure infrastructure projects are safely operated and fully utilized. Safe operation will only build investor confidence that large infrastructure projects in the horn of Africa will provide stable returns in the 21st century.

I. Problem Statement & Proposal Plan

The populations of African countries are increasing at a dramatic rate. Before the end of the twenty first century nearly all of the most populous cities will be located in Africa (United Nations Department of Economic and Social Affairs Population Division, 2018). With population densities growing in major cities, it becomes critical to have nationwide safety systems in place to ensure citizens and infrastructure remain as safe as possible. Implementation of a seismic early warning network would be one of the many important tools governments can implement to ensure environmental risks are mitigated while simultaneously establishing the region as a knowledge base of seismic research. The lack of such systems have led to disastrous outcome in Haiti (2010) from a magnitude 7.0 M_w earthquake, and Nepal (2015) from a magnitude 7.8 M_w earthquake.

This proposal's goal is to establish a region wide seismic network, at minimal cost, with the goal of implementing an earthquake early warning system and collecting seismic data where there currently are no collection capabilities. As it stands, large parts of Ethiopia have minimal to no seismic data available (Herbert, Assessing Seismic Risk In Ethiopia, 2013). With the impending population growth of the twenty first century, Ethiopia would benefit greatly from having an easily implemented, cost effective, and universal seismic network that would provide early warning notifications to affected populations while filling the seismic data gaps that currently exist. Beyond the safety benefits, this network can serve as a seed program for future IT projects by laying the IT foundation needed. The paper will begin with a brief overview of what earthquakes are and how they are measured in the Horn of Africa, a review of the current systems in place and their capabilities, an overview of two potential systems that can replace or supplement current systems, and finally a plan for full implementation of the Ethiopian Seismic Monitoring Network.

II. Brief Overview of Earthquake Seismic Sensing

The Earth we live on is made up of several plates. Within Africa, there is the Nubian/African Plate, the Arabian Plate, and the Somali Plate. Earthquakes happen when parts of the Earth's crust/plates move (Incorporated Research Institutions for Seismology). What we consider large earthquakes are typically associated with a few meters of movement between the earth's crust plates. Many of the mountains in the horn of Africa were formed at the edges these plates. The edges of the plates are also the regions that are most susceptible to earthquakes. With all these active plates, the African horn needs a robust monitoring system, and has a huge opportunity to develop state of the art seismic sensing capabilities.

The principles of detecting and locating earth quakes are well established in the seismology community, and are based on wave propagation/traveling in the earth's crust. An earthquake creates different seismic waves. The most relevant are the S (secondary/shear/transverse) elastic waves, and P (primary/compressional) waves. The different waves travel at different speeds through the earth's crust; as a result, the two waves arrive at seismic stations at different times. Of the two waves, P waves travel the fastest, so they arrive first, while S waves travel at roughly half the speed of P waves, and arrive later (Incorporated Research Instiutions of Seismology). A seismic sensing station close to the earthquake records P waves and S waves one after another. The further away a seismic sensing station is located from the earthquake the time difference between the arrival of the P waves and the arrival of the S waves increases. A key to understanding the meaning of the time interval between the S and P waves is having data on hand from previous earthquakes to assist in making accurate predictions on the distance and location of the earthquake in the region of interest. Additionally, several stations need to be in place to be able to calculate the exact location of the earthquakes' epicenter.

In general, not all earthquakes are significant enough to warrant concern. The scale used to measure the magnitude of an earth quake ranges from 1 to 10 (Richter energy scale). Magnitude 2 M_w events occur millions of times a year, and in most cases, are not considered a significant threat (Incorporated Research Institutions for Seismology). Earthquakes having a magnitude of 5 or greater pose the greatest risk to infrastructure and citizens. As a general reference, a magnitude 5 earthquake roughly possesses the same amount of energy as an average tornado. In the past, it was typical for Ethiopia to experience magnitude 4 or greater earthquakes at least once a year (Gouin, 1970). *Figure 1* shows regions of the African rift that have moved, and all the earthquakes of $M_w > 4$ (Matthew Wilks, 2017). The location of the capital city, Addis Ababa is marked with a blue star in the map. It can be seen from the map in *Figure 1* (Matthew Wilks, 2017).

Several earthquakes that range from magnitude 4 up to magnitude 6 have been recorded in the African Rift in the twentieth century. This includes the M_w 6 1989 Dobi Graben, M_w 6 1993 Nazret earthquake, and 1997 earthquake ~22km from Addis Ababa (Ogubazghi & Goitom, 2015). A majority of the risk is concentrated in the center and coastal region of the country, and the available data doesn't take into account the smaller earthquakes, .i.e., < M_w 4, which in most cases go unreported. Large infrastructure projects, like GERD, are located in the western region of Ethiopia where the seismic activity is significantly less than in the Africa Rift (Herbert, Assessing Seismic Risk In Ethiopia, 2013). Despite this, the lack of any data in the GERD region [Benishangul-

Gumuz Region] should be a cause for concern considering the large capital and time horizons needed for the investment to break even on the infrastructure investment (Mikael, 2018).

Recently in Kenya, a large crack stretching several kilometers suddenly appeared in south west Kenya damaging a section of the Narok-Nairobi highway and could be related to activity occurring in the East African Rift Valley (Diaz, 2018). With a more robust seismic sensing network, large seismic monitoring networks and early earthquake warning systems can be implemented to safeguard regions and infrastructure projects of interest. Fully functional seismic sensing networks would not only ensure seismic events similar to the one that occurred in Kenya cause little to no financial damage, but also help the region define areas of high seismic activity.

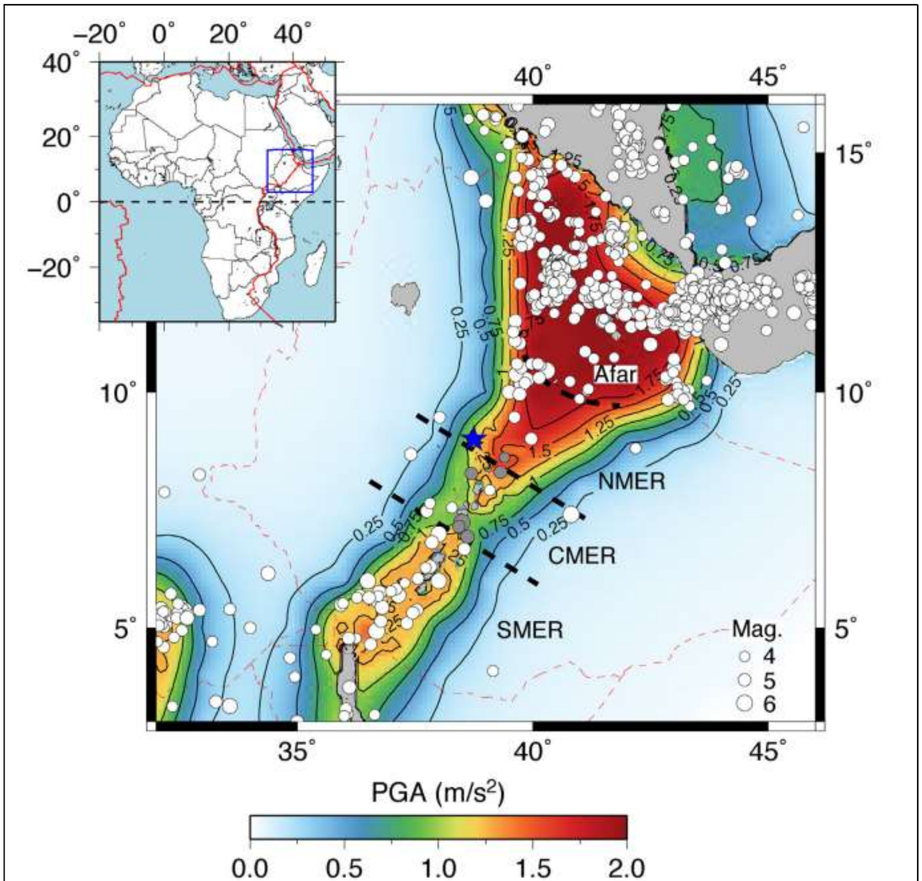

Figure 1. (Matthew Wilks, 2017) Shows the earthquakes peak ground acceleration (PGA) in multiple regions of Ethiopia and neighboring countries. Earthquakes since 1900 of M > 4 are white circles, and the gray circles indicate significant earthquake events. The blue star indicates the location of Addis Ababa. This figure shows that the concentration of seismic activity occurs at the interface of African/Nubian and Somali pates. The red region shows locations with the greatest ground acceleration and the blue with the least over the past century.

III. ESSN Current Systems & Capabilities

All of the mentioned and recorded earthquakes were captured using the existing seismic tools in Ethiopia at the time. Currently there are several sensors in Ethiopia's ESSN (Ethiopian Seismic Station Network). Of the available sensors, some are real time, meaning the data can be transmitted with the appropriate hardware configuration, and others are non-real time, meaning the data is locally stored on the sensing tool. Other papers have different names for the sensors but the locations are roughly the same (Ayele, 2005). The sensors are:

Sensor Name/Acronym	Sensor Location	Year of Installation	Sensor Type/Data Logger Type	Additional Information
SEME	Semare University	?		
DESE	Dese W/Sehen	1999	LE-3D-20S sensor/RT130 data logger	Discontinued/ 2Hz geophone
WLRA	Wolmera	2017	CMG-3T sensor/REF TEK data logger	Vault or Post Hole/Force Balance VBB/Thermal Shielding Needed
AAE	Addis Ababa	1959	CMG-3T sensor/ RT130 data logger	Vault or Post Hole/ Force Balance VBB/ Thermal Shielding Needed
ANKE	Ankober Museum	2007	Trillium Compact/RT130 data logger	Force Balance BB
HARA	Harar	2012	CMG-3ESP sensor/Taurus data logger	Vault or Post Hole/ Force Balance VBB/ Thermal Shielding Needed
FURI	Mount Furi	1997	STS1 & STS2 sensor/Quantera 330 data logger	Discontinued/Force Balance VBB
BEKO	Bekogi Tech	2016		
DILA	Dilla University	2012	CMG-3ESP sensor/Taurus data logger	Vault or Post Hole/ Force Balance VBB/ Thermal Shielding Needed
ALME	Alemaya University	1976		

KOFE	Kofele High School	2012		
ARBA	Arba Minch University	2012		
MEKE	Mekelle University	?		
Table 1. List of active seismic sensors in Ethiopia as of 2019.				

These sensors are located along the African Rift and vary in tool configuration, tool capabilities, and reporting capabilities. This makes using and comparing the data between sensors difficult and prevents additional data/conclusions from being drawn from the collected seismic information. One key aspect of this proposal is to fully utilize the IT infrastructure that is available. Beyond seismic sensing, world economies rely heavily on generating data and analyzing that data. A seismic network that was built with the end goal of interfacing with back end servers and analysis software would not only improve the networks ability to detect earthquakes but also disseminate information quickly to affected parties. As it stands, based on the available sensors installed (Table 1), the current ESSN does not have this capability. *Figure 2a* below compares the different sensors currently in use in the ESSN. The CMG-3T, STS1, STS2, LE-3D-20S, and Trillium are all capable tools with low noise floors. *Figure 2b* shows the recording of a M_w 5.3 on January 27th, 2017 with some of the data coming from the ESSN. All of these seismic sensors in the ESSN have a long history of deployment, but in most cases require costly vaults and dozens of man hours to reach the stated performance noise floors. Most sensor deployment locations are not silent enough to take advantage of sensors with such low noise floors, adding unnecessary cost to the sensors. Additionally, it wouldn't necessarily make financial sense to update tools that were never designed for IT/network configuration and in some cases are discontinued. Besides the cost, it's not clear how the information is stored/retrieved and made accessible to decision making agencies and affected populations. To achieve the goal of a robust seismic sensing (monitoring & warning) network and IT connectivity, a few critical parameters must be taken into consideration.

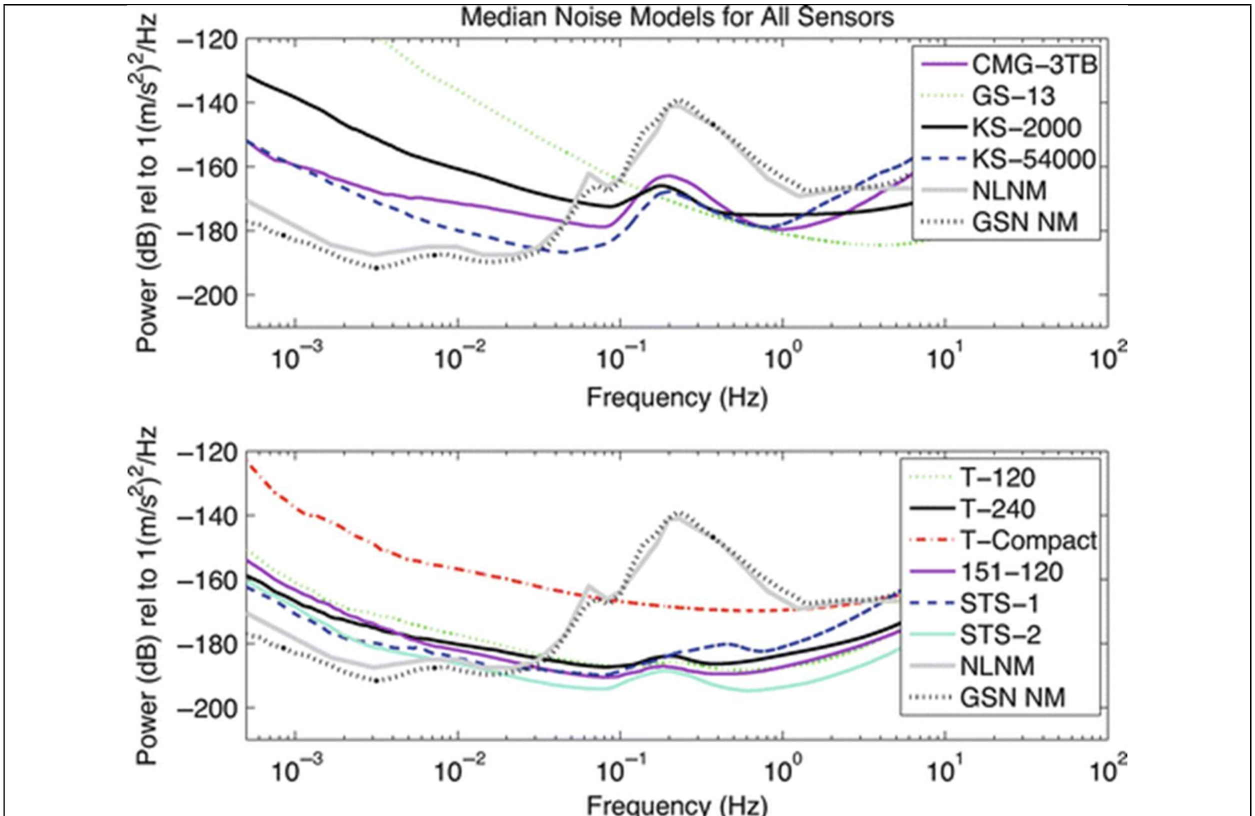

Figure 2a. A comparison on of the noise floors of the different types of sensors. The sensors in the Ethiopian Seismic Network are the CMG, T-Compact, STS-1, and STS-2. (Ackerley, 2015)

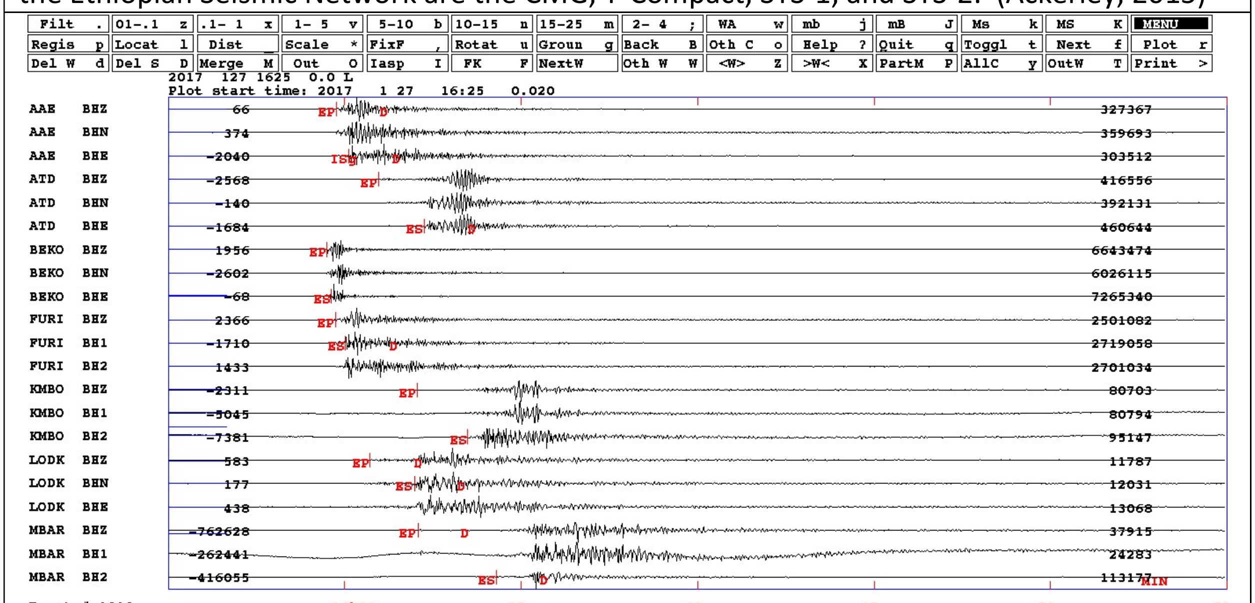

Figure 2b. Recording from the ESSN sensors displaying the January 27th 2017 Ziway M_w 5.3 earthquake. ATD Sensor → Djibouti, KMBO Sensor → Kenya, and MBAR Sensor → Uganda data is made available by Institute of Geophysics, Space Science and Astronomy of Addis Ababa University (IGSSA).

IV. Parameter Evaluation in Selecting a New Seismic System

Large scale sensing networks provide a safety net for the region implementing them, and generate the data needed for decision makers. Many aspects of large systems must be taken into consideration to ensure they meet minimum standards and provide the required information. Parameters like cost, technical performance (noise floors), accessibility, and potential secondary projects are all aspects that must be considered when attempting to expand seismic sensing capabilities. When all these parameters are taken into considerations, two primary options present themselves for large scale seismic sensing (monitoring & warning) networks. The first is MyShake cellphone sensing, and the second is Raspberry Pi Shake discrete sensors. The next sections will discuss the two systems, their capabilities, and where they have been implemented.

V. MyShake Cell Phone Seismic Sensing System

The MyShake cellphone sensing tool is an application that can run on any Android or Apple phone. Using the internal accelerometers in the phones the application communicates with central servers and determines if there is enough statistical data present to issue an earthquake warning. The data collected can also be recorded and serve as a library of seismic activity in a region. A key issue with this system is that cell phone performance varies from manufacturer to manufacturer. Also, there is a requirement that the region of interest has high cellphone penetration. Currently Ethiopia has relatively low cell phone penetration and limited high speed wireless connections (GSM Association, 2017), making this cell phone dependent implementation difficult. Its major draw is the low cost to government agencies and the zero implementation time before data is being generated. To date, no other system can be implemented so affordably, quickly, and with little to no maintenance. The MyShake tool was capable of detecting magnitude 5 or greater earthquakes consistently, while providing location data and eliminating false positives from the collected seismic information. The active MyShake sensors can be viewed at https://myshake.berkeley.edu/ which provides a map of all the seismic activity recorded (Qingkai Kong, 2016).

Figure 3 below shows the sensing capabilities of several commercial cell phones compared to highly sensitive MEMS (micro-electro-mechanical systems) devices (blue and purple). The plot also shows different magnitude earthquakes and the amplitude of their activity. From the plots, it's clearly observed that the MyShake tool can detect earthquakes >M5 that are less than 10km away in the frequency range of 1 to 10Hz without difficulty. One of the primary draw backs would be addressing the question of ownership of the seismic data and the willingness of citizen to bear the cost of additional cell phone data charges. Another main challenge would be cellphone variability characteristics. No cell phone was intended to be used for this purpose, as a result it may require testing many make and models of cellphones before a trustworthy manufacture with acceptable noise floors and performance can be used. Considering the pace of cellphone development, it's expected that performance and cost should improve with updated models. Lastly, the original paper was published in 2016, which implies the technology is still relatively new. The MyShake system, despite its drawbacks could serve as a means to establish seismic hotspots for early warning systems and monitoring systems. Once locations are identified, more robust and capable tools can be put in place that would ensure all the data collected remains in the collecting agencies hands and does not directly impact citizens cell phone data usage.

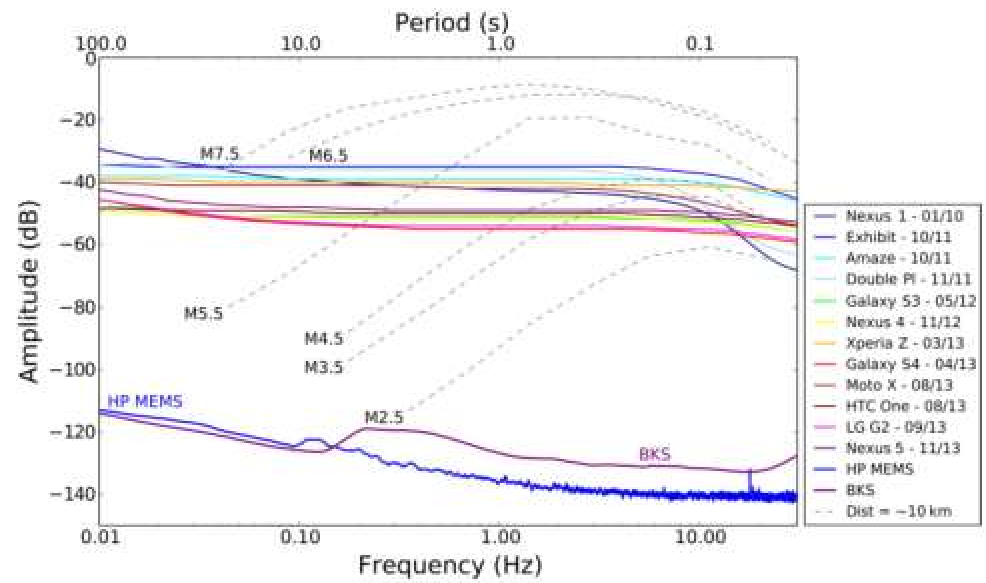

Figure 3. Noise floors of smartphones. Grey dashed lines show the frequency response of earthquakes of magnitude 2.5-7.5. The lower 2 plots for BKS and HP-MEMS show noise floors for expensive state of the art systems.

VI. Raspberry Pi Shake Seismic Sensing System

The Raspberry PI Shake is a standalone tool specifically made for sensing seismic activity. The base of the tool is the Raspberry PI computer which is roughly the size of a cell phone, and is comprised of an ARM processor, can run several OS flavors, and has many attachments to add features to the base unit. The Raspberry PI Shake builds on the base Raspberry PI by adding accelerometers, geophones, GPS, and cellular communication features. These systems would be able to provide uniformity at high spatial resolution for a large region. The tool, called the OSOP Raspberry Shake 4D, includes a vertical-component geophone, three component accelerometers, digitizers, and near real time mini-SEED data transmission at a cost of a few hundred US dollars per unit. When compared to expensive units like the Trillium seismometer, the Raspberry Shake requires earthquake intensity ~0.3 in magnitude larger to detect reliably. The root cause of this is they have higher than average self-noise when compared to the more expensive units like the Nanometrics Trillium. Despite this, the Raspberry Shake is able to detect earthquakes of magnitude 2-4 at distance of 20-100 km from seismic events. This is significantly more sensitive than the MyShake cellphone sensors at roughly the same cost (cost of the phone), and without the cellphone to cellphone detection variation. With the addition of a geophone the Raspberry Shake can extend the detectable frequency range down to 0.5 Hz and increase the clipping range (max detectable signal) to 22 mm/s (Trillium clips at 26 mm/s).

Figure 4 below shows the noise floors for the Raspberry Shake, and establishes the tool does have higher noise floors than more expensive units, but is still significantly better than the cellphone implementation in MyShake. In most real world cases the sensors are deployed in noisy areas (cars, human traffic, planes, construction, etc.) and cannot take advantage of extremely low noise floors. All the collected data is then digitized with an internal 24bit digitizer and recorded at 100 Hz. The collected data can be locally stored or transmitted in near real time (4 Hz packet transfer) through a local network in miniSEED (seismic exchange for earthquake data) format. Time stamps and GPS locations can also be added to the collected data to provide additional detail to the seismic information (Robert E Anthony, 2018). Twenty of these tool has been implemented in several districts within Nepal. One of the districts, Baglung station, has been recording since May 2nd 2018 and streams data in real time (R023E), and can be viewed at R023E [https://raspberryshake.net/stationview/#?net=AM&sta=R023E]. This sensor and the data cataloged by the Nepali National Seismological Center (NSC) have shown that local earthquakes have been reliability identified by the Raspberry Shake. One of the main challenges with the Raspberry shake is it will require power stations to operate in remote regions for > 1year. Implementations using lead acid batteries and solar cells are possible but will add to the underlying cost of the systems. Additionally, to receive real time data cell tower coverage will be required which could be an issue in some regions of the Horn of Africa. Despite this the Raspberry Pi Shake has sold thousands of these devices and many have been in operation for several years, with the general design being available for over 10 years. The link [https://raspberryshake.net/stationview/#] shows all the active sensors in the world with the ability to view the live seismic information from a standard web browser from any internet connected device.

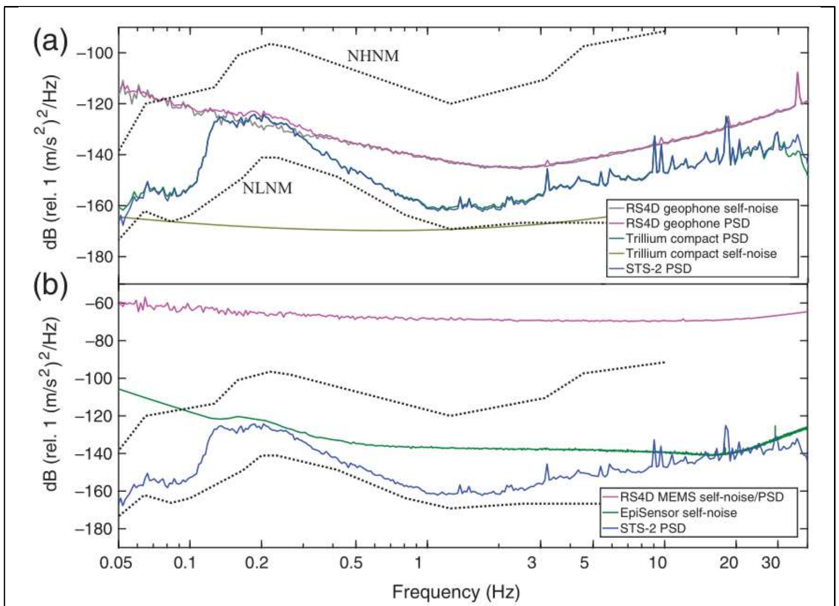

Figure 4. Self-noise/noise floors of the raspberry pi shake device compared to Trillium and STS devices, both of which are deployed in Ethiopia. ANKE & DILA both have Trillium devices.

VII. Proposed Plan for implementation of ESMN

Taking the capabilities of the tools, cost, and practicality of the systems, a combination of the two systems would yield the best results for the Ethiopian Seismic Monitoring Network (ESMN) and the African Horn Seismic Monitoring Network (AHSMN). First steps would include collecting data using MyShake and establishing regions that have no or high seismic activity in the country. The MyShake platform would serve as a monitoring and early warning tool for the regions it's implemented. Once there is an understanding of where the most relevant locations are, installation of Raspberry Shake sensors (for monitoring and early warning) would enhance the recording capabilities in regions of interest and regions that have no data at all. The initial cost from MyShake would be zero, and would help to engage and include citizens in the study of seismology. Using local high schools and universities the identified regions of interest could then be awarded Raspberry Shake sensors. The sensors have a robust library of documentation, and interface well with modern computers and networks. This in part would help build the foundations for IT education at the university and high school levels. With a dual MyShake and Raspberry Shake seismological network, real time information can be collected/monitored and the foundations for early warning system can be implemented. This type of project could seed future IT infrastructure projects while also training the next generation of scientists and engineers. Despite all these advantages more expensive seismic tools will generally outperform both the MyShake and Raspberry Shake sensors. Ideally as data is collected the costlier sensors could be implemented adhoc to ensure the best return on investment for ESMN and AHSMN.

Implementation Stage	Description of Work	Estimated Time
Stage 1	MyShake Data Collection - Citizens download cell phone app and begin collecting preliminary data.	4 months • collection of baseline data
Stage 2	Based on data from Stage 1 regions of interest would be awarded Raspberry Pi Shake sensors. The sensor would then start collecting data once installed.	8 months • installation • personnel training
Stage 3	Making the data available to all interested parties and decision makers in government through a web interface.	6 months • establishing the internet IT needed in Ethiopia • presentations to officials on tools availability

Stage 4	Polish & Refining system.	3 months • address any system issues and implement fixes as needed
Table 2. Sensing network roll out time line		

VIII. Conclusion

It should be every community member's responsibility to contribute to the wellbeing and advancement of regional safety. As Ethiopia and the Horn of Africa begins a new chapter of economic growth, critical safety systems should be in place to ensure the region develops it human capital while ensuring against environmental uncertainties. To achieve this all community members, local and diaspora bear a responsibility to contribute to the health and development of the region. Small IT investments today will bear dividends in the future and serve as a means of transitioning away from manufacturing lead economic growth. Large scale infrastructure projects like GERD (Mikael, 2018) and widespread e-Education will significantly help the region transition away from subsistence agriculture and into the knowledge based economy. The ESSN/AHSMN is one of many potential projects that helps the Africa Horn achieve these goals by 1) increasing seismology education 2) developing IT education 3) building a regional early warning system, and 4) seeding future project by laying the ground work for successful implementation. By selecting project that achieve multiple goals the Horn of Africa will accelerate advancement in multiple sectors within the region ranging from education, IT development, and safety awareness. As the population in the region continues to grow, the future of Africa will be reinforced by supporting projects like ESMN/AHSMN and ensure the region will become a global leader in seismological studies and research.

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