A low-cost seismic network for Papua New Guinea

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Abstract

Papua New Guinea (PNG) is situated at the edge of the Pacific "ring of fire" and is exposed to frequent large earthquakes and volcanic eruptions. Earthquakes in PNG, such as 2018 Hela Province event (M7.5), continue to cause loss of life and widespread damage to buildings and infrastructure. Given its high seismic hazard, PNG would benefit from a dense seismic monitoring network for rapid (near real-time), as well as long-term, earthquake hazard and risk assessment. Geoscience Australia (GA) is working with technical agencies of PNG Government to deliver a Department of Foreign Affairs and Trade (DFAT) funded technical disaster risk reduction (DRR) program to increase community resilience on the impact of natural hazards and other secondary hazards.

As part of this program, this study explores the feasibility of establishing a low-cost, community-based seismic network in PNG by first verifying the performance of the low-cost *Raspberry Shake* 4D seismograph, which includes a three-component strong-motion MEMs accelerometer and one (vertical) short-period geophone. A *Shake* device was deployed at the Rabaul Volcanological Observatory (RVO) for a period of one month (May 2018), relaying data in real-time via a 3G modem. To assess the performance of the device, it was co-located with global seismic network-quality instruments that included a three-component broadband seismometer and a strong motion accelerometer operated by GA and RVO, respectively. A key challenge for this study was the rather poor data service by local telecommunication operators as well as frequent power outages which caused repeated data gaps. Despite such issues, the *Shake* device successfully recorded several earthquakes with magnitudes as low as m_b 4.0 at epicentral distances of 600 km, including earthquakes that were not reported by international agencies. The time-frequency domain comparisons of the recorded waveforms with those by the permanent RVO instruments reveal very good agreement in a relatively wide frequency range of 0.1-10 Hz. Based on the estimated noise model of the *Shake* device (seismic noise as well as instrument noise), we explore the hypothetical performance of the device against typical ground-motion amplitudes for various size earthquakes at different source-to-site distances..

Keywords: Seismic network, Community, Raspberry Shake

INTRODUCTION

Papua New Guinea (PNG) is one of the most seismically active regions in the world, situated at the continental collision zone of two major tectonic plates, i.e. Pacific and Indo-Australia plates (Craig & Warvakai, 2009). The region's complex tectonic evolution also involves the formation of several microplates explaining the ongoing active crustal deformation within the country (Baldwin *et al.*, 2012). The expected high level of seismic hazard (Ghasemi *et al.*, 2016) coupled with rapid population and economic growth makes PNG vulnerable to earthquakes. For instance, the recent 2018 Hela Province event (M7.5) claimed at least 160 lives and cost over US$61m, leading to the state of emergency following this major event.

The impact of strong earthquakes on local communities can be significantly reduced by appropriate earthquake preparedness and response measures being in place. Furthermore, the efficiency of the emergency response operations to an earthquake can be improved considerably by generating products similar to US Geological Survey's *ShakeMaps*, which represent the spatial extent and level of ground shaking following a major earthquake (Wald *et al.*, 1999). Such products would enable emergency responders to take timely and targeted actions immediately following an earthquake. It should be noted that a *ShakeMap* can be produced at minimum based on earthquake origin information, i.e. hypocentral location and magnitude, and using a pre-configured empirical ground-motion and site-class models. However the accuracy of the *ShakeMaps* can be significantly improved if sufficient number of recorded levels of ground shaking are available in near real-time following the major event (e.g. Pramono *et al.*, 2016). Ideally, this can be achieved through the installation of a dense seismic network at the region of interest providing data in real-time mode.

Since 2013, the Port Moresby Geophysical Observatory (PMGO) have operated and maintained a seismic network of 10 stations. Each station is equipped with a three-component short period seismometer collocated with a strong motion accelerometer. Both sensors are recording continuously, but only data from short period seismometer are retrieved in real-time. The data are acquired via internet and through SeedLink protocol plugins installed with Seiscomp3 system at the central server in Port Moresby. This network is complimented by 3 broadband seismometers, two of which are operated and maintained by Geoscience Australia (GA) as part of Australian National Seismic Network (ANSN) since 2009, and the other one by USGS as part of the Global Seismographic Network (GSN). The data from these stations are also retrieved in real-time by PMGO via FDSN web service provided by the Incorporated Research Institutions in Seismology (IRIS) Data Management Centre. This network provides minimum requirements to generate *ShakeMaps* for earthquakes in PNG, i.e. earthquake origin information; however the produced maps would be merely based on pre-selected empirical ground-motion models. It should be noted that none of the available ground-motion models are developed using PNG ground-motion data. This may diminish the quality of the *ShakeMaps* produced for earthquakes in PNG. In contrast, expanding the national seismic network, and hence producing data driven *ShakeMaps*, is currently impossible given the high costs associated with the installation and maintenance of PMGO's seismic stations.

One plausible approach to densify the current seismic network of PNG is to utilize low-cost seismic sensors across the country (e.g. Evans *et al.*, 2005). Prior to these decisions being made, it is first crucial to better assess the performance and limitations of such sensors for the earthquake monitoring purposes in PNG. In this study we explore the performance of a certain brand of low-cost sensors known as Raspberry Shake 4D seismograph (hereafter "RS4D device"). We first introduce the experiment settings to assess the quality of the RS4D sensor's recordings. Then we present our assessment results in a quantitative way and finally outline opportunities for future work.

EXPERIMENT SETTINGS

In this study, the RS4D device was studied to explore the feasibility for establishing a low-cost, community-based seismic network in PNG. In addition to an affordable cost, the RS4D device has attributes which make it suitable for this application:

- It integrates a three-component strong-motion MEMs accelerometer, one (vertical) short-period geophone, the digitizers, and the acquisition unit (i.e. Raspberry Pi) into a compact single box.
- The data is retrieved in real-time by the native SeedLink server running on the acquisition unit. The data is stored locally on the device and at the same time can be sent to the configured remote server in real-time.
- The short period geophone has a nominal flat velocity response spectrum from ~0.5 to 40 Hz. This makes the device suitable for earthquake locating purposes.
- The MEMs accelerometer has a nominal flat acceleration response spectrum up to ~40 Hz, and remains on-scale for ground accelerations up to 2g. This makes the device suitable for recording medium-to-large earthquakes at near-source distances, and also for reliable estimation of engineering parameters such as Peak Ground Acceleration (PGA) and/or response spectra. Such device can also be used for structural monitoring purposes.

To verify the performance, we deployed two RS4D devices at the Rabaul Volcanological Observatory (RVO) and Port Moresby Geophysical Observatory (PMGO) for the period of one month (May 2018). During this period, the stations were continuously relaying data in real-time via a 3G modem to a remote server that is hosted and maintained by Gempa (https://doi.org/10.7914/SN/AM). This server is collecting and archiving data from all of the Raspberry Shake devices around the globe. The collected data is freely available through FDSN web service and are in use to detect and locate earthquakes worldwide (https://raspberryshake.net/) .

Here, we present the results for RVO station recordings. The benefits for co-locating the device with the RVO station include:

1- A high rate of seismicity in New Britain region where the instrument is located; this allows us to study the performance of the device using both local and regional earthquakes.
2- The RS4D device is co-located with GA's STS-2 broadband seismometer, and RVO's Kinemetrics accelerometer. This makes it feasible to directly explore the performance of the device against recordings from observatory-quality instrumentation.
3- The amplitude of background noise at RVO station is relatively low, making it suitable to detect earthquakes with low signal-to-noise amplitudes (e.g. small local earthquakes).

The PMGO station is located in an area of low-to-moderate seismicity and as expected in comparison with the RVO station, registered fewer events during the operational period. However we note that this station better represents an urban environment in terms of expected level of background noise and its effects on earthquake recordings.

RESULTS

In this section we first present the level of background noise (seismic and instrumental noise) at the RVO station and explore its implications on earthquake detectability as a function of magnitude and source-to-site distance. This is followed by presenting the results of direct comparisons between earthquake time-series registered by RS4D device and those from standard seismic instruments.

Background noise level and detection threshold

Background noise, together with specifications of the seismic instrument in-use, are the key factors controlling the earthquake detection thresholds at a seismic station. Background noise is characterised as a stationary stochastic process and consequently has no defined phase spectrum. It can be caused by ambient or cultural noise and electronic instrumental self-noise, contaminating the earthquake signal over a wide frequency range.

To quantify the level of background noise in RS4D recordings, we followed the approach of McNamara & Buland (2004) in which the continuous record is divided into one-hour data segments. The noise levels of each segment is then computed in terms of power spectral density (PSD). The PSDs are then used to calculate the probability mass function of the noise power at individual frequencies. The final result is presented as a frequency-power plot where at each frequency the corresponding power is colour coded based on associated probability of occurrence (Figure 1). This technique has the advantage of not being sensitive to low probable, transient events such as earthquakes and/or data gaps. In other words there is no need trying to isolate stationary background noise from transient waves.

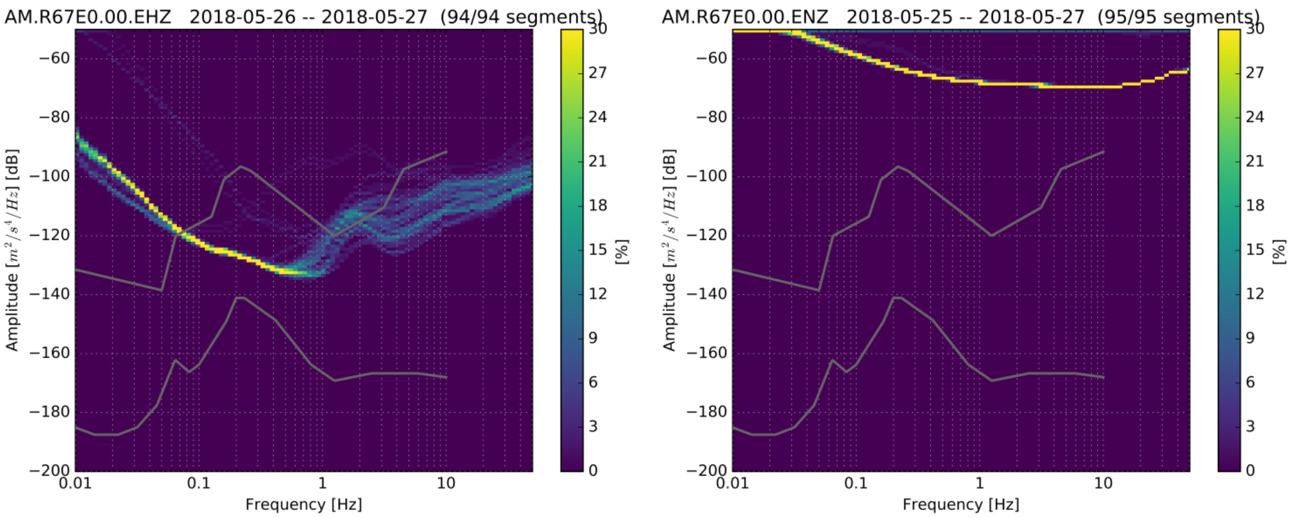

Figure 1. Probability mass function (PMF) plots of the noise power spectral density (PSD) at RVO station. This plot is produced based on two days of continuous data recorded by short-period geophone (left panel) and MEMs sensor (right panel). The two thick curves indicate the global average of high and low bounds of the noise level at seismic stations (Peterson, 1993).

Figure 1 shows the noise levels per frequency in the continuous recordings of short-period geophone, and MEMs accelerometer at the RVO station for a period of two days (25th to 27th of May, 2018). For comparison, the global high and low noise models derived based on recordings from 75 worldwide distributed seismic stations are also displayed (Peterson, 1993). It can be seen that the geophone's noise levels are well within the limits of global high and low noise models over the frequency range of ~0.1 to 10 Hz. In contrast, the MEMs noise levels are clearly above the global high noise model over the entire frequency range of interest due to high level of instrumental self-noise. Such levels of high background noise would indeed effects the earthquake detectability of such acceleration sensors.

To further explore the effects of background noise on earthquake detectability, we plotted the median levels of background noise along with typical ground-motion amplitudes for various size earthquakes at different source-to-site distances (Figure 2). It can be seen that, on average, local and/or regional earthquakes with magnitudes as low as M~2.0 can be detected by the geophone at the RVO station. Conversely, only local and/or regional earthquakes with magnitudes larger than

M_W~4.5 can be detected by MEMs sensor. Overall, this may suggest the appropriateness of RS4D device, i.e. combination of geophone and MEMS sensors, for urban seismic monitoring purposes. However, it should be noted that the displayed "typical ground-motion amplitudes" are actually reflecting the characteristics of the ground-motion database from which these average amplitudes are computed. Hence, they may not necessarily reflect the characteristics of station specific earthquake recordings. In addition, the computed noise model here is only representing the background noise at RVO station and is not necessarily a valid model for other recording stations. Ideally similar analysis should be carried out at any location of interest.

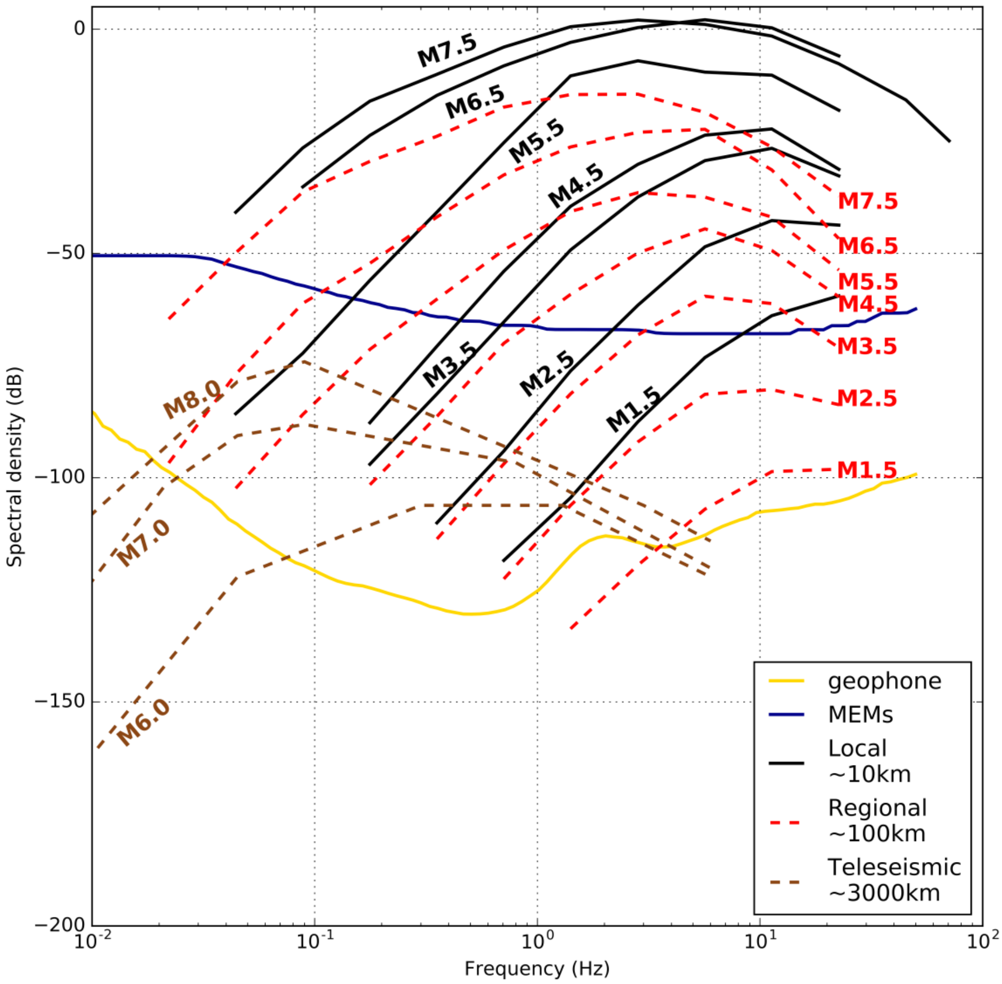

Figure 2. The mean background noise level of geophone and MEMs sensors measured at RVO station. The typical ground-motion amplitudes for various size earthquakes at different source-to-site distances are also displayed (adapted from Clinton & Heaton (2002)).

Quality of earthquake recordings

To assess the quality of the recordings, we compared the registered earthquake waveforms by RS4D device with those from standard seismic instruments, i.e. STS-2 broadband seismometer, and Kinemetrics accelerometer. Such comparisons are performed quantitatively by calculating time-frequency (TF) misfit functions based on Kristeková *et al.* (2006) methodology. Following this approach, for each earthquake the reference time-series (i.e. a record from standard seismic instrument), and corresponding record by RS4D device are represented in TF domain using the continuous wavelet transform. In this way the envelope (amplitude) misfit and the phase misfit can be quantified separately in both time and frequency domains through a series of goodness-of-fit (GOF) criteria defined by Kristeková *et al.* (2009). Table 1 summarises all of the GOF measures to compare waveforms in TF domain in a quantitative way. Each of the GOF measures ranges from 0, (i.e., no fit) to 10 (i.e., perfect fit) based on the corresponding amplitude and phase misfits (Table 2).

Table 1: Definitions of goodness-of-fit (GOF) criteria

Criteria	Description
TEG	GOF of envelope (amplitude) in time domain
FEG	GOF of envelope (amplitude) in frequency domain
TFEG	GOF of envelope (amplitude) in time-frequency domain
EG	Overall GOF of envelope (amplitude)
TPG	GOF of phase in time domain
FPG	GOF of phase in frequency domain
TFPG	GOF of in time-frequency domain
PG	Overall GOF of phase

Table 2.GOF values along with corresponding misfit values (adapted from Kristeková *et al.* (2009)).

Misfit envelope	Misfit phase	GOF	
		Value	Description
±0.00	±0.0	10	
±0.11	±0.1	9	excellent
±0.22	±0.2	8	
±0.36	±0.3	7	good
±0.51	±0.4	6	
±0.69	±0.5	5	fair
±0.92	±0.6	4	poor

In this study we analysed earthquake waveforms of 12 events that were recorded during the operational period of RS4D device. For demonstration purposes we only present the results for a shallow, M_W 6.0 earthquake on 2018/05/09, and one of its aftershocks that occurred shortly after the mainshock. The mainshock is located in New Britain region, ~200 km away from RVO station, while the location and magnitude of the following aftershock is unknown. Figure 3 compares the mainshock record by broadband seismometer with that recorded by short-period geophone, in time domain. Computed TF domain GOF measures are also displayed. It is evident that there is an excellent agreement among selected time-series in terms of phase match over the whole TF domain, with overall PG value of 9.68 out of 10. The results also indicate a good agreement in terms of amplitude match over the selected TF domain. Furthermore, the match is excellent in the frequency range of 0.5 to 10 Hz (i.e., the nominal flat region of the geophone's amplitude response). In this case the main differences are observed at frequency range of 0.1-0.2 Hz due to arrival of long-period surface waves at ~45 sec after the P-wave arrival time.

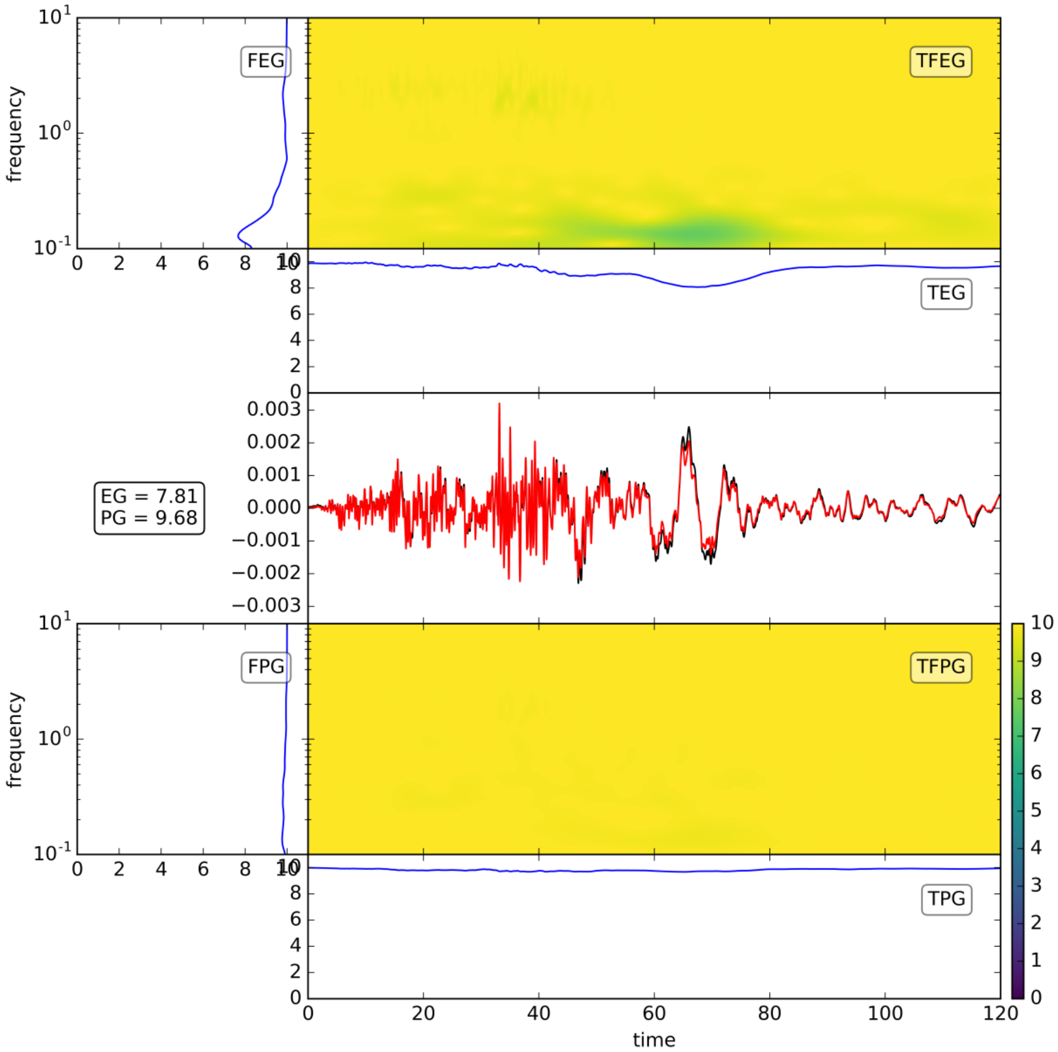

Figure 3. Comparison of the velocity time-series from the 2018-05-09 mainshock recorded by broadband seismometer (in black) and short-period geophone (in red). Computed GOF measures are also displayed (see Table 1. & 2. for details)

Figure 4 summarizes the comparison results between the mainshock time-series by Kinemetrics accelerometer with that recorded by MEMs sensor. Again an excellent agreement can be observed in terms of phase match with overall PG value of 8.67 out of 10. In terms of amplitude comparison, overall there is a good agreement among displayed waveforms in the frequency range of 0.1-10 Hz with an excellent match for the frequencies above 0.3 Hz. The mismatch, mainly at frequency range of 0.1-0.3 Hz, can be attributed to the high level of instrumental self-noise of MEMs sensor. Finally, Figure 5 compares the aftershock waveform recorded by broadband seismometer with that by short-period geophone. Similar conclusions as Figure 3 can be made. However, here the whole aftershock record is contaminated by the long-period waves of the mainshock with frequencies <~0.2 Hz. Also slight mismatch can be observed at frequencies ~1.0-2.0 Hz that can be attributed to the relatively high level of RS4D geophone's noise at these frequencies (Figure 1).

All of the selected events were processed following the above procedure and the time-histories were very consistent in the valid frequency ranges. In particular, there was typically an excellent phase match over the entire selected TF domain, and generally excellent amplitude match at frequencies larger than ~0.3 and ~0.5 for MEMs and geophone sensors, respectively.

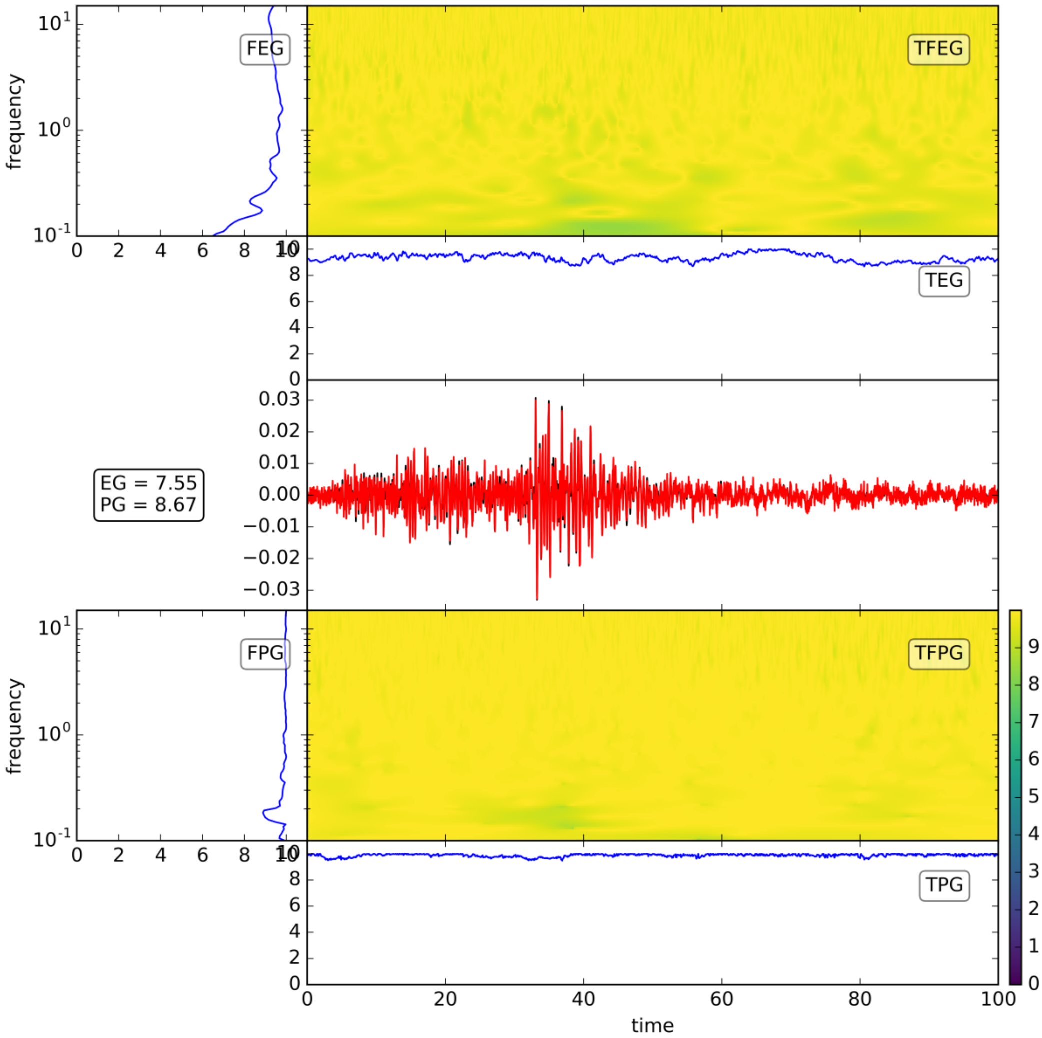

Figure 4. Comparison of the acceleration time-series from the 2018-05-09 mainshock recorded by the Kinematrics accelerometer (in black) and MEMs sensor (in red). Computed GOF measures are also displayed (see Table 1. & 2. for details)

CONCLUSION

Given its high level of earthquake hazard and associated risks, PNG would benefit from a dense seismic monitoring network for rapid (near real-time), as well as long-term, earthquake hazard and risk assessment. Since 2013, the PMGO has operated and maintained a seismic network of 10 stations with co-located velocity seismometers and accelerometers. However, given the high costs associated with the installation and maintenance of the PMGO's seismic stations, it is impossible to densify the current network to a standard commensurate with other network stations in the near future. To address this issue, we explored the feasibility of establishing a low-cost, community-based seismic network in PNG by first verifying the performance of the low-cost RS4D device, which includes a three-component strong-motion MEMs accelerometer and one (vertical) short-period geophone. During the operational period of one month, a RS4D device was collocated with observatory-quality seismic instruments at RVO station. A key challenge for this experiment was the rather poor data service by local telecommunication operators as well as frequent power outages which caused repeated data gaps. Furthermore given the relatively high cost of the data service in PNG, it is not feasible for government agencies such as RVO and PMGO to host a permanent low-cost sensor continuously relaying data in real-time. In future work, we are seeking locations with reliable yet free of charge internet service, such as bank buildings, to host RS4D devices.

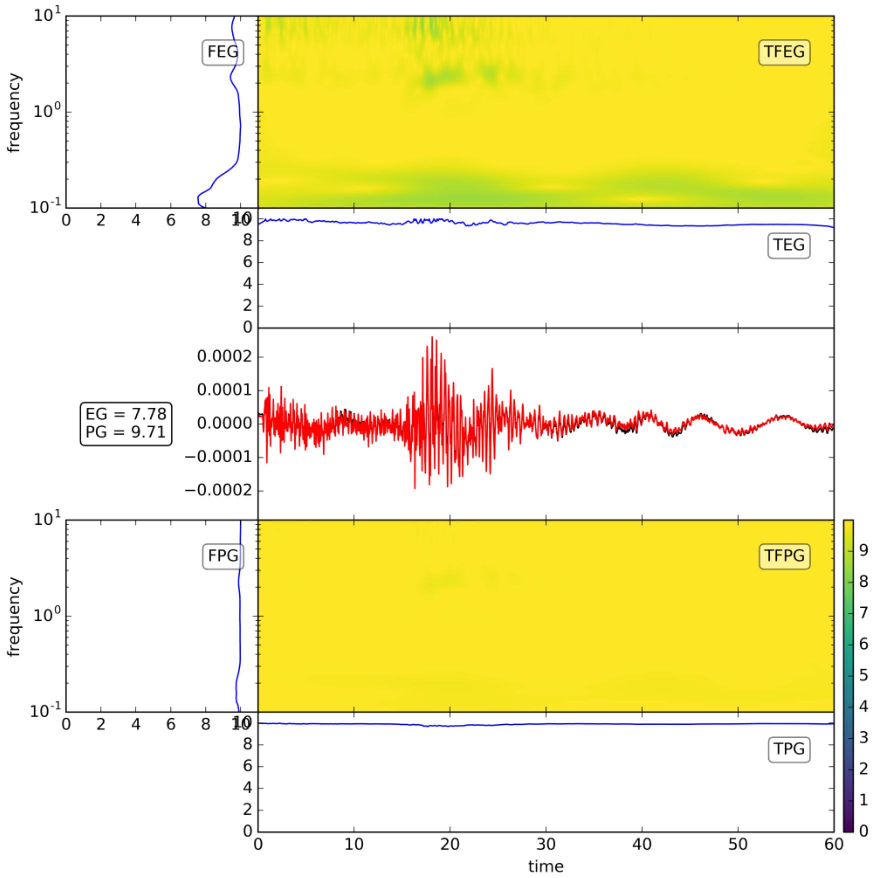

Figure 5. Comparison of velocity time-series recorded from the 2018-05-09 aftershock by broadband seismometer (in black) and short-period geophone (in red). Computed GOF measures are also displayed (see Table 1. & 2. for details)

Due to the frequent data gaps, a background noise model for RS4D device at RVO station was derived based on only two days continuous data with no gaps. Individual noise models were derived for short-period geophone and MEMs sensors. The results indicate that the geophone's noise levels are well within the limits of global high and low noise models over the frequency range of ~0.1 to 10 Hz. In contrast, the MEMs noise levels are clearly above the global high noise model over the entire frequency range of interest due to high level of instrumental self-noise. Comparisons of the noise models with typical ground-motion amplitudes for various size earthquakes at different source-to-site distances, revealed the overall appropriateness of RS4D device for urban seismic monitoring purposes.

We also quantitatively verified the performance of RS4D device by comparing the recorded earthquake time-series with those from observatory-quality seismic instruments. Unfortunately data gaps limited this analysis to 12 events occurring at regional distances from the RVO station. Overall, the results demonstrated an excellent phase match over the entire selected TF domain, and generally excellent amplitude match at frequencies larger than ~0.3 Hz and ~0.5 Hz for MEMs and geophone sensors, respectively.

Also noted was the relatively low level of ambient seismic noise at RVO station that may not represent a common urban environment. Future work includes deployment of RS4D devices at major cities such as Lae city to further explore the performance of such sensors for urban monitoring and situational awareness (i.e., *ShakeMap*) applications.

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In this study we used Obspy toolbox (Megies *et al.*, 2011) for analysing the waveforms. This article is published with the permission of the CEO, Geoscience Australia.

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