Earthquake Early Warning in Kathmandu

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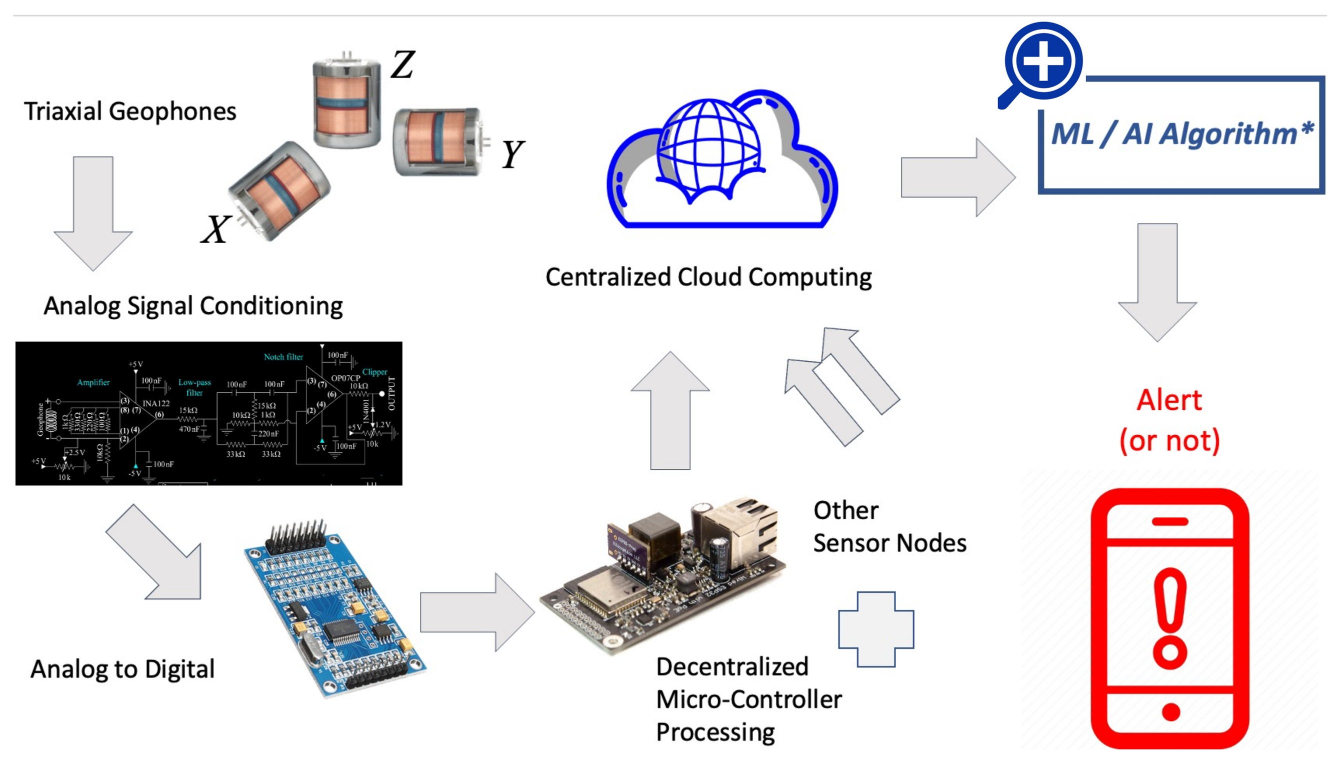
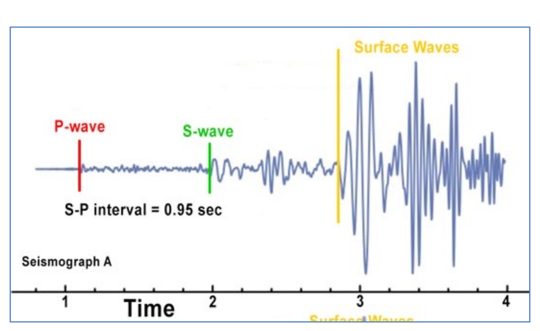
Introduction

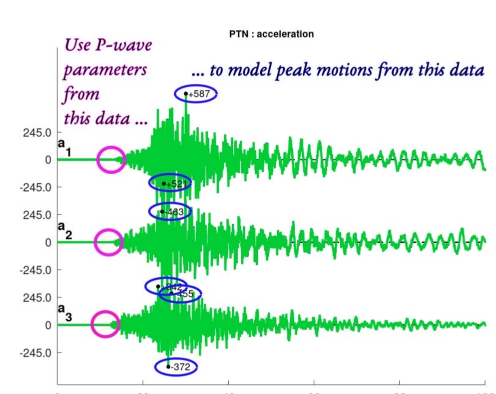
- The 2015 Gorkha Earthquake[1], which caused 9,000 deaths and 100,000 injuries, highlighted the necessity for an on-site earthquake early warning system in Kathmandu, Nepal.
- Our partner Bass Connections team is working on implementing suitable on-site earthquake warning sensors that will use Machine Learning methods developed from our proof-of-concept study.
- In this project, our Machine Learning Models use the faster, less intense P-waves to warn about the stronger surface Waves.



Objectives

- Relate **waveform characteristics** from the **initial moments** of shaking to **predict expected shaking** at the monitored site by using **Gaussian process regression.**





- Investigate the **Gaussian process regression** to see if it is **a better predictive model** than the currently-used **linear regression method[2].**

Methods

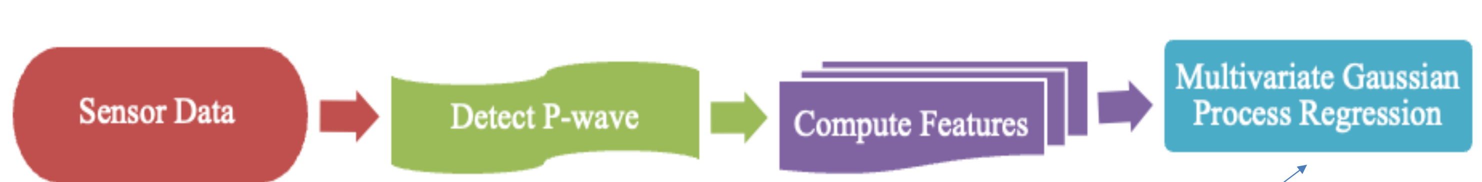


Table 1 **Regional earthquakes recorded during 2010-2019**

Nr	Date D/M/Y	UTC time hh:mm:ss	M	Lat N	Long W	Depth km	Δ km
1	10/01/2010	00:27:38	6.5	40.640	124.760	21.7	950

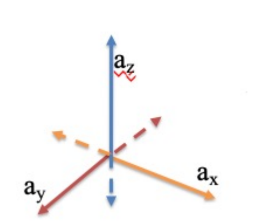
Our Raw Data: Zaicenco & Wier-Jones, “Reducing False Positives in the On-Site and Regional Earthquake Early Warning Systems,” *2019 SSA Annual* Meeting.

```
     PGV       PGA
1.133815  2.428995
1.417162  2.505093
```

Predictor Features:
5D Input

Response Features:
2D Output

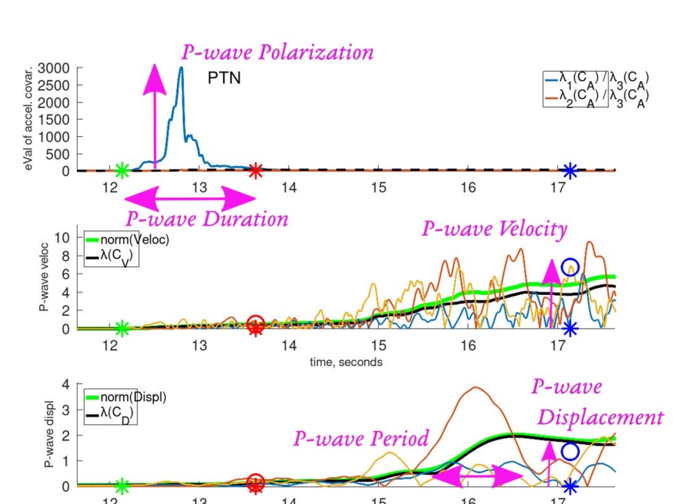
```
      Pa         Pv         Pd      durP      tauP
1.129946  -0.035267  -0.543730  0.688061  0.285557
0.358292  -1.252666  -1.070777  0.845499  0.296665
```

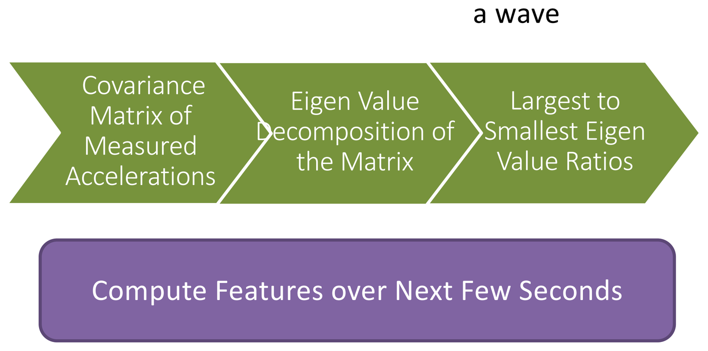


Triaxial Records of Acceleration

P-waves are highly polarized

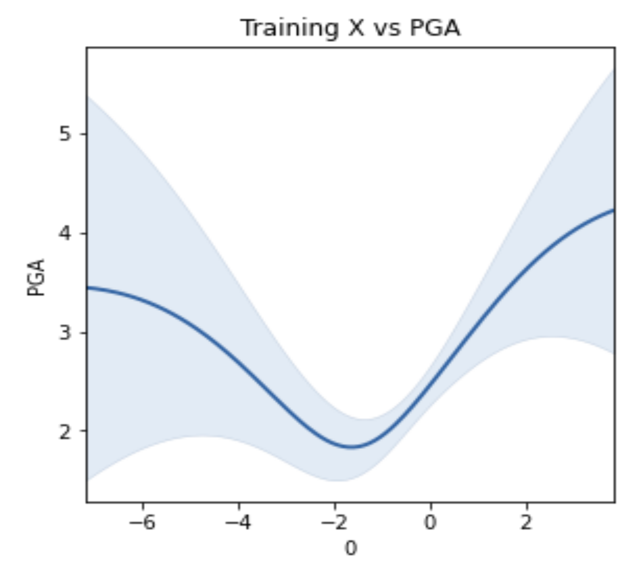
Eigenvectors are useful for evaluating polarized nature of a wave





Gaussian Process Regression (GPR)

- The Gaussian Process Regression models the data as an infinite dimensional Multivariate Normal Distribution with the covariance between points being computed using the **kernel function**.
- Predictions on unseen points are made by conditioning on the distribution of known data. They are in the form of individual Gaussian Distributions with corresponding **means and variances (quantifying uncertainty).**
- GPR can also be implemented to model **multi-output** data.



The joint distribution of **f** and **f**. is expressed as

$$\begin{bmatrix} y \\ y_* \end{bmatrix} = \mathcal{N}\left(\begin{bmatrix} m(X) \\ m(X_*) \end{bmatrix}, \begin{bmatrix} K & K_* \\ K_*^T & K_{**} \end{bmatrix}\right),$$

where $\mathbf{K} = K(\mathbf{X},\mathbf{X})$, $\mathbf{K}_* = K(\mathbf{X},\mathbf{X}_*)$ and $\mathbf{K}_{**} = K(\mathbf{X}_*,\mathbf{X}_*)$. And the mean $(m(\mathbf{X}), m(\mathbf{X}_*)) = \mathbf{0}$.

Expansion of Kernel Matrix would be:

$$y = \mathcal{N}\left(\mathbf{0}, \begin{bmatrix} k(x_1,x_1)+\sigma_n^2 & k(x_1,x_2) & \dots & k(x_1,x_n) \\ k(x_2,x_1) & k(x_2,x_2)+\sigma_n^2 & \dots & k(x_2,x_n) \\ \vdots & \vdots & \ddots & \vdots \\ k(x_n,x_1) & k(x_n,x_2) & \dots & k(x_n,x_n)+\sigma_n^2 \end{bmatrix}\right)$$

- We used the python package **GPy[3]** from SheffieldML. We tested permutations of GPR models and used the best performing one, a single output regression incorporating a matern3/2 kernel function and a length scale of one, to compare with Linear Regression.

Results

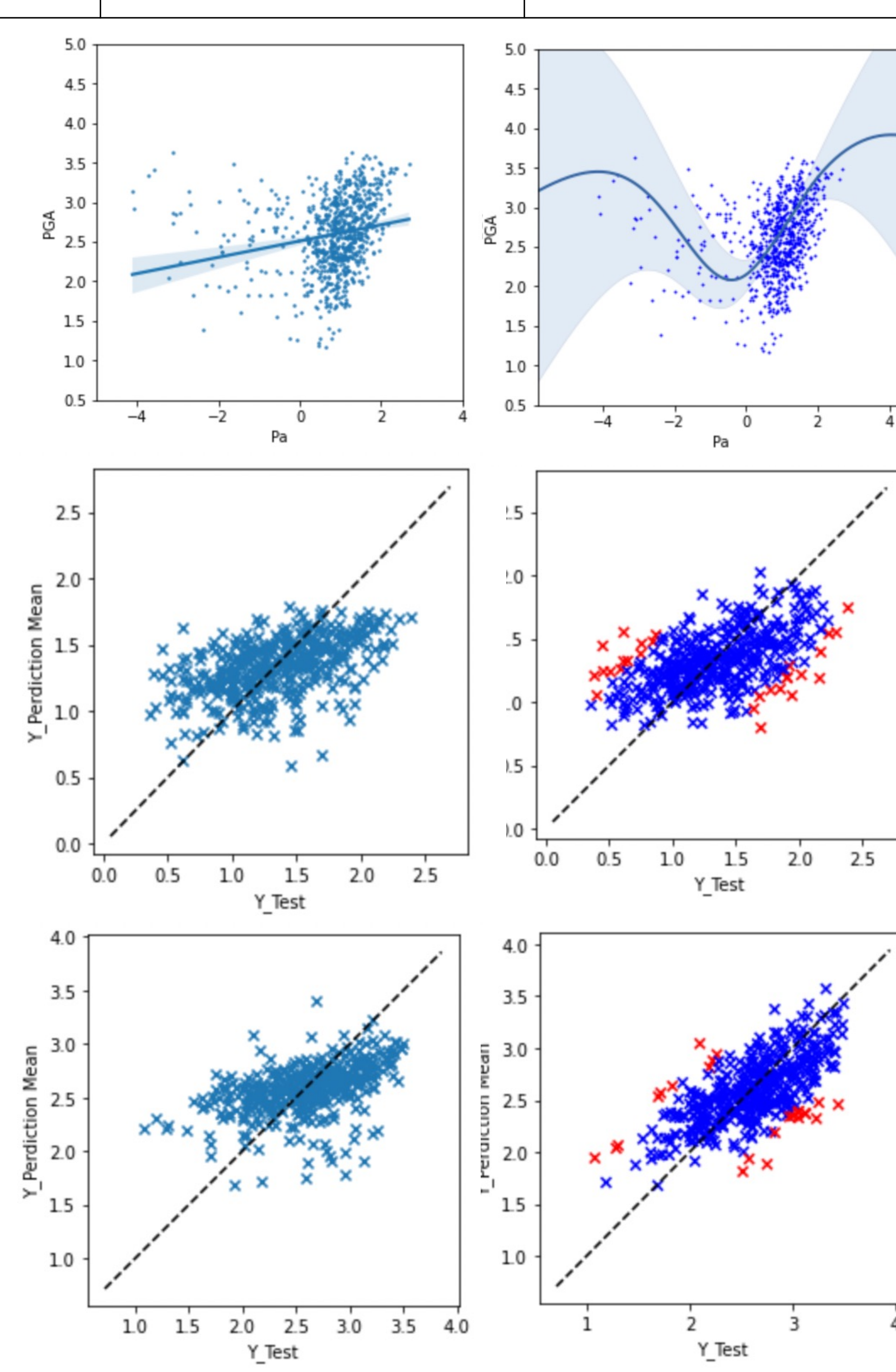
GPR outperforms linear regression on the metrics: Area Under the ROC Curve (AUC), and the log likelihood on the test set. The figures below help to visualize model performance of LR and GPR:

Comparison Metrics	Linear Regression Model	GPR
AUC	0.75	0.82
Log likelihood	0.48	0.31

Model Plotted with Training Data

Actual vs Predicted Plots PGV

Actual vs Predicted Plots PGA



Acceptable points are closer to line y=x

Blue points are within the acceptable uncertainty (1.96 *std) boundary

Discussion

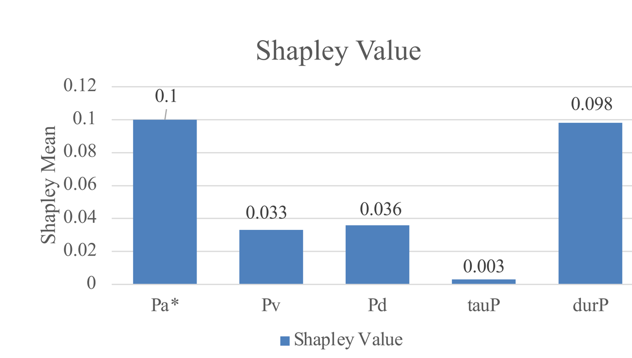
Variable importance:

To investigate which of the five input features influence the model most, we implemented two methods:

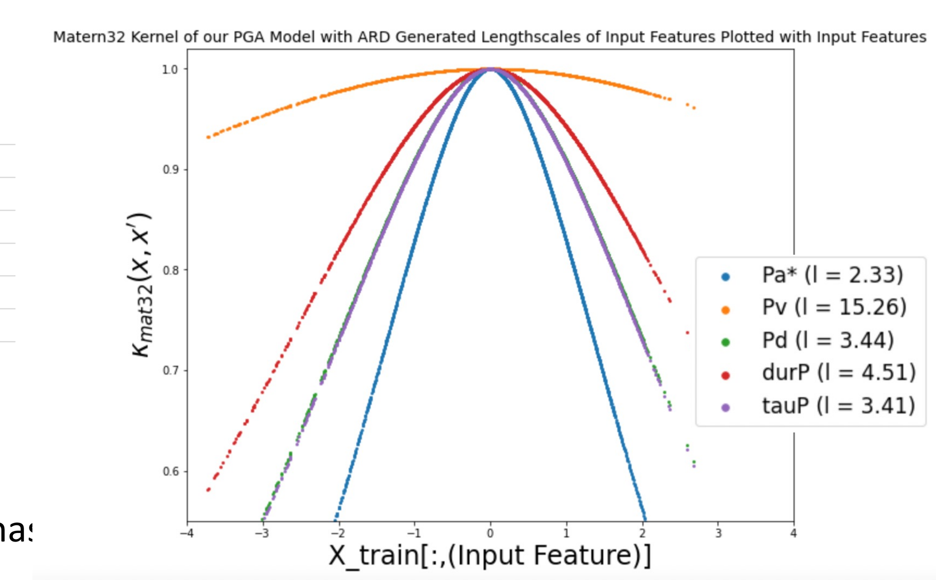
i. Shapley value: The Shapley value is the marginal contribution of one feature averaged over all possible combinations of features. Larger shapely value denotes larger marginal contribution, and hence it is associated with higher variable importance.

ii. Length scale: For an anisotropic Gaussian process, the length scale of a kernel (length from mean to an extreme point of curve) is not even across all input dimensions. Lower length scale implies steeper slope of the kernel function which is means that a small change in the input dimension corresponds with a larger change in the kernel function. Hence, smaller length scale is associated with larger variable importance.

Both of the methods indicated that Pa is the most important variable.



Shapley: Pa (Peak Acceleration) has the highest Shapley value.



Lengthscale: Pa (Peak Acceleration) has the lowest lengthscale.

Mercalli Index[4]:

- The Mercalli Intensity Scale is a scale used to quantify earthquakes intensity based on the danger posed by shaking felt at a location.
- Here, we group Mercalli Scales into “Weak”, “Medium”, and “Strong” and evaluate our models based on how well they can classify earthquakes into these categories.

Mercalli Index Confusion Matrix (%)

Actual \ Predicted	Weak	Medium	Strong
Weak	1.23	7.34	0.00
Medium	0.99	49.01	7.40
Strong	0.00	16.50	17.49

	True Positive Rate	True Negative Rate	Accuracy
Medium + Strong	0.98	0.17	91.67
Strong	0.51	0.89	76.10

True Positive Rate: True Positive / (True Positive + False Negative)
True Negative Rate: True Negative / (True Negative + False Positive)
Accuracy: (True Positive + True Negative) / (Sum of all predictions)

References

[1] Goda K, Kiyota T, Pokrel RM, et. al. The 2015 Gorkha Nepal earthquake: insights from earthquake damage survey. Front. Built Environ. June 2015. DOI: 10.3389/fbuil.2015.00008

[2] Colombelli S, Caruso A, Zollo A, Festa G, Kanamori G. A P wave-based, on-site method for earthquake early warning. Geophysical Research Letters. Mar 2015.

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[3] GPy. GPy: A Gaussian Process Framework in python. http://github.com/SheffieldML/GPy. 2012.

[4] Gutenberg B, Richter CG. Earthquake magnitude, intensity, energy, and acceleration. - Bulletin of the Seismological Society of America. July 1942. DOI: 10.1785/BSSA0320030163.

Acknowledgements:

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