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Distributed travel-time seismic tomography in large-scale sensor networks

Goutham Kamath [a,*], Lei Shi [a], Wen-Zhan Song [a], Jonathan Lees [b]

[a] Department of Computer Science, Georgia State University, United States

[b] Department of Geological Sciences, University of North Carolina at Chapel Hill, United States

HIGHLIGHTS

- We present a distributed method to obtain seismic image on wireless sensor networks.
- We perform in-network computing and avoid data gathering.
- High resolution image can be obtained using proposed multi-resolution scheme.
- We evaluate the method using synthetic seismic data in a CORE emulator.
- Our method is able to recover velocity model of Mt. St. Helens.

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ABSTRACT

Current geophysical techniques for visualizing seismic activity employ image reconstruction methods that rely on a centralized approach for processing the raw data captured by seismic sensors. The data is either gathered manually, or relayed by expensive broadband stations, and then processed at a base station. This approach is time-consuming (weeks to months) and hazardous as the task involves manual data gathering in extreme conditions. Also, raw seismic samples are typically in the range of 16–24 bit, sampled at 50–200 Hz and transferring this high fidelity sample from large number of sensors to a centralized station results in a bottleneck due to bandwidth limitations. To avoid these issues, a new distributed method is required which processes raw seismic samples inside each node and obtains a high-resolution seismic tomography in real time. In this paper, we present a component-averaged distributed multi-resolution evolving tomography algorithm for processing data and inverting volcano tomography in the network while avoiding centralized computation and costly data collection. The algorithm is first evaluated for the correctness using a synthetic model in a CORE emulator. Later, our proposed algorithm runs using the real data obtained from Mt. St. Helens, WA, USA. The results validate that our distributed algorithm is able to obtain a satisfactory image similar to centralized computation under constraints of network resources, while distributing the computational burden to sensor nodes.

1. Introduction

Current volcano data collection and monitoring systems lack the capability of obtaining real time information and recovering the physical dynamics of seismic activity with sufficient resolution. At present, the seismic tomography process involves aggregation of raw data from seismic sensors into a centralized server for post-processing and analysis. The raw seismic samples are typically in the range of 16–24 bit at 50–200 Hz. This process of high precision sampling from each node makes it extremely difficult to collect raw, real-time data from a large-scale dense sensor network due to severe limitations on energy and bandwidth. Due to these constraints, volcanologists worldwide use less than 20 stations on many of the threatening active volcanoes [30], limiting our ability to understand dynamics and physical processes of volcanoes in real-time. The centralized solution also introduces a computational bottleneck and increases the risk of data loss in case of node failures. With the advancement in sensor technology it is now possible to deploy and maintain a large-scale network for environmental monitoring and surveillance. However, currently used

* Corresponding author.
E-mail addresses: gkamath1@student.gsu.edu (G. Kamath), lshi1@student.gsu.edu (L. Shi), wsong@gsu.edu (W.-Z. Song), jonathan.lees@unc.edu (J. Lees).

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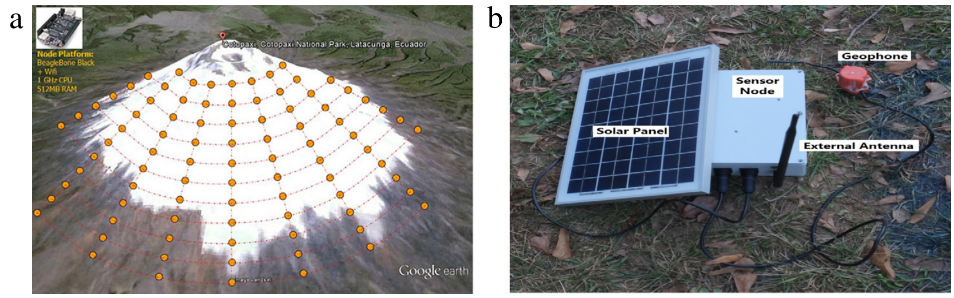

Fig. 1. (a) Illustration of our proposed deployment. (b) Our custom designed station (OpenNode) along with solar panel, geophone and external antenna.

tomography inversion algorithms cannot be easily implemented under this distributed scenario, as they are designed for the centralized processing. Thus, real-time volcano tomography requires a practical approach which is distributed, scalable, and efficient with respect to current tomographic methods.

1.1. State of the art

At present, tomography inversion methods rely on centralized methods where data gathered by instruments is manually collected and transferred to a centralized unit for further processing. This scheme has been implemented on a number of volcanoes including Mount St. Helens [24] and Mount Rainier. Currently, the seismic community faces two major hurdles in order to obtain both real-time and high-resolution tomography. First, the data logged at each station is of high fidelity, and due to limited communication bandwidth, information from only a small number of sensors can be obtained for real time imaging. With limited sensors, high resolution tomographic images cannot be obtained. On the other hand, large arrays of sensors can be deployed to obtain high-resolution tomography as proposed by iMush[1] project. However, limited bandwidth restricts the transfer of large volume of data from these sensors, in which case seismologists resort to manual data gathering which takes months for post processing and imaging. To obtain high resolution and real time imaging we need a large number of sensor stations which have the capability of performing in-network computing and also avoid expensive data collection. The authors in [26] have discussed the use of low-cost sensors for P-wave arrival time picking and earthquake location. The earthquake hypo-center detection forms the basic step for seismic tomography and we extend this further to obtain in-network imaging. Here, we assume that the sensors used are low-cost and have low computational power e.g. Raspberry Pi/Beagle-Bone/Android.

1.2. Contributions and outline

Our project aims at constructing high resolution seismic tomography using large dense array of stations as shown in Fig. 1(a). Fig. 1(b) shows a seismic station that consists of a geophone (vibration recording sensor), MSP430/BeagleBone Black acts as a computational unit and Xbee radio which acts as a low power communication module. The stations are powered by battery and solar panel.

This paper mainly focuses on building a distributed algorithm suitable for performing in-network tomographic inversion. Here we present a Component-Averaged Distributed Multi-resolution Evolving Tomography (CA-DMET) algorithm to compute tomographic inversion in a distributed fashion without sending the raw data to a centralized location. The sensor nodes deployed use the arrival times of seismic events and earthquake locations to derive a 3D tomographic model of the velocity structure within the volcano. As more earthquakes are recorded, the velocity model evolves over time to refine the existing one. To our best knowledge of literature, our work is the first attempt to perform seismic tomography in sensor networks. The algorithm proposed here has application to fields far beyond the specifics of volcanoes, e.g., oil field explorations have similar problems and needs.

The rest of the paper is organized as follows. Section 2 presents the background knowledge of seismic tomography, while in Section 3 we formulate the tomography problem. In Section 4, we discuss the related works of distributed algorithms in wireless sensor networks. The algorithm and design of distributed tomography inversion are presented in Section 5. Synthetic data simulation results are obtained in Section 6. Results from Mt. St. Helens are presented in Section 7. Discussions and future work are presented in Section 8. We then conclude the paper in Section 9.

2. Seismic tomography background

Tomography can be defined as the science of computing reconstructions in 2D and 3D from projections, i.e., solving the system of linear equations obtained by integrations along the rays that penetrate a domain Ω, typically a rectangle in 2D, and a box in 3D. In this paper we use first-arrival travel time of the p-wave (primary wave) to derive the internal velocity structure of a volcano. Fig. 2(a) shows the sample of p-wave obtained at four different stations and the blue line indicates its corresponding arrival time. Next, we explain four basic principles involved in travel-time seismic tomography.

(i) P-wave arrival-time picking: P-waves travel faster than any other waves though the earth and are the first to be recorded in the seismic sensors. Inside the earth, density varies due to the presence of different layers and materials. These cause the seismic waves to travel at different velocities in different directions as shown in Fig. 2(b). By picking the arrival time of the p-wave at different stations we can obtain the difference in the propagation delay. Picking arrival time is inherently distributed and authors in [26] have proposed methods to automatically pick the arrival time which can be implemented on each station.

(ii) Event location: Once the arrival times of p-waves have been detected by each station, their differences can be used to obtain the exact location and the origin time of the earthquake. Geiger's [12] method is used to calculate the event location along with origin time and it requires travel time differences from at least four different stations. This method is one of the classic and widely used event localization schemes to obtain the exact location and time.

(iii) Ray tracing: This is the technique used to find the ray paths between the seismic source locations (earthquake) and the receiver nodes with minimum travel time, following an event.

[1] http://imush.org/.