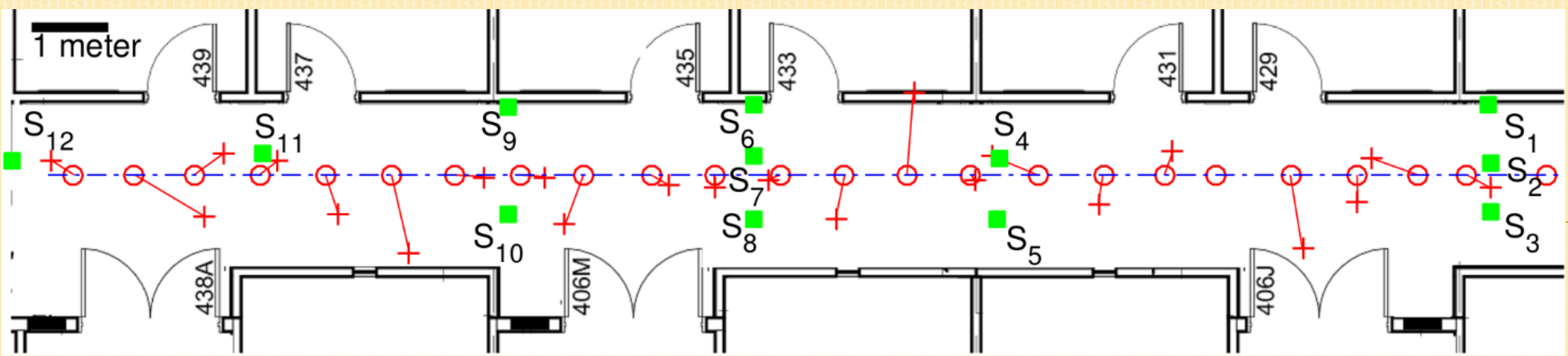
I-LoViT

Indoor Localization via Vibration Tracking



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Invent the Future®

Why create another technique for indoor localization?

- **The difficulties of indoor localization by means of GPS or cellular-based methods are well known and prompted many other approaches:**
  - **UWB, Bluetooth beacons, RFID proximity to RFID readers, many Wi-Fi schemes, smartphone accelerometer/gyro INS,…**

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  → Significant privacy concerns
- It would be preferable to offer an ambient localization service free of any demands on the building occupants

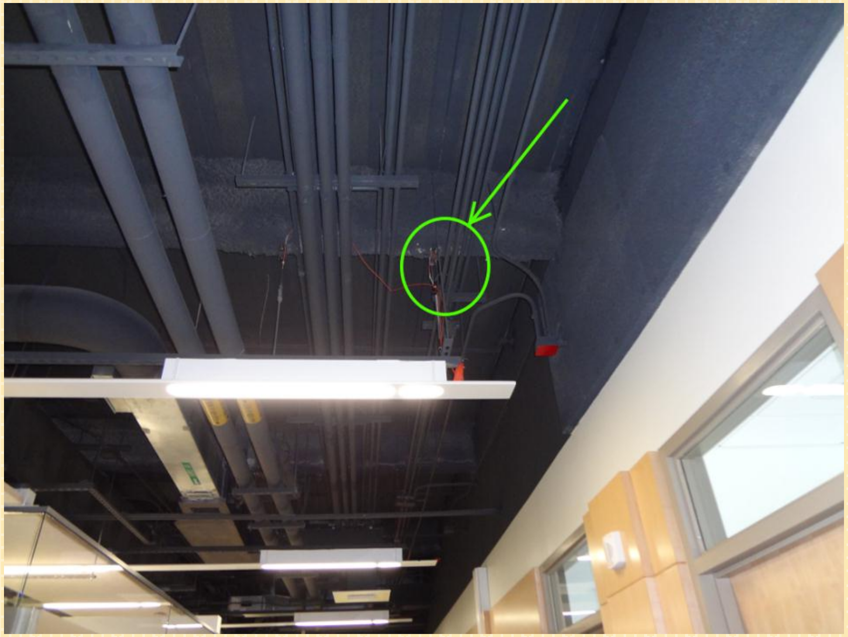
The proposed solution measures footstep vibrations with smart building accelerometers for localization

- **Here "smart building" draws from a mature technology developed in civil and mechanical engineering:**
  - **Pioneering work by Kuroiwa in the 1960s instrumented buildings to measure seismic response**
- **The footstep localization is an emergent cyber physical system, a new role for an existing sensor network**

Virginia Tech's Goodwin Hall is the smart building for validating algorithms created in this research

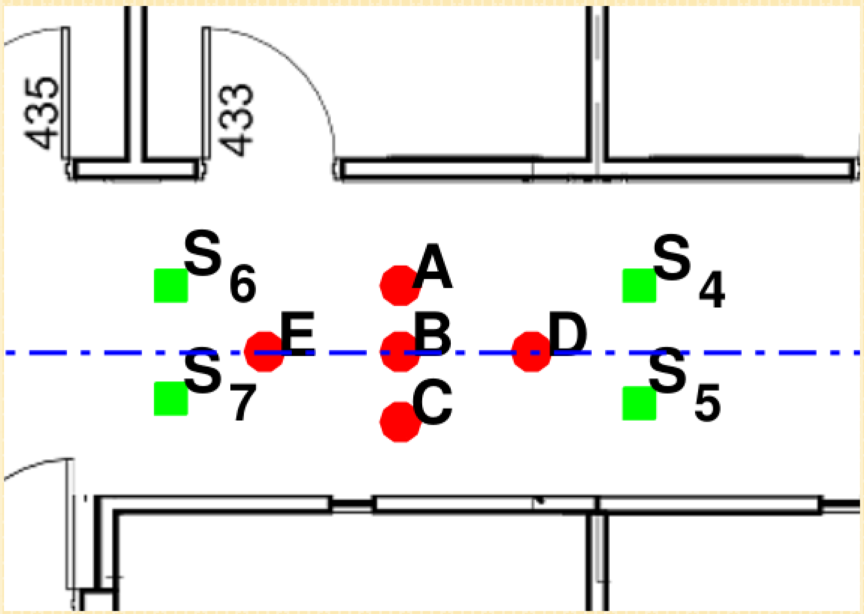
- **Installation of 200+ vibration sensors complied with building codes for a public building**

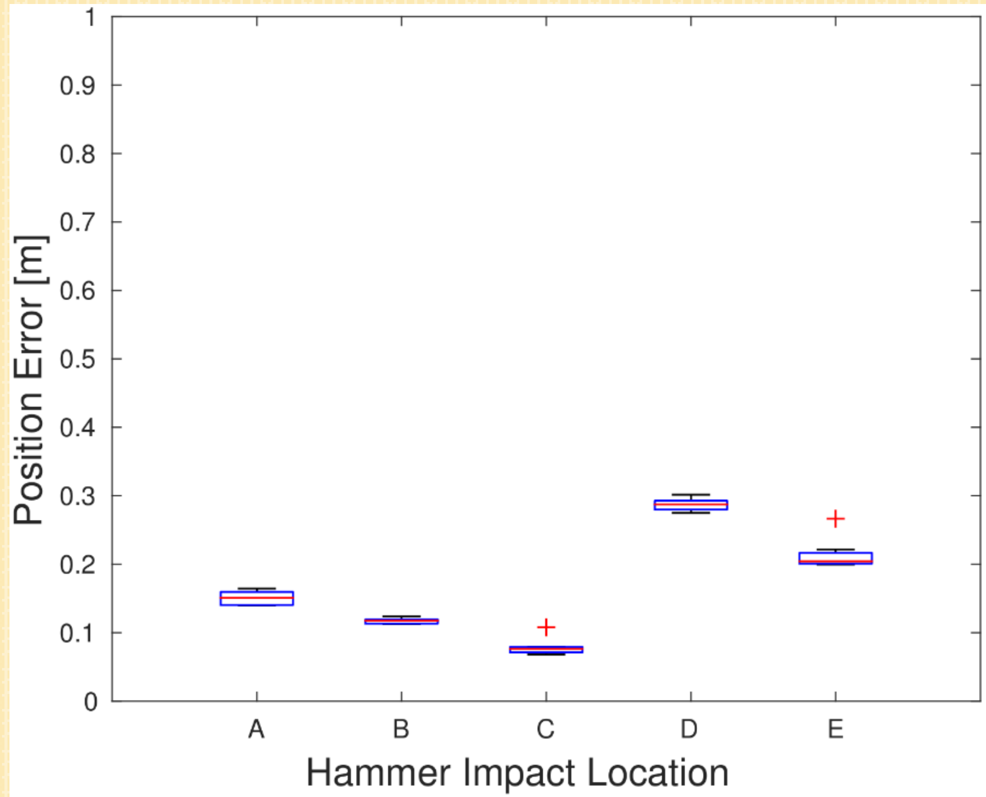
- **The sensors were mounted to steel girders supporting concrete floor slabs**



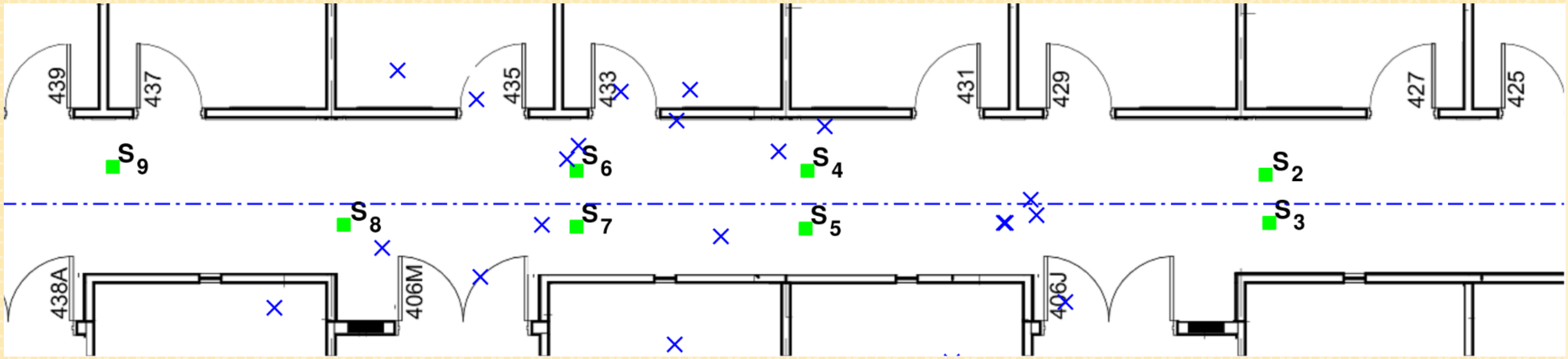
Initial testing with conventional TDOA applied to measured hammer impacts appeared promising

- **Localization of floor impacts (●) from an instrumented hammer appeared to offer sub-meter accuracy from a conventional TDOA algorithm, with suitable sensor choice, geometry, etc.**





Attempting to localize footsteps over larger areas resulted in estimation errors of many meters . . . What happened?



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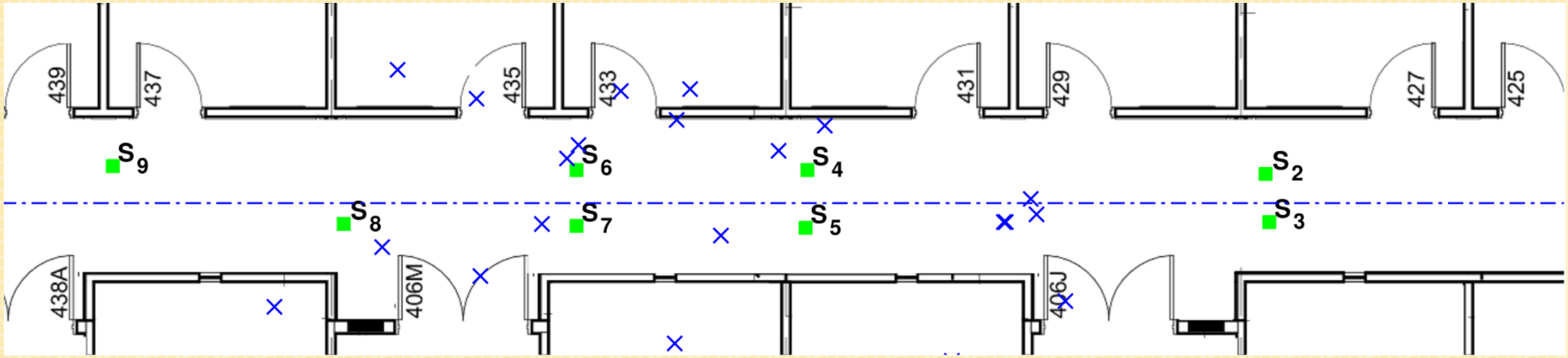
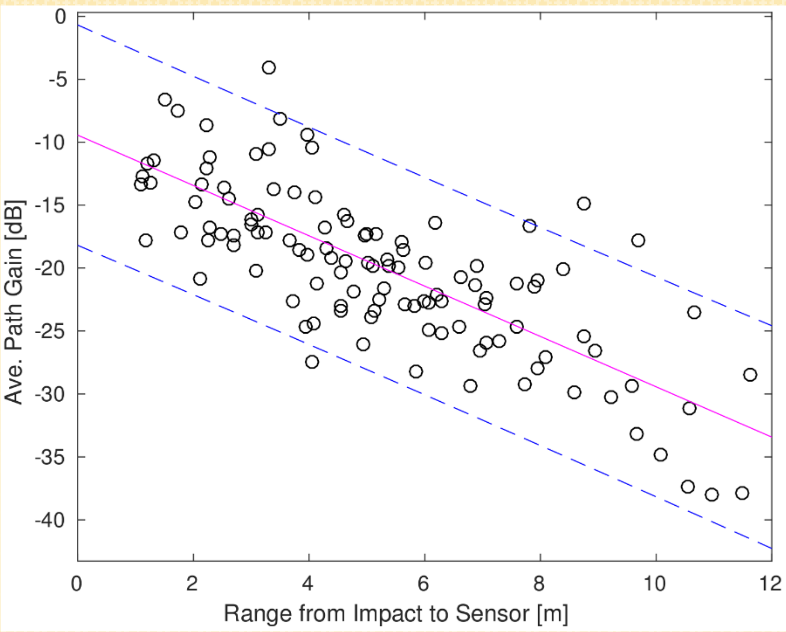


- **Initial investigation worked within the framework of conventional TDOA**
  - **Detectability: TDOA needs at least 4 detections for unambiguous estimates**
  - **Localizability: Both measurement error and sensor geometry (“GDOP”) influence accuracy of multilateration**

Detections generated by a footstep template matched filter

Prior impact measurements enable prediction of how footstep vibrations attenuate with distance



Given received signal, instrument noise and a decision threshold γ_{th} the following can be computed

<u>Probability of detection</u>

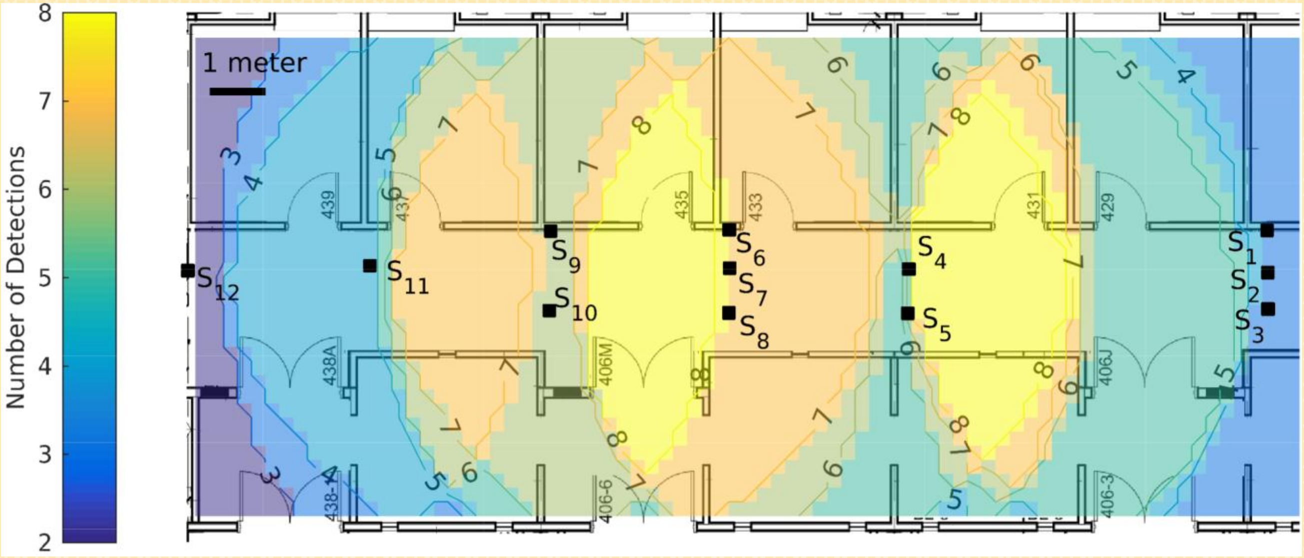
$$P_D = \mathrm{Q}\left(\frac{\gamma_{th} - E_S}{\sqrt{\sigma_N^2 E_S}}\right)$$

<u>Probability of false alarm</u>

$$P_{FA} = \mathrm{Q}\left(\frac{\gamma_{th}}{\sqrt{\sigma_N^2 E_S}}\right)$$

Detections generated by a footstep template matched filter; Plot shows semi-analytical forecast of detectability

- **Plot shows number of sensors having** $P_D \geq 0.9, P_{FA} = 10^{-3}$



- **Most of the positions in the hall would satisfy the need of at least 4 detections required by TDOA.**

Localizability performance quantified by means of the Cramér-Rao Lower Bound (CRLB)

- **An unbiased estimator of footstep coordinates θ has a variance no better than the CRLB:**

$$\mathsf{Var}(\hat{\boldsymbol{\theta}}) \geq \mathsf{FIM}^{-1}(\boldsymbol{\theta}), \quad \mathsf{FIM}\left(\boldsymbol{\theta} : [\theta_i, \theta_j, \ldots]^\mathsf{T}\right) = -\mathsf{E}\left(\frac{\partial^2 \log p(\boldsymbol{x}|\boldsymbol{\theta})}{\partial \theta_i \theta_j}\right)$$

FIM: Fisher Information Matrix

- **For TDOA the FIM has the form:** $\mathsf{FIM} = \left[\frac{\partial f_{\mathrm{TDOA}}(\boldsymbol{x})}{\partial \boldsymbol{x}}\right]^\mathsf{T} \boldsymbol{C}_N^{-1} \left[\frac{\partial f_{\mathrm{TDOA}}(\boldsymbol{x})}{\partial \boldsymbol{x}}\right]$

- **The localization accuracy is constrained by both the measurement uncertainty (covariance C_N) and the cofactor of Geometric Dilution of Precision (GDOP)**

Geometric Dilution of Precision (GDOP) can be expressed as ratio relative to other TDOA error sources

$$\text{GDOP ratio} = \sqrt{\text{Tr}\left(\text{FIM}^{-1}\right)}/\sigma_{\text{TDOA}}$$

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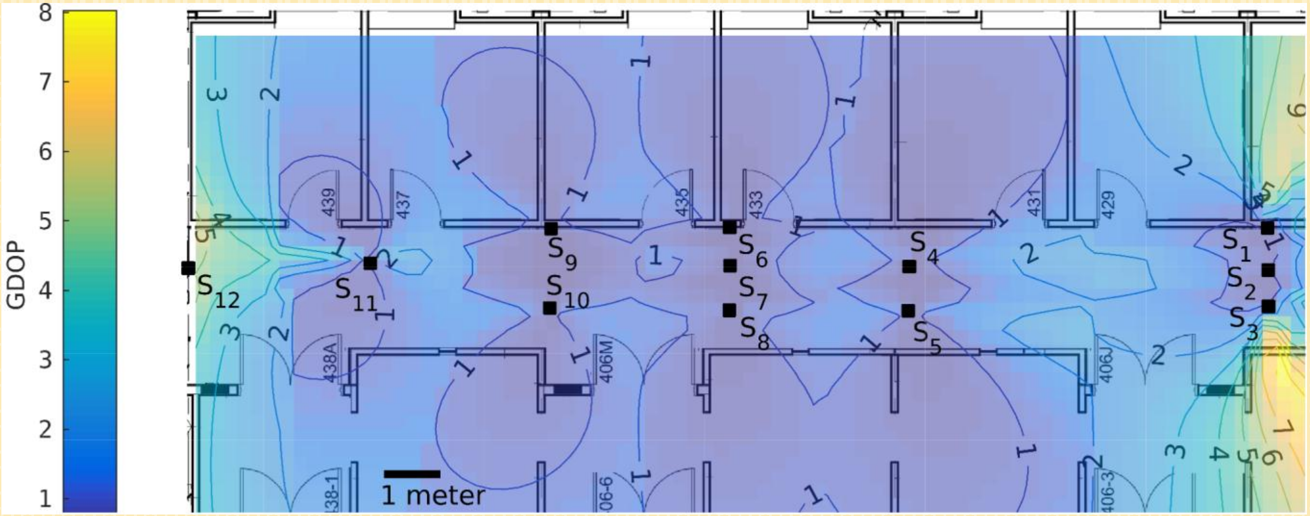
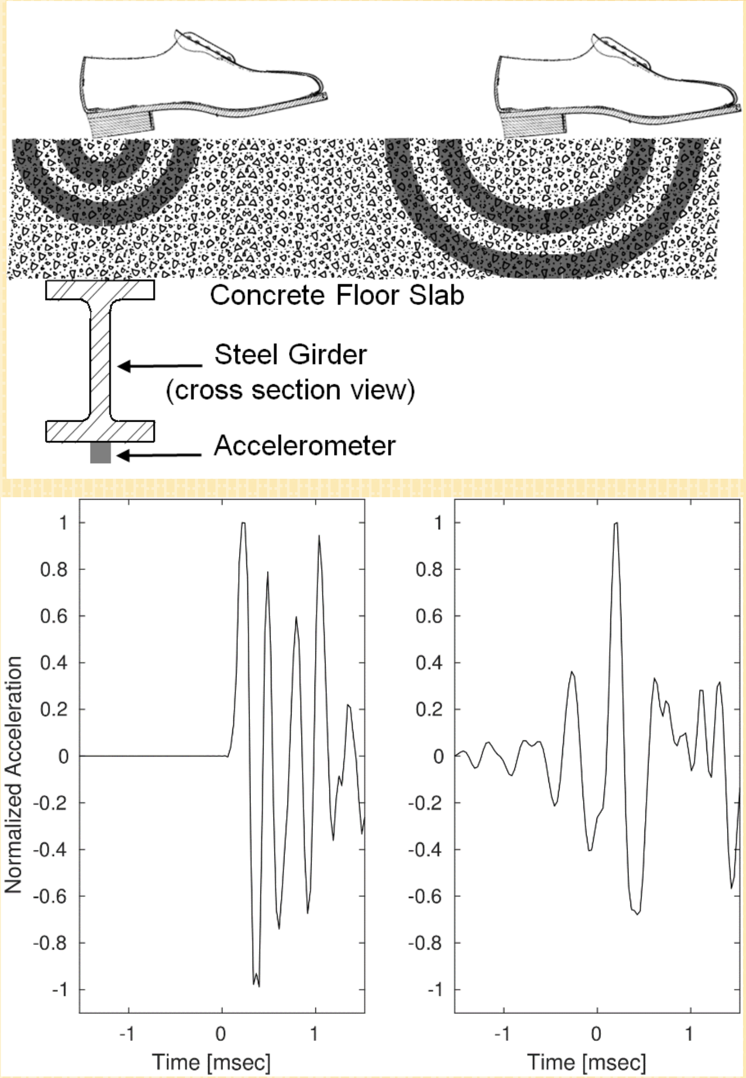


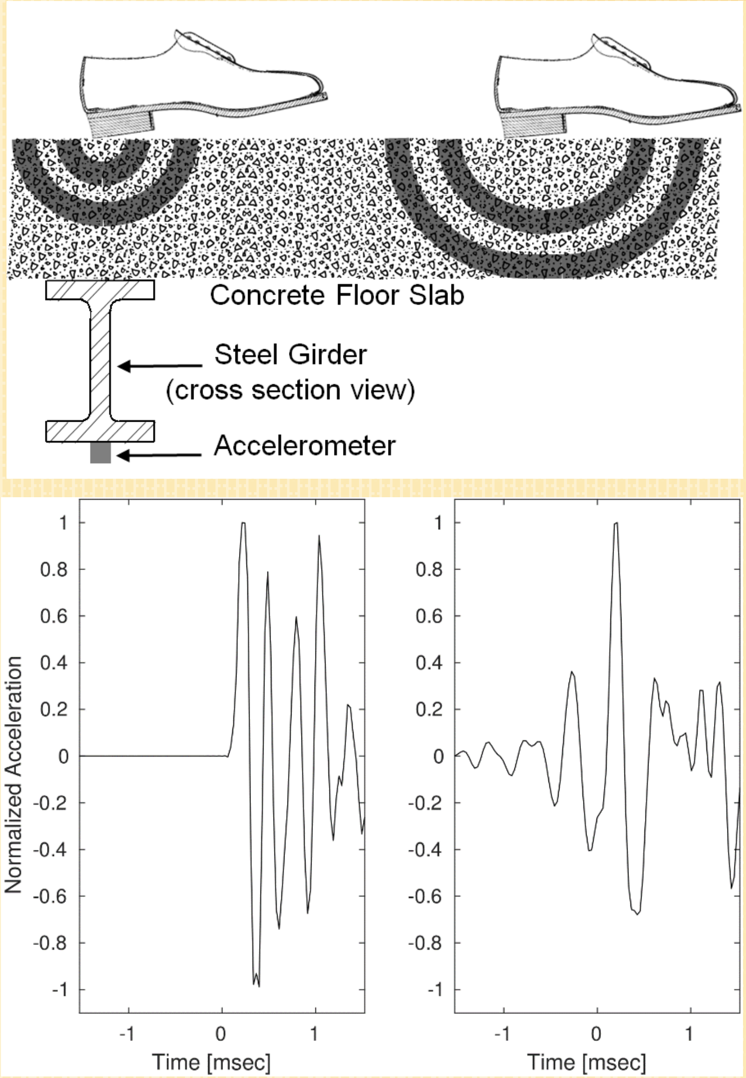
- **The hall asymmetry of sensor placement does influence GDOP, but doesn’t fully explain poor localization.**

A key insight comes from understanding the types of footstep-to-sensor interaction



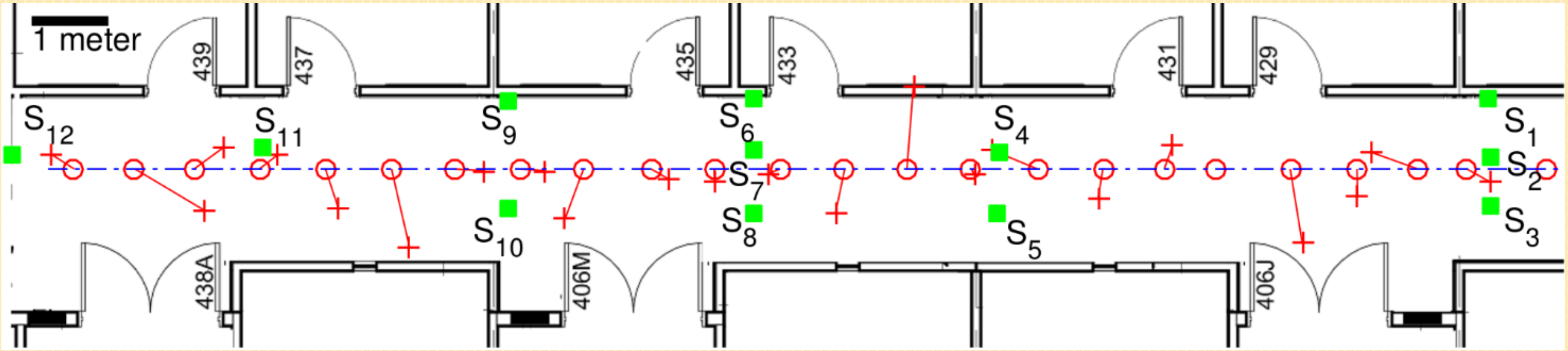
- **Footsteps directly above a girder-mounted sensor have a clear wave arrival (lower left), but those that travel laterally many meters undergo dispersion, reflections, etc. producing the complicated arrival wave (lower right)**
- **This is why footstep localization is not a trivial application of TDOA techniques from wireless or acoustics literature**

Different footstep-to-sensor interactions call for different arrival time estimation methods



- For footsteps directly above a sensor the matched filter's detection time suffices
- For distant footsteps, a method from seismology (Maeda'85) is appropriate for arrival time estimation
- Also, a search for the best fit propagation speed makes TDOA robust to uncertainty about building materials

Proposed approach applied to footsteps on Goodwin 4th floor Northeast hall gives 0.6 m RMSE

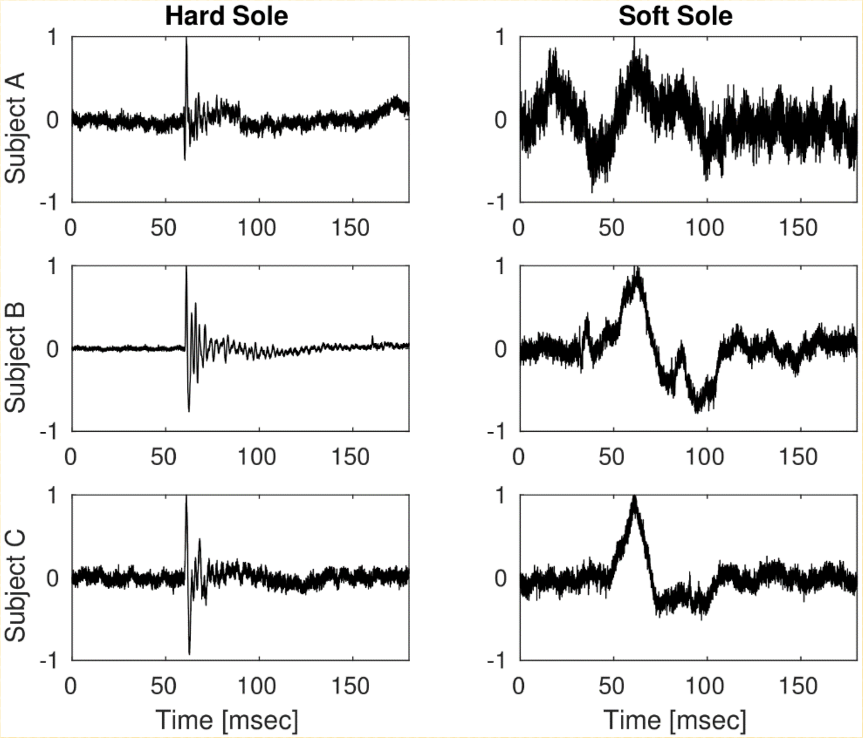


- A person walked a path (- - -) marked by tape
- Ground truth (o) provided by a LIDAR synchronized to the building sensor system
- Estimated positions (+) linked by line to ground truth point.
- Additional trials in were similar (RMSE 0.54 m to 0.8 m)

Indoor localization of footsteps to sub-meter accuracy is feasible. What about occupancy counts, tracking, …?

- **How to link a footstep to the person generating it?**
- **Footwear and gait could be discriminating features**

One sensor's record of distinct footsteps at the same place



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- **How to link a footstep to the person generating it?**
- **Footwear and gait could be discriminating features**
- **Eventually the combination of the footstep biometrics and location may pose a privacy risk**

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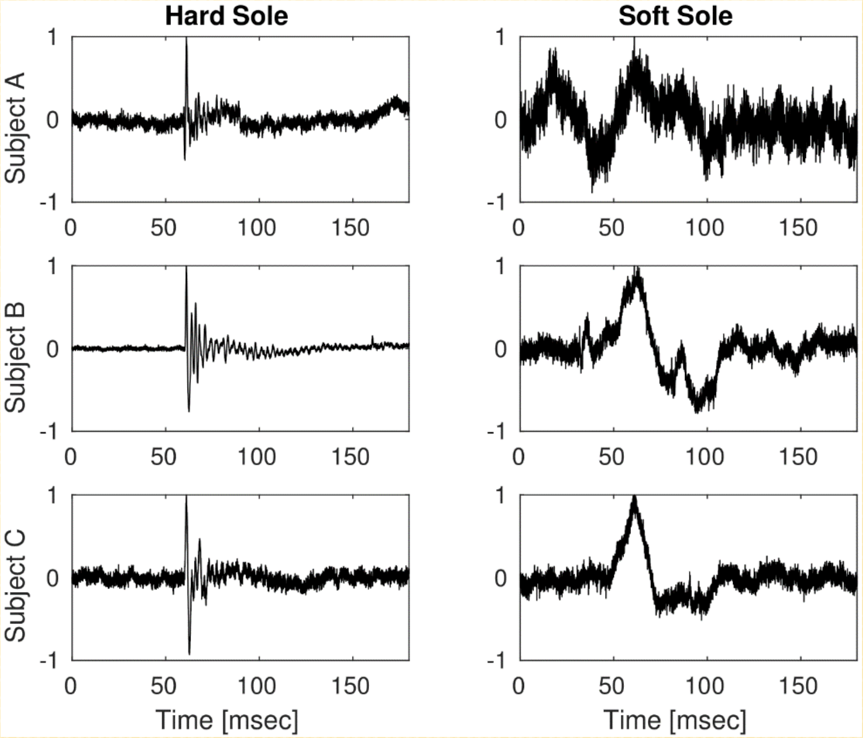

Closing Remarks

- This localization task needs to account for the physics of footstep-to-sensor interaction and, thus, must do more than recycle TDOA methods in acoustics and wireless literature

<u>Benefits</u>

- Enables a device-free, ambient localization service
- Avoids burdening radio spectrum
- May facilitate fall detection and localization