



Recent Developments in Laser-Based Optical Sensor Systems for Seismic Monitoring

DOE/NRC NPH Workshop 2020

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Monitoring system development from sensor concept to operational system

Concept

Use-inspired R&D cycle

Prototype testing

Simulation / testing
lessons learned

**Value engineering
deployable design**

Conceptualization
from Livermore Lab
lasers program

Computer simulation,
sensor design,
experimental testing

System design,
testing

First field
deployments

2003

2016 - 2018

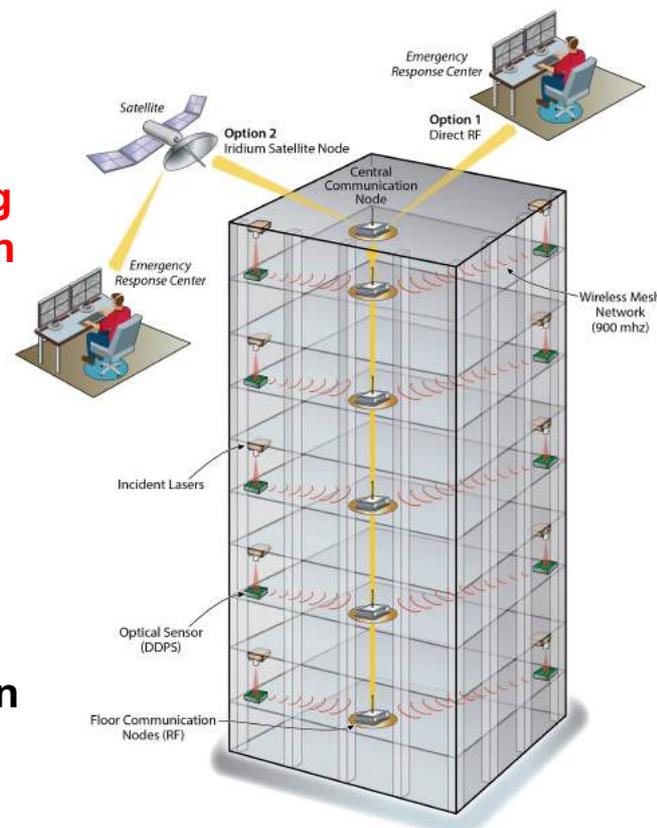
2019

2020



Research and Development accomplishments:

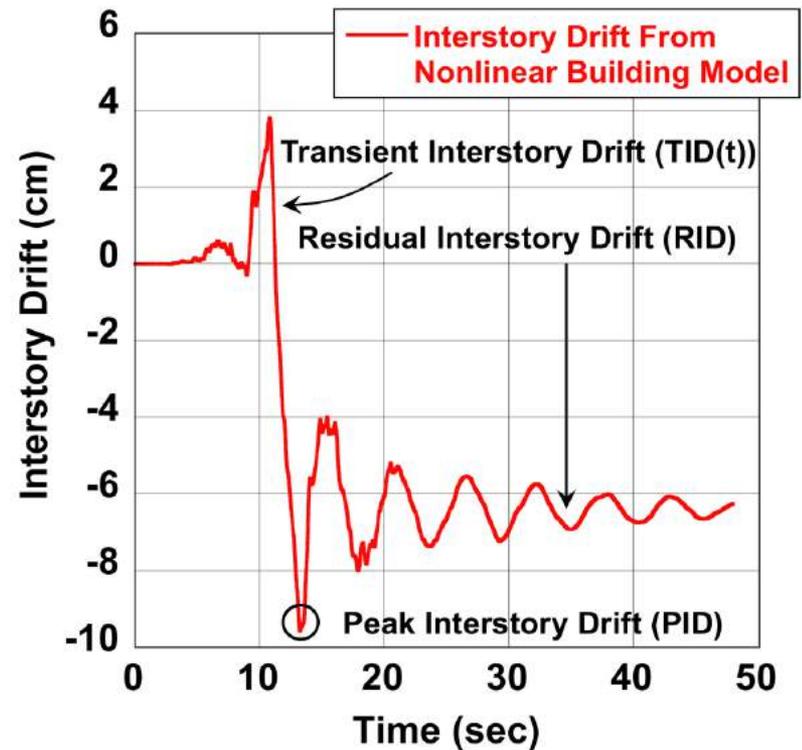
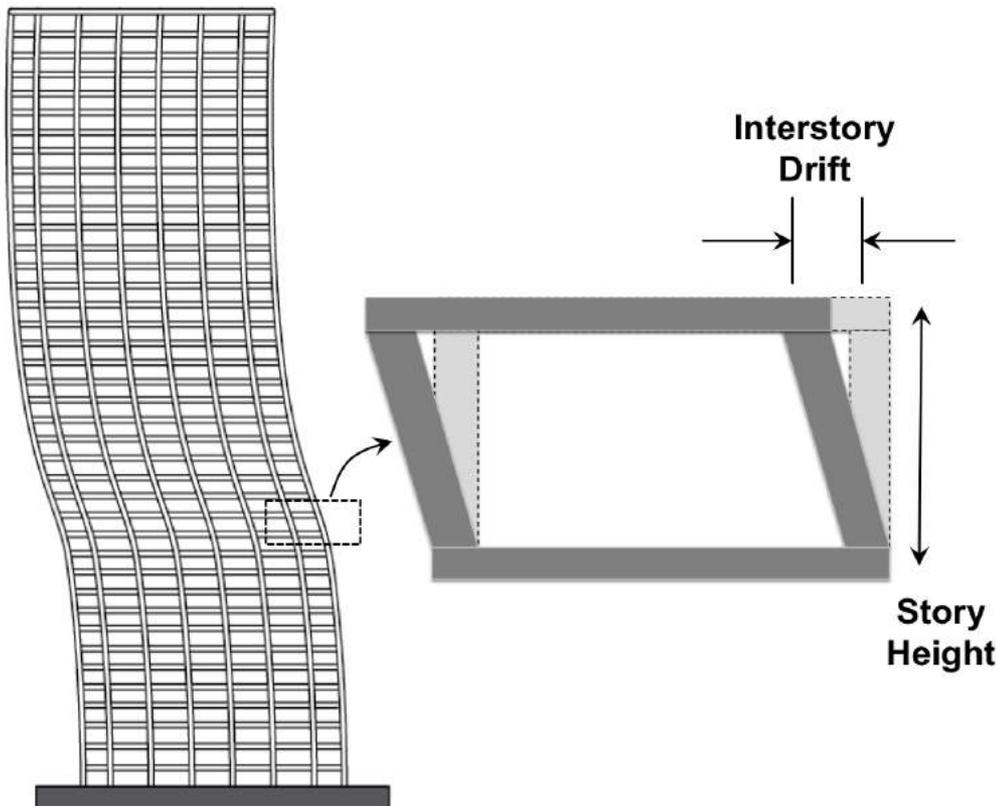
- Demonstration of concept through extensive simulation and experimental campaigns
- Major advancements based on R&D lessons-learned
- Value engineering for a robust and cost effective design



Deployable Sensor /
Communication Systems

Idea – can we take advantage of the physics of light to directly measure earthquake drift?

Building interstory drift during an earthquake



Interstory drift is used in many standards to assess building performance



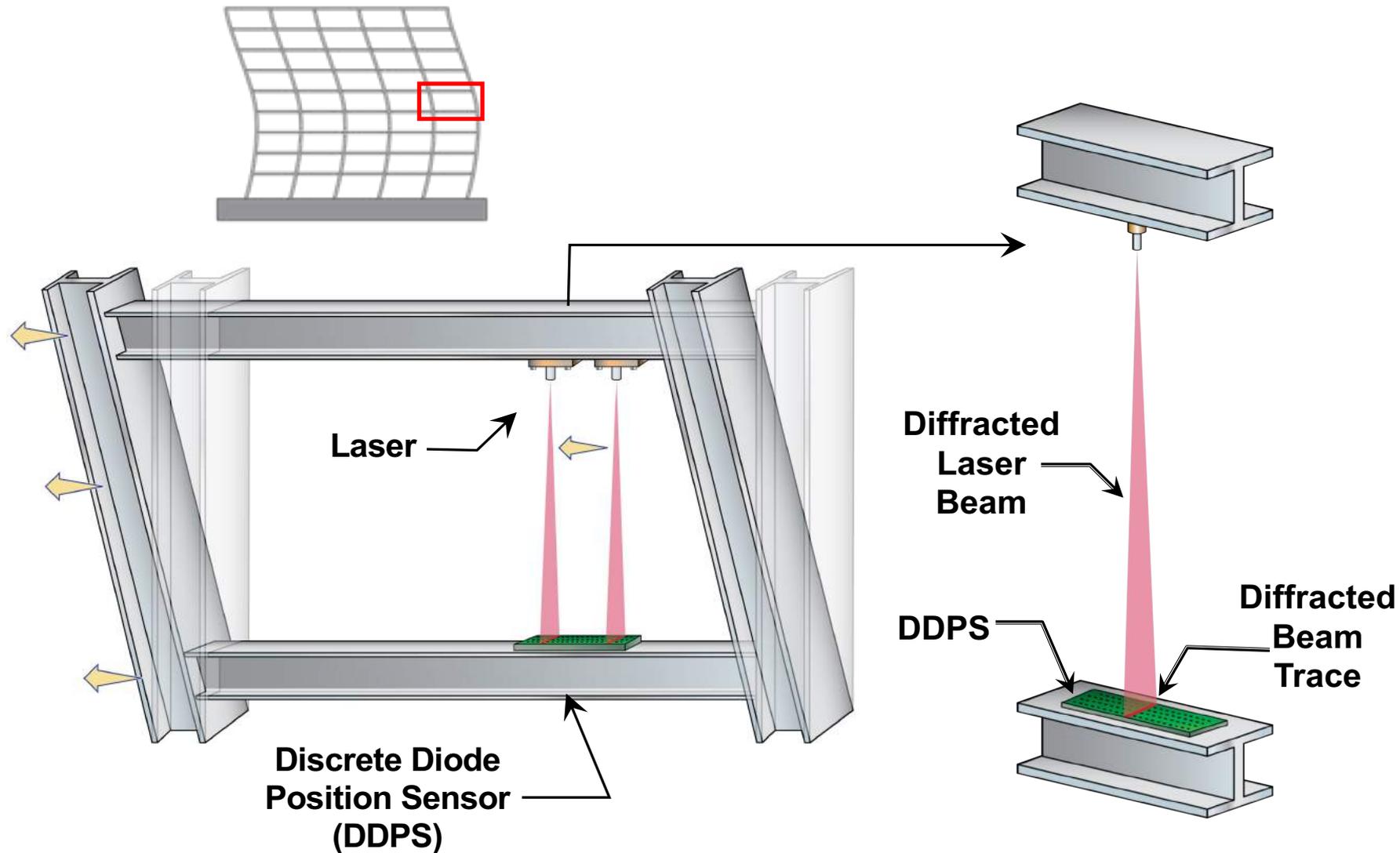
Limit States

Specification	Standard	Drift Specifications			
Specification of performance limit states (drifts for steel moment frame example)	ASCE 43-05	<i>Limit State A</i> Large permanent distortion short of collapse <i>Significant Damage</i> ID 3.5%	<i>Limit State B</i> Moderate permanent distortion <i>Generally repairable damage</i> ID 2.5%	<i>Limit State C</i> Limited permanent distortion <i>Minimal damage</i> ID 1.0%	<i>Limit State D</i> Essentially elastic behavior <i>No damage</i> ID 0.5%
	ASCE 7-02	<i>Seismic Group I</i> ID 2.0%	<i>Seismic Group II</i> ID 1.5%	<i>Seismic Group III</i> ID 1.0%	
Specification of maximum allowable drift limits	European Standard EN 1998-1	Buildings with non-structural elements that do not interfere with structural deformation ID 1.0%/v	Buildings having ductile non-structural elements ID 0.075%/v	Buildings having brittle non-structural elements ID 0.5%/v	
	New Zealand Standard NZS - 1170.5	Upper bound limit applicable to the ultimate limit state of all buildings, imposed to limit the probability of instability ID 2.5%			
	Tall Building Initiative (TBI) 2.01	Drift limit to provide protection against nonstructural element damage and ensure permanent lateral displacement of the structure is negligible ID 0.5% Story transient drift from analyses not to exceed ID 3.0%			
Specification of residual drift limits for post-earthquake structural assessments	FEMA P58-1	<i>Damage State DS4</i> Residual drift is sufficiently large that the structure is in danger of collapse from aftershocks High ductility systems RID 4.0% Moderate ductility systems RID 2% Limited ductility systems RID 1%	<i>Damage State DS3</i> Major structural realignment is required to restore margin of safety for lateral stability RID 1.0%	<i>Damage State DS2</i> Realignment of structural frame and related structural repairs required to maintain permissible drift limits RID 0.5%	<i>Damage State DS1</i> No Structural realignment is necessary for structural stability RID 0.2%
	Tall Building Initiative (TBI) 2.01	Residual drift to protect against excessive post-earthquake deformations that likely will cause condemnation or excessive downtime to perform repairs RID 1.0%			

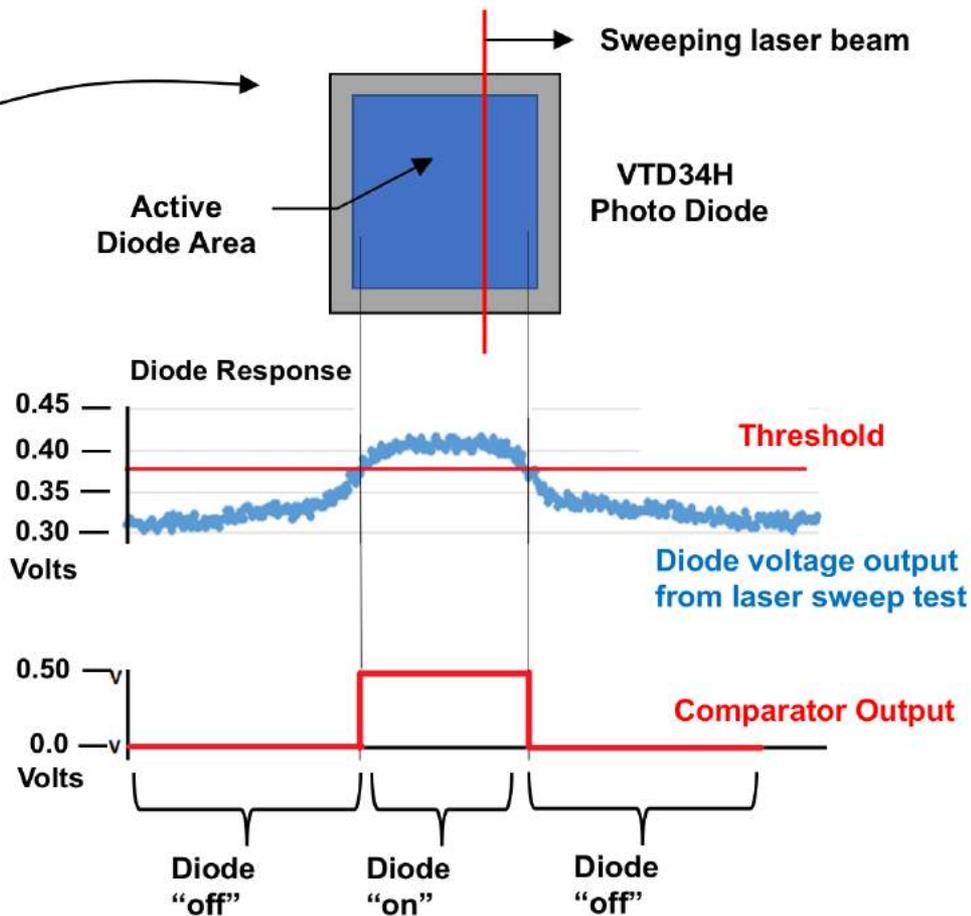
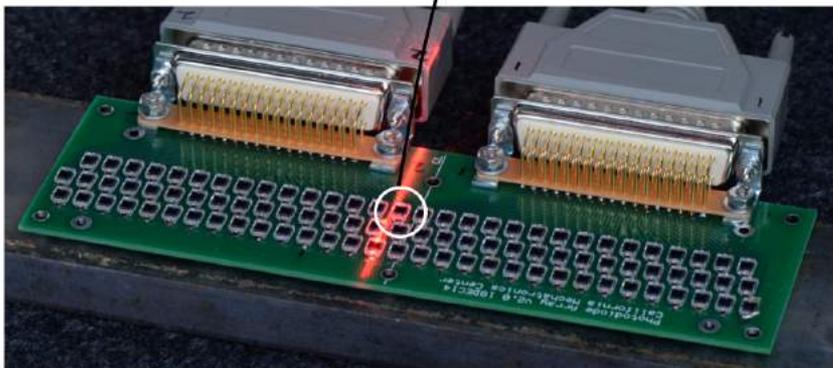
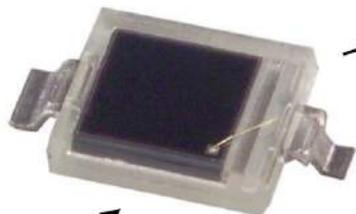
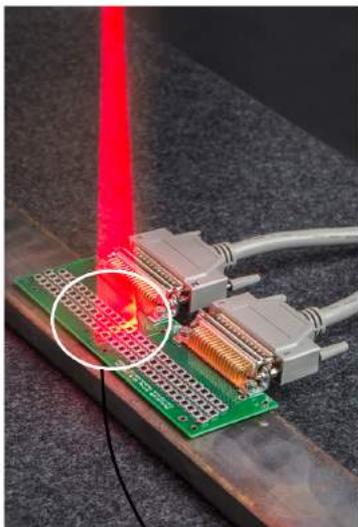
Not-to-Exceed Drift Limits

Damage State Drift Limits

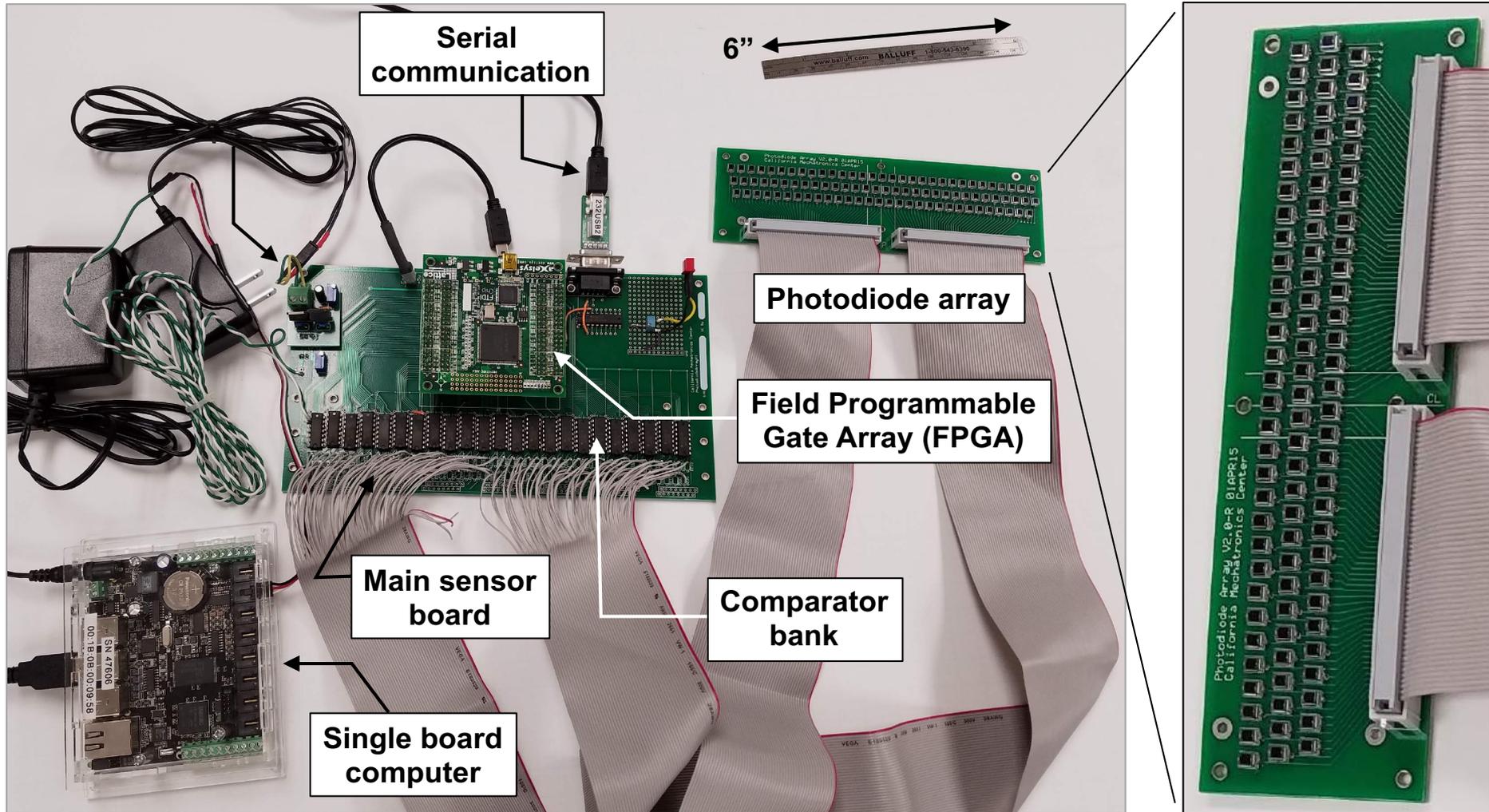
The concept - exploit the physics of light for direct, broad-band drift measurement



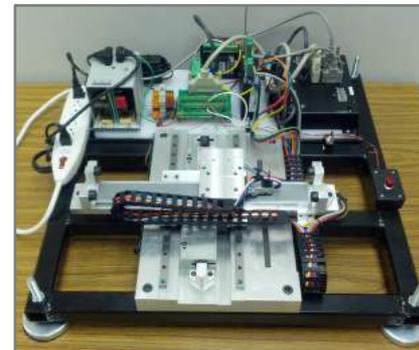
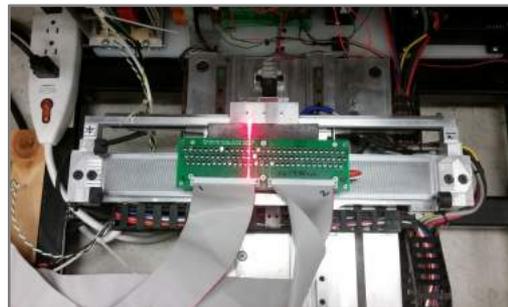
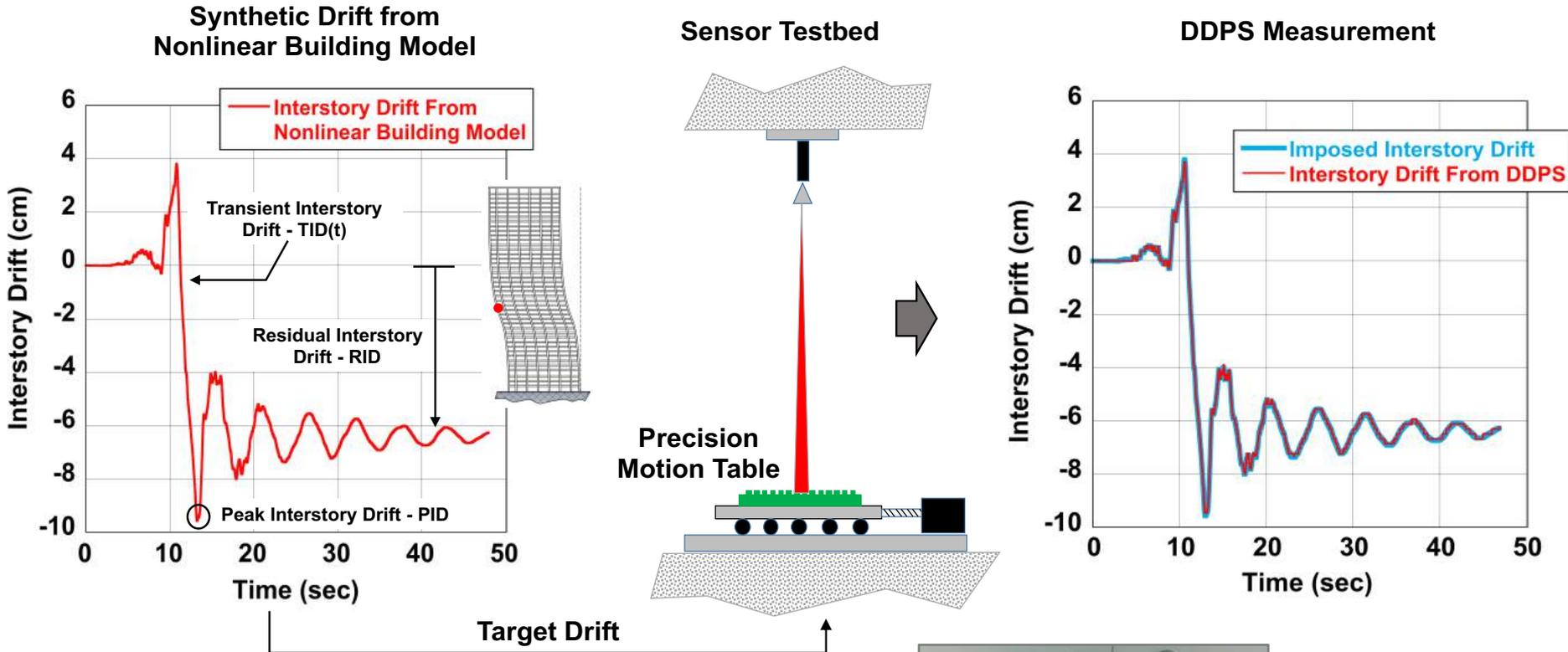
Inexpensive light-sensitive diodes are at the heart of our sensor concept



Generation 1 - a prototype sensor for proof of concept

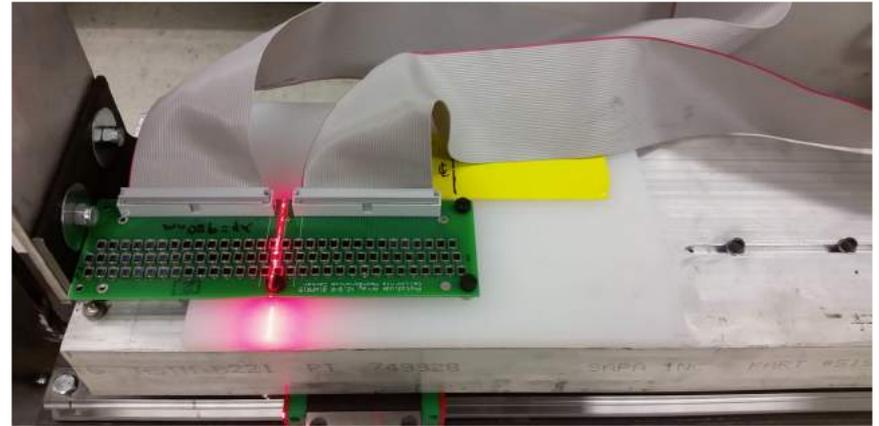
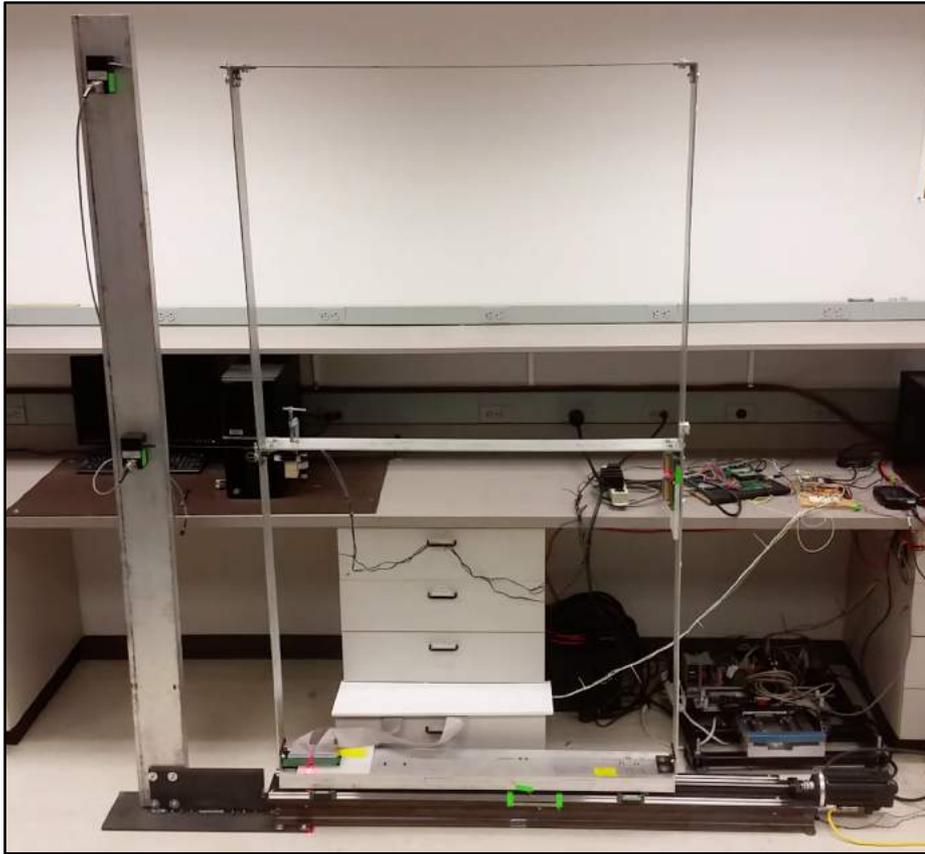


Testbed #1 - a motion table for generating realistic interstory drifts was developed

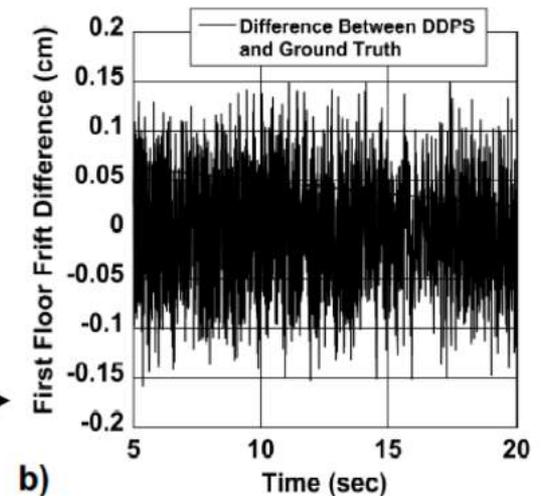
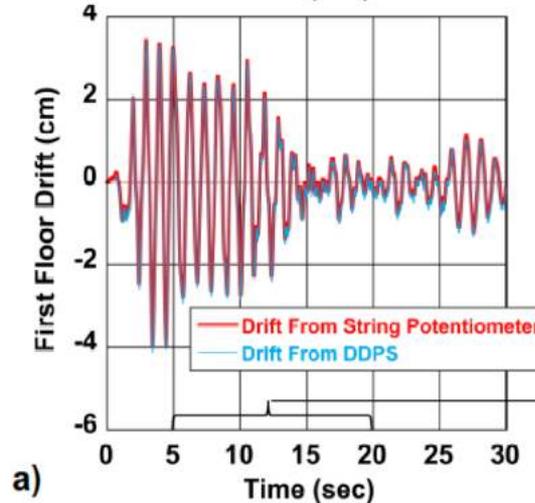
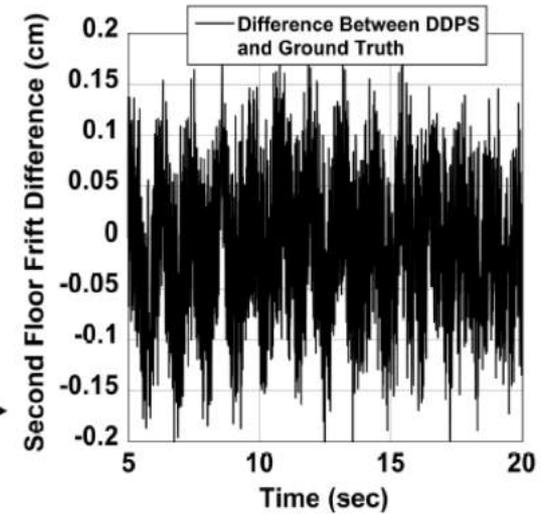
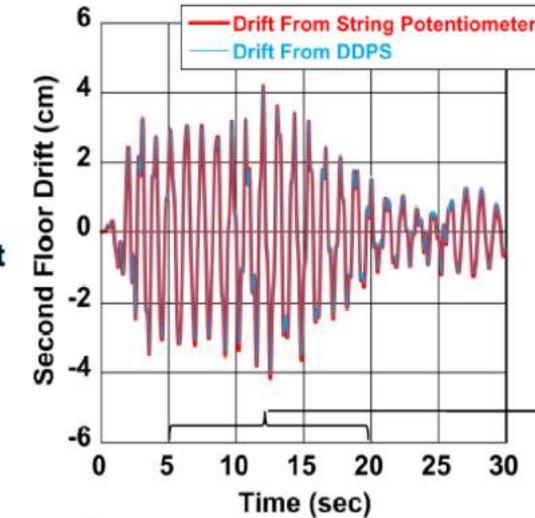
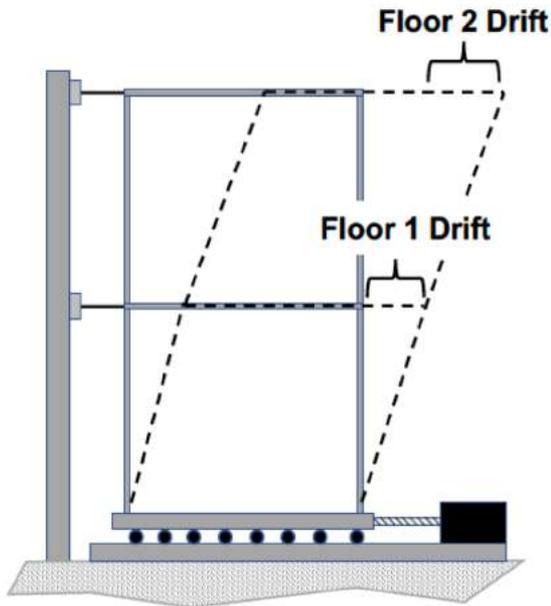


Testbed #2 - a simple laboratory scale frame structure

El Centro motion test



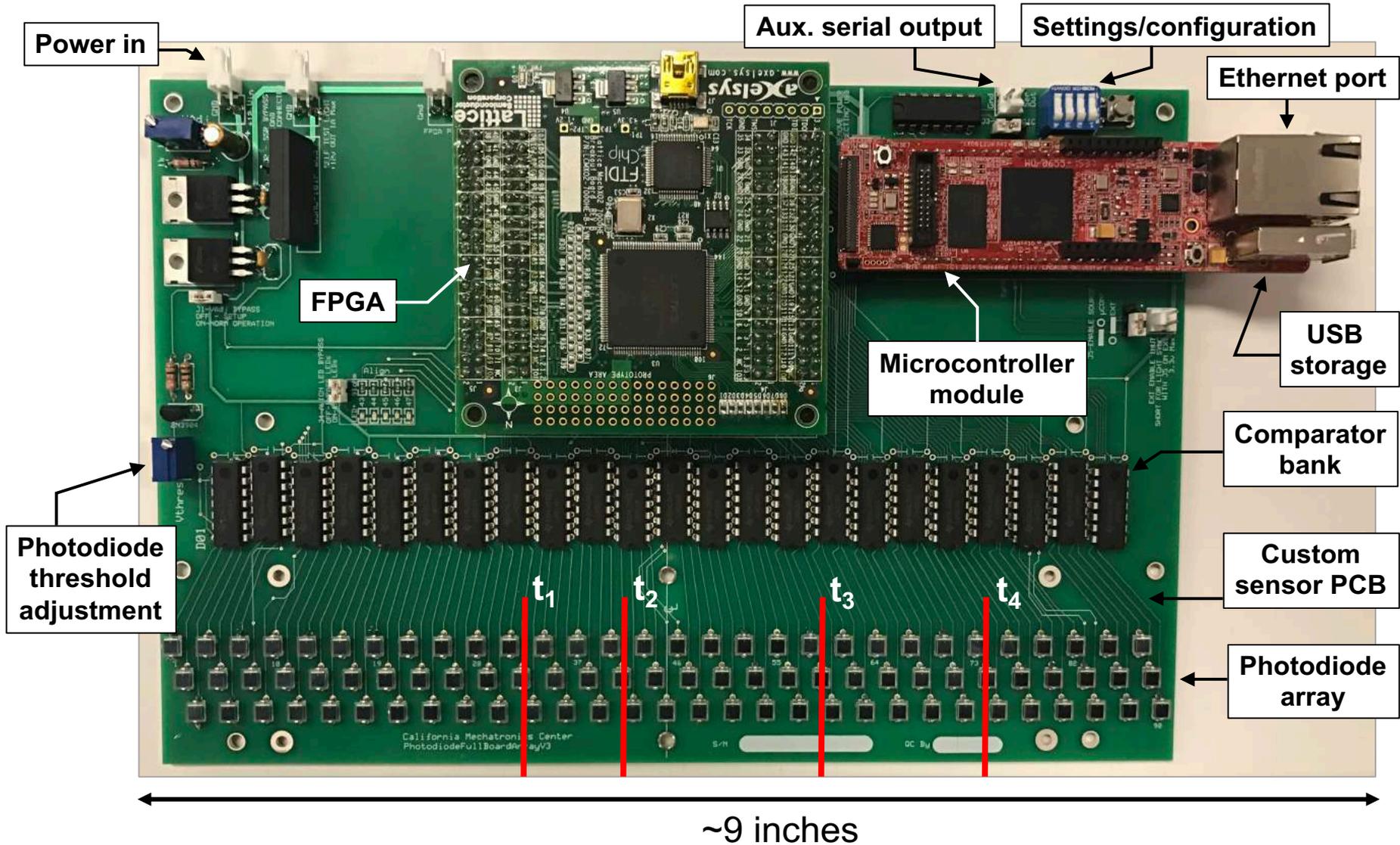
Sensor measurements exhibited excellent agreement with ground truth drifts



a)

b)

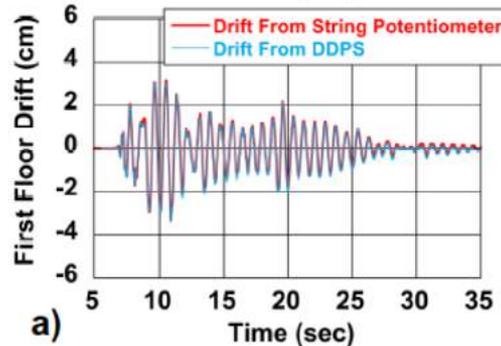
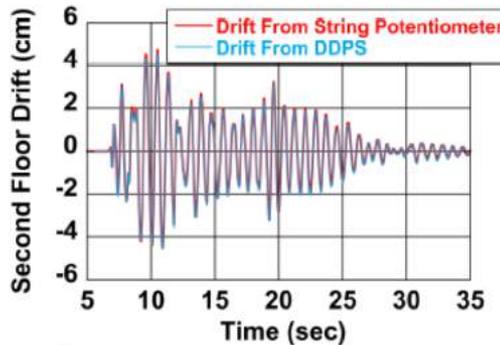
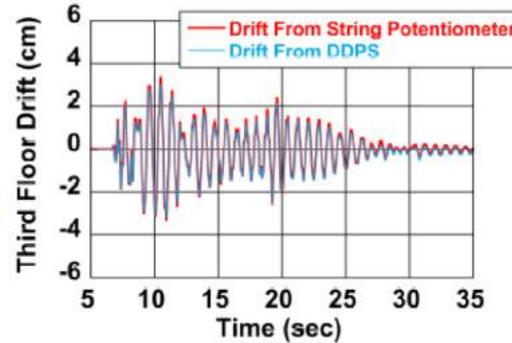
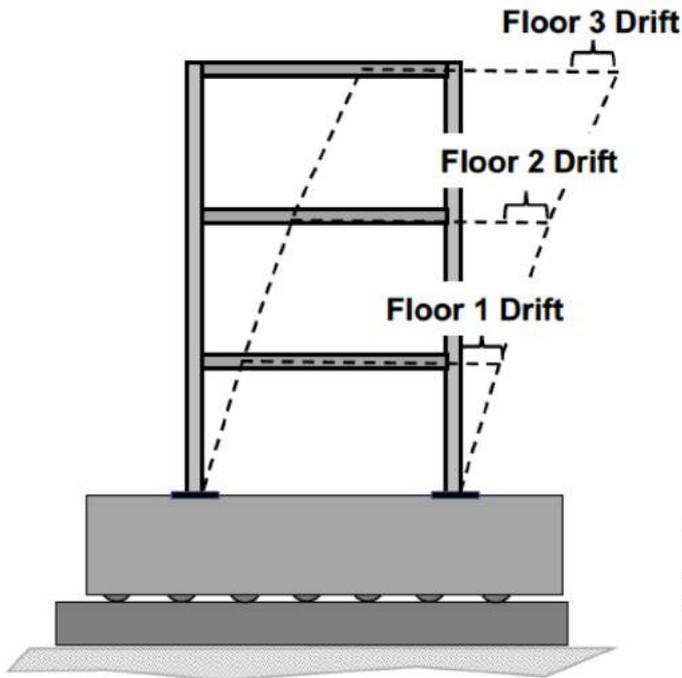
Generation 2 - an integrated sensor on a single circuit board



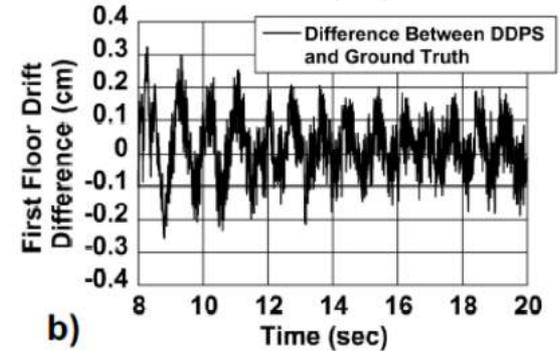
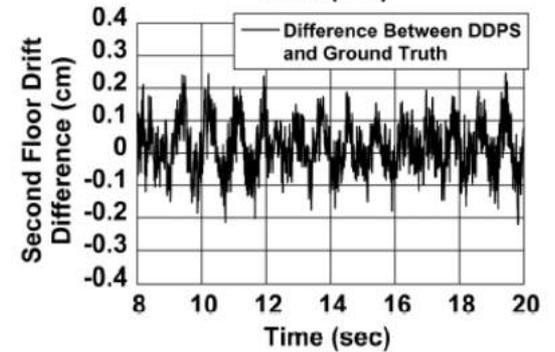
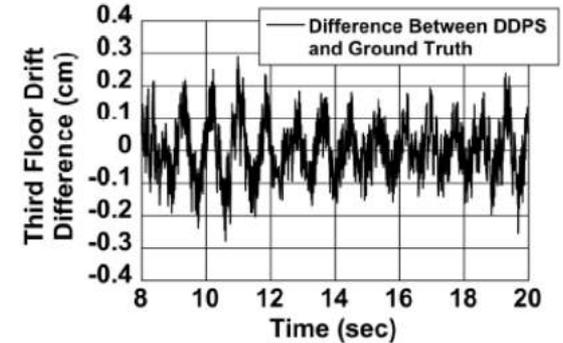
Testbed #3 - the DOE Office of Nuclear Safety supported a larger 3D test at UNR in 2017



Drift measurements - ground truth versus DDPS

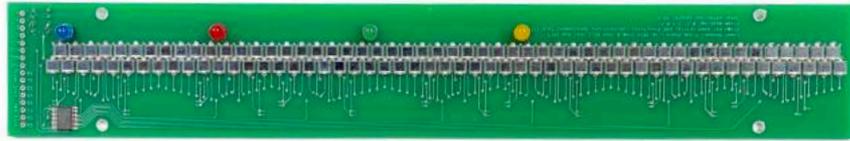


a)

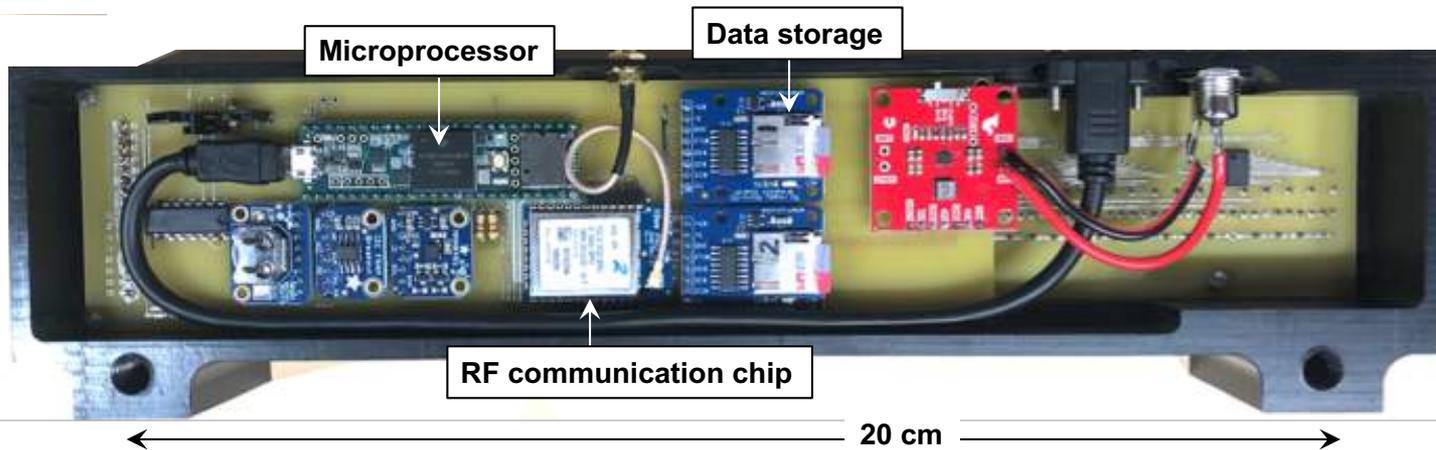


b)

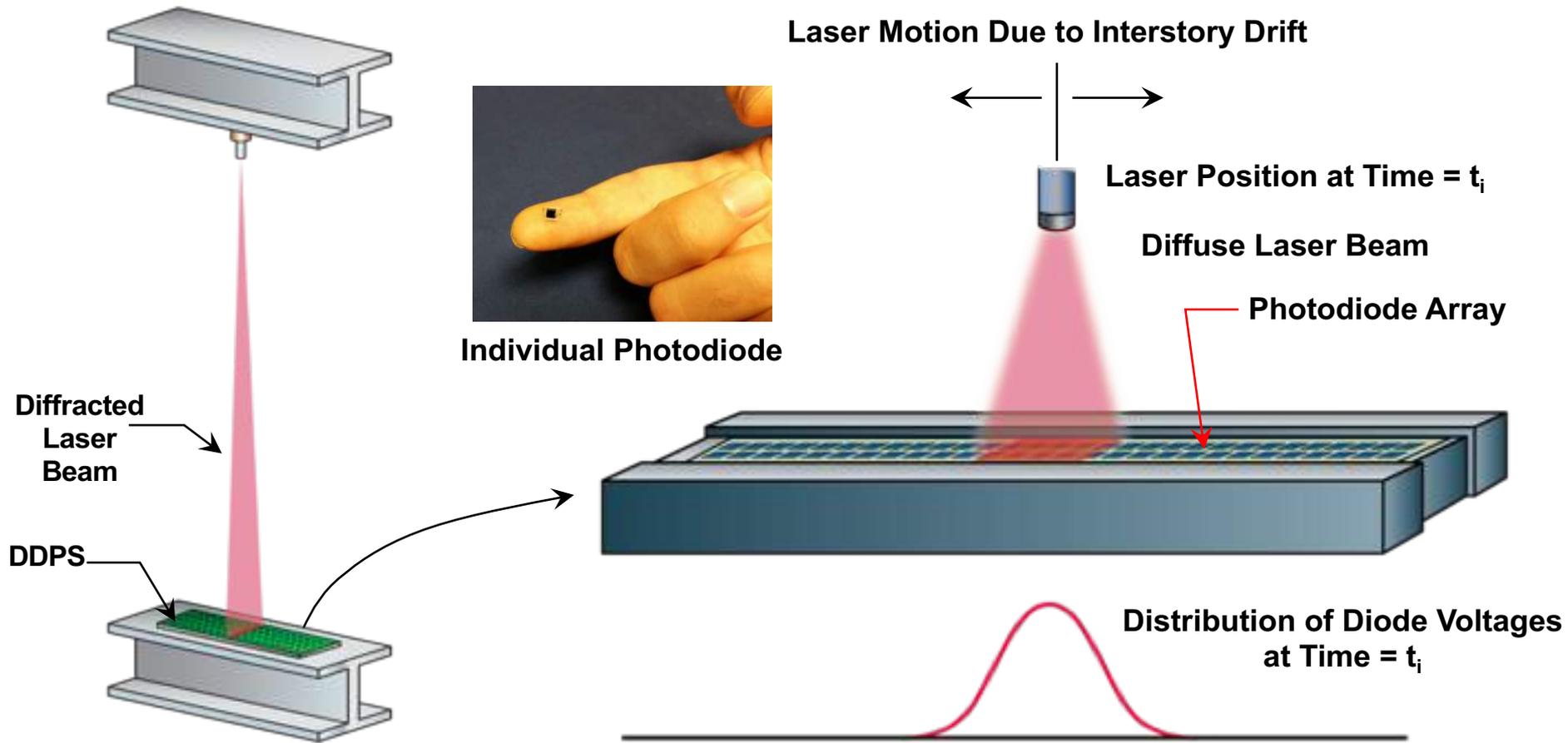
Generation 3 - a deployable sensor based on value engineering and lessons learned



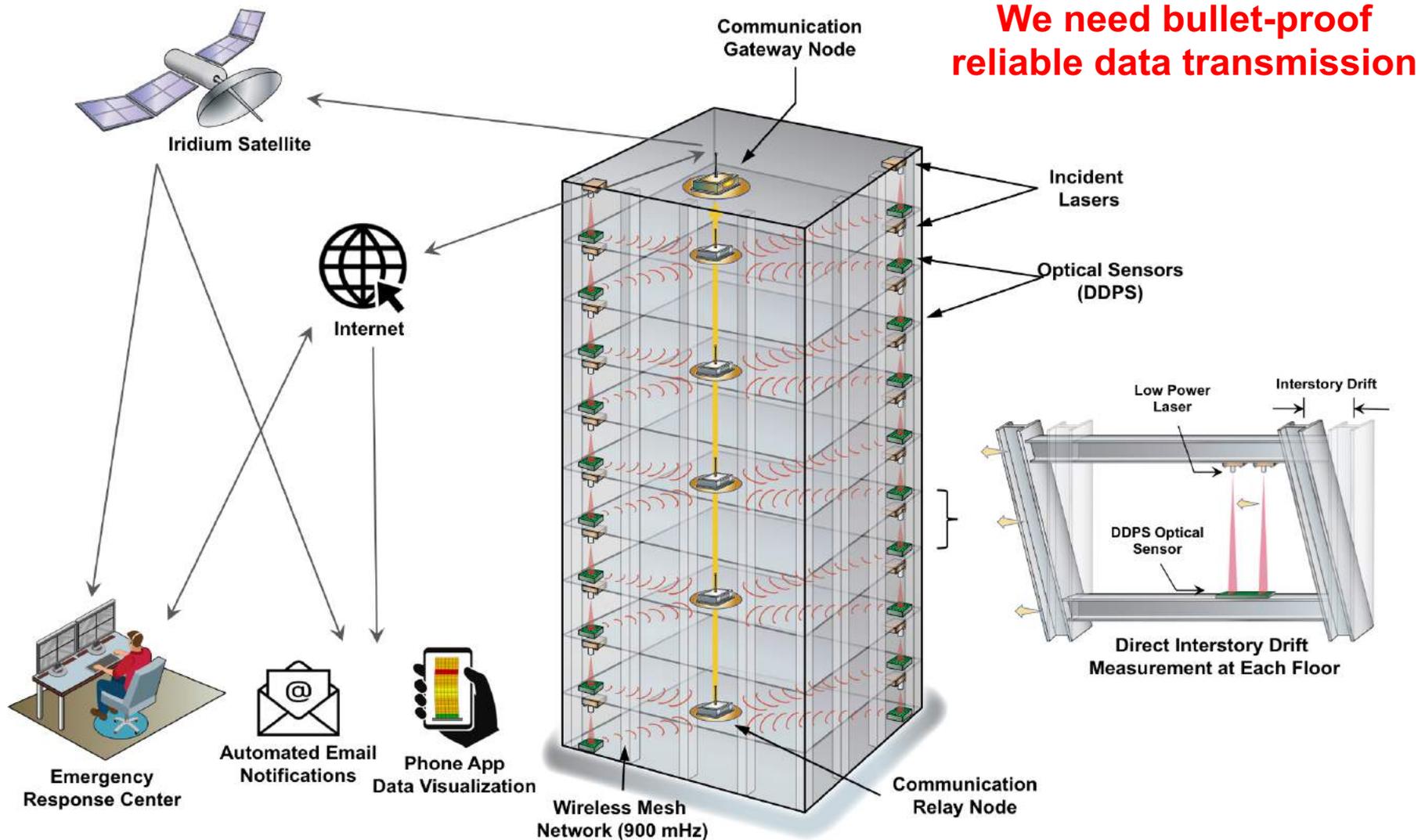
Low power laser



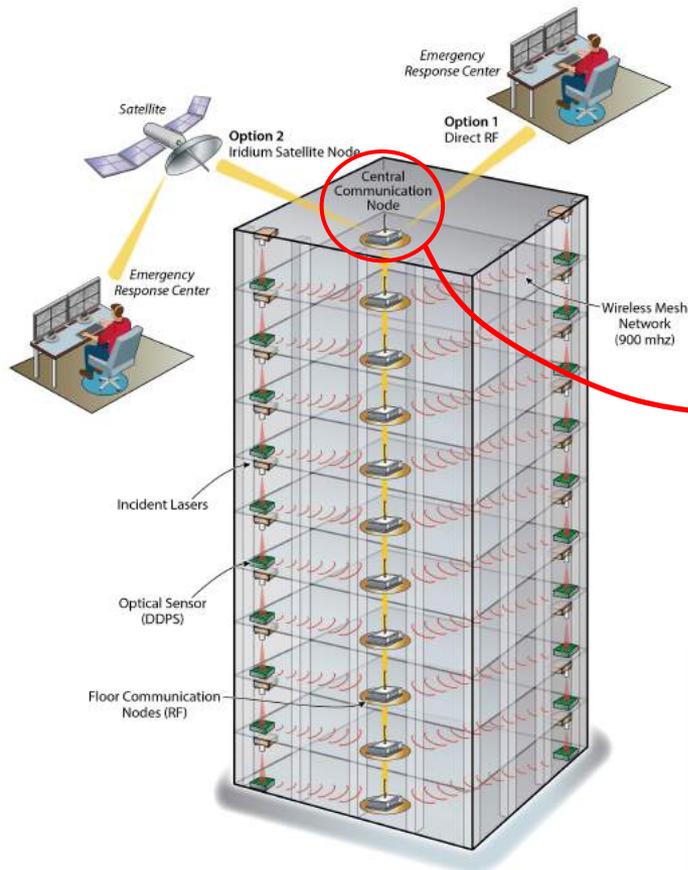
Generation 3 – Advancements through incorporation of many lessons learned



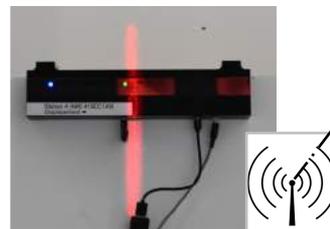
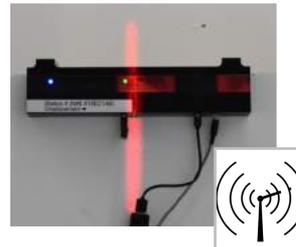
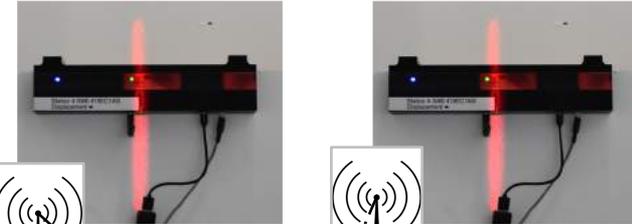
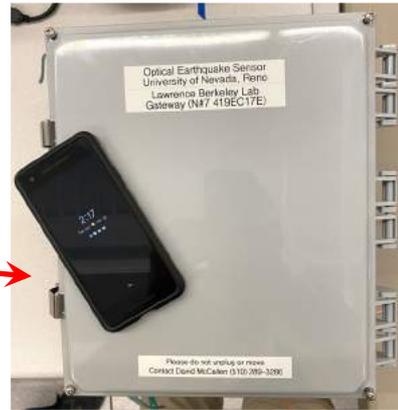
A new wireless mesh network has been developed for deployment and operations



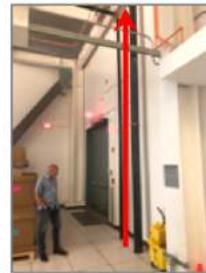
The communication gateway



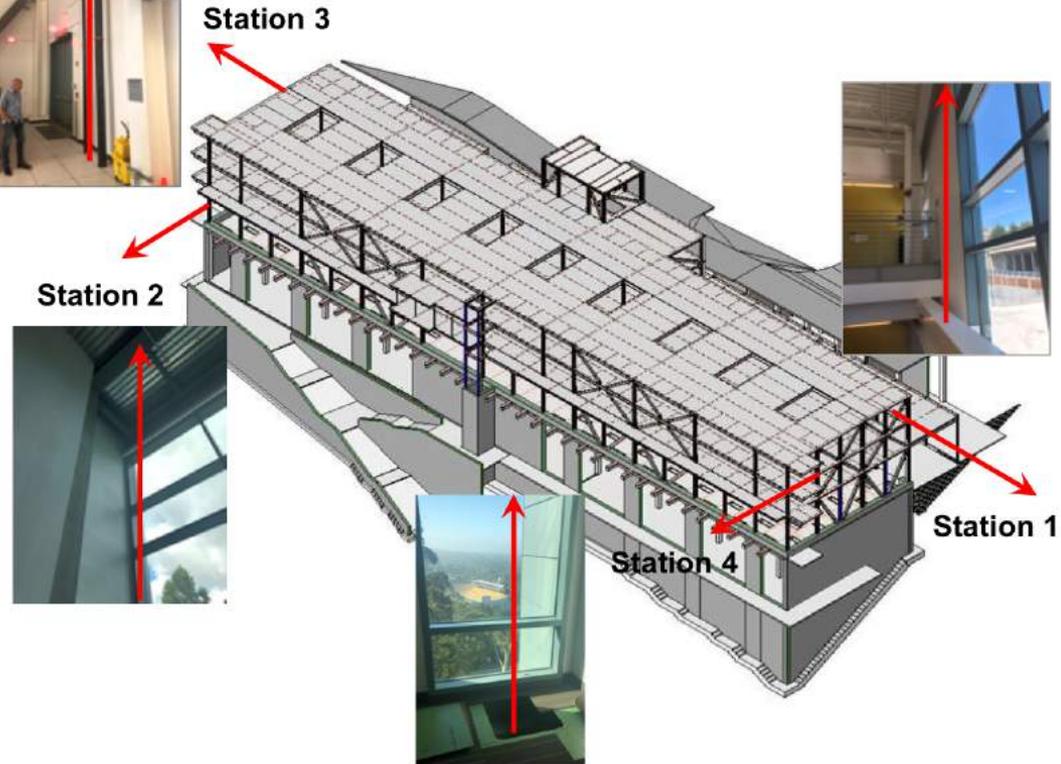
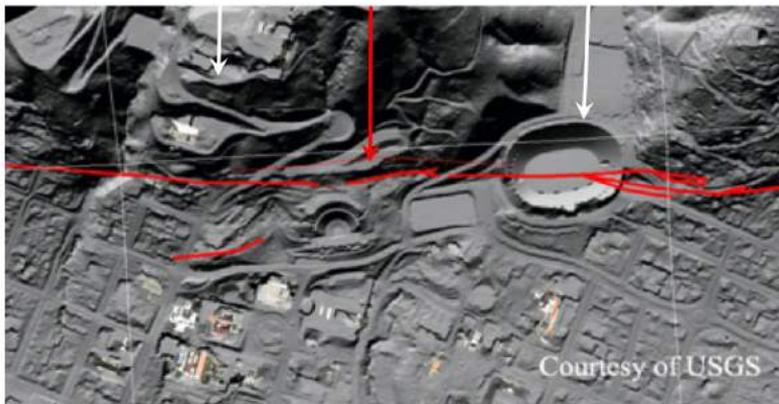
Gateway



Four sensors were deployed at Lawrence Berkeley Lab in September 2019



Wang Hall
Hayward Fault
UC Berkeley Memorial Stadium

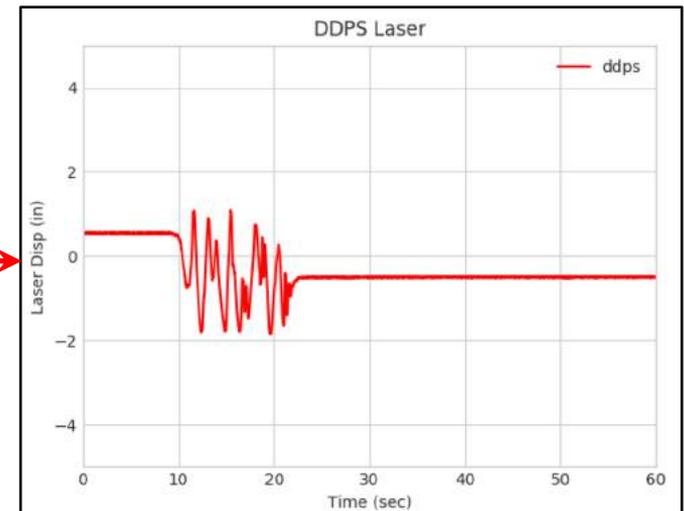
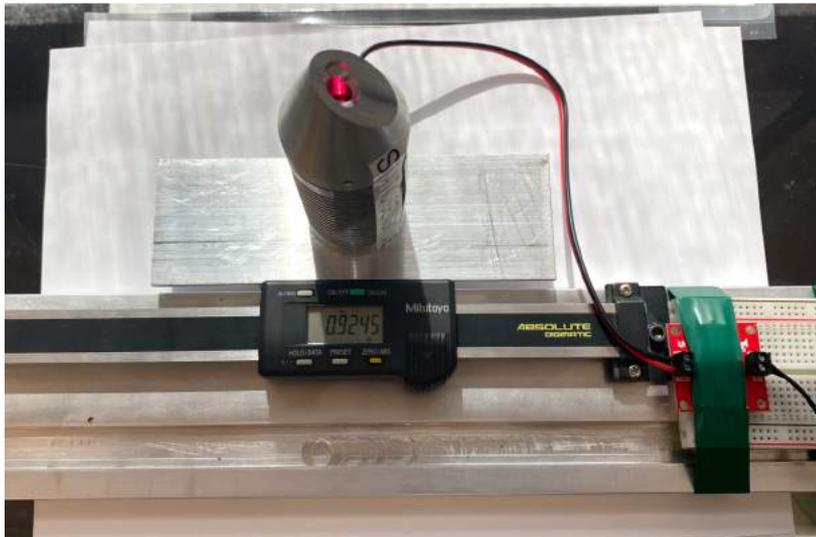
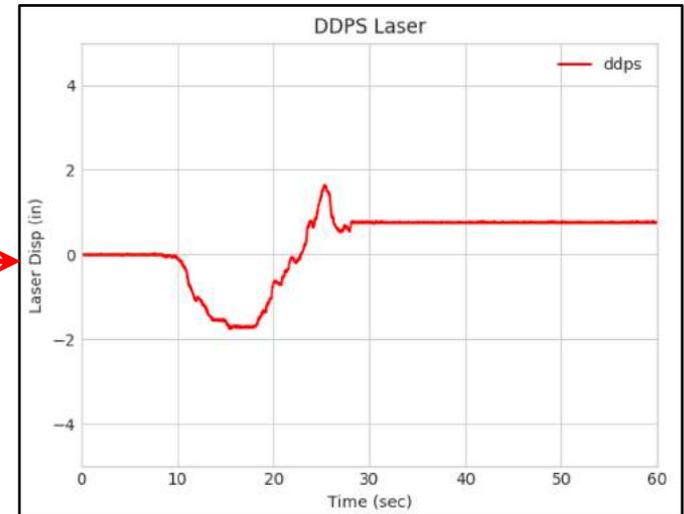


The sensors have operated continuously with complete reliability for 14 months



**“Triggered”
earthquakes**

Automated email delivery of data



The system can send an automatic email once an event is detected

Earthquake Event Detected at UNR Structures Labs on Node Prototype

earthquakeengineeringlab@gmail.com

to laplace, me, florianapetrone ▾

Event detected! See attached files for data.

Event statistics:

DDPS Node #: 4

DDPS File: EQ000043.txt (Auto Triggered Event)

2020/9/25(Friday)11:22:47

Init disp (in): 0.0164

Max disp (in): 1.6392

Min disp (in): -1.7529

End disp (in): 0.7659

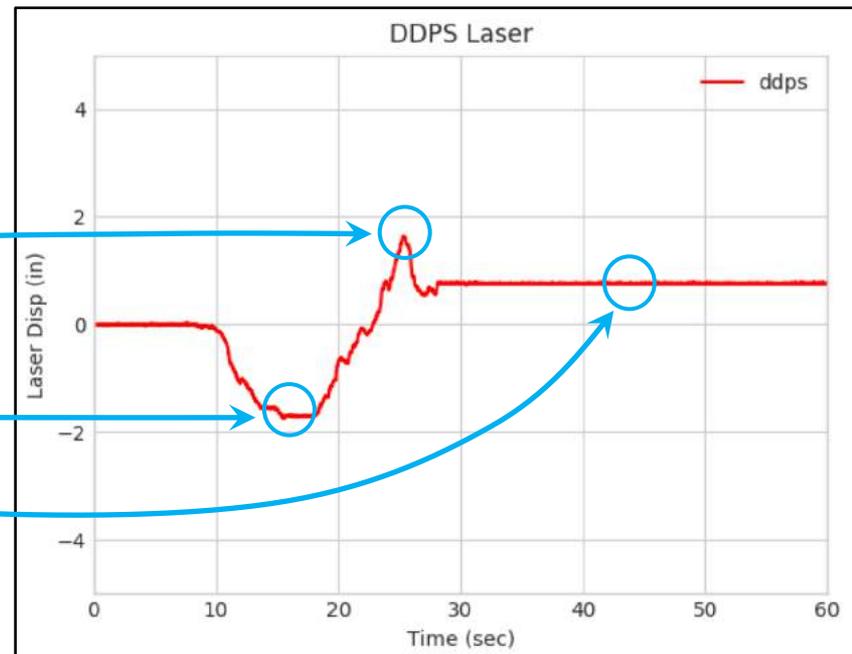
Data sample rate: 100 Hz

Peak diode index: 55

Peak diode voltage: 0.2836

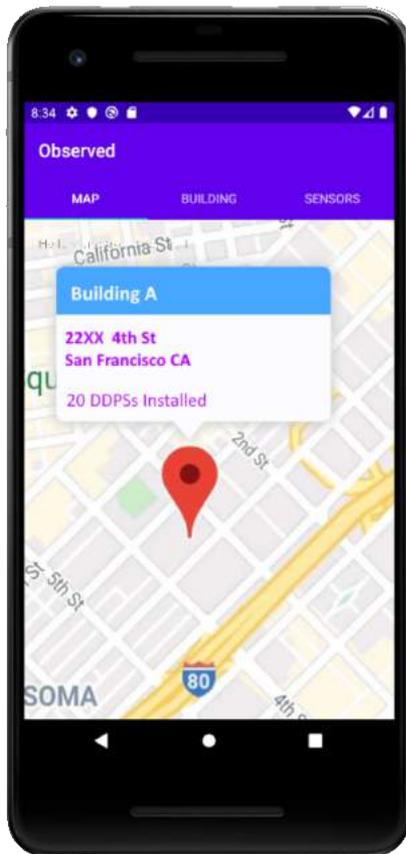
Number of diodes above ambient: 13

Ambient voltage: 0.2066

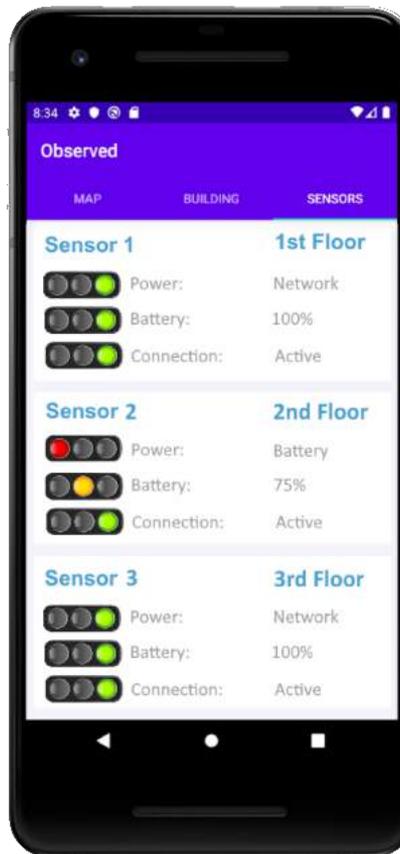


A smartphone app has been created to accept and display drift data remotely

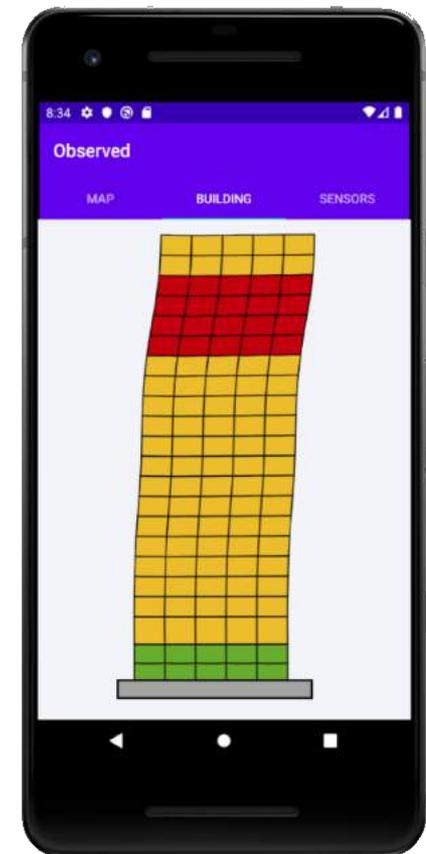
Tab 1 Building Location



Tab 2 Sensor Status



Tab 3 Data Visualization

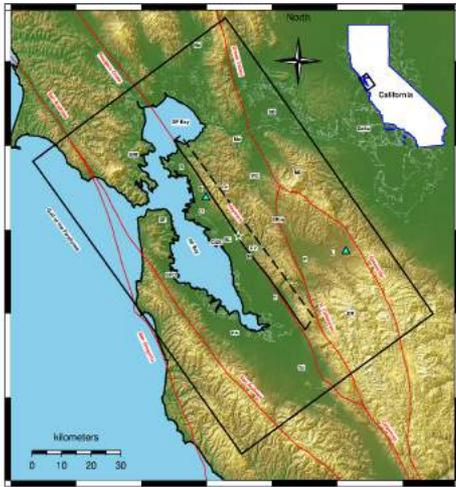


Android smartphone app developed by computer scientist Vincenzo Quinto

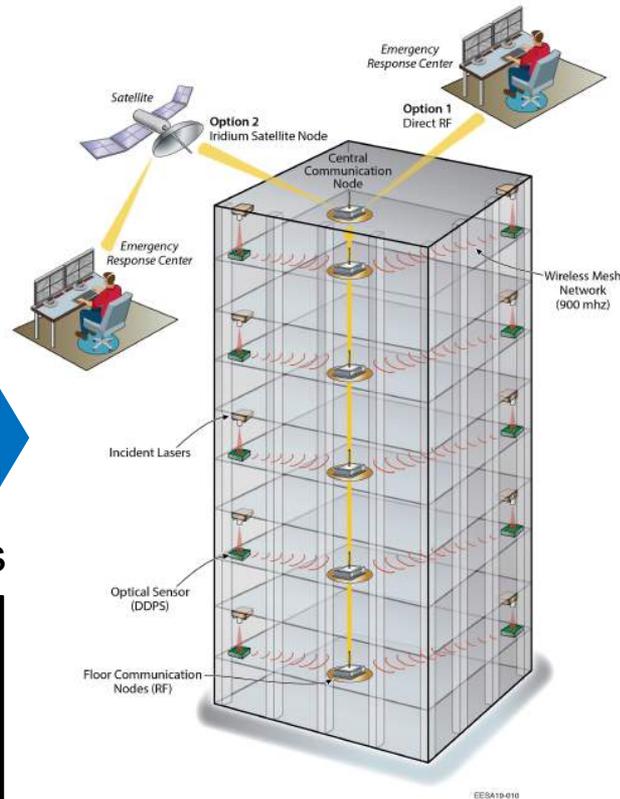
Our final objective is to provide rapid data to transform post-event response

Disruptive Events

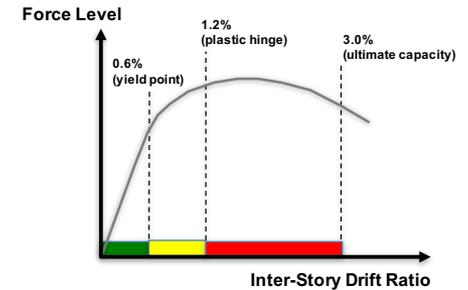
Earthquake event occurs



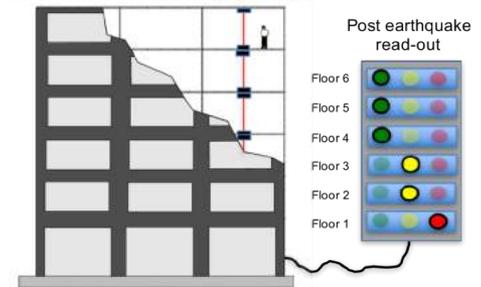
Rapid real-time measurements with reliable data transmission



Immediate data to inform response decisions



Optical Drift Measurement (ODM) Sensors (1 per floor)



- Emergency responders
- Re-occupancy
- Continuity of operations
- Guidance for detailed inspections

Extreme storm event occurs

