6.1820/MAS.453: Mobile and Sensor Computing aka IoT Systems

https://6mobile.github.io/

Lecture 13: Agriculture IoT

Fadel Adib
6mobile@mit.edu

Some slides adapted from Deepak Vasisht (UIUC) and Sayed Saad Afzal (MIT)

Announcements

1. Project Proposals due today
2. Lab 4 due next week, April 8
3. PSet 2 due April 9

Objectives of Today's Lecture

- Learning about aerial-based Connectivity (Loon, Aquila)
- Agriculture IoT
  - The IoT Challenges
  - An IoT System solution
- Wireless sensing for agriculture

Aerial-based Connectivity for Remote Areas

Google X's Project Loon

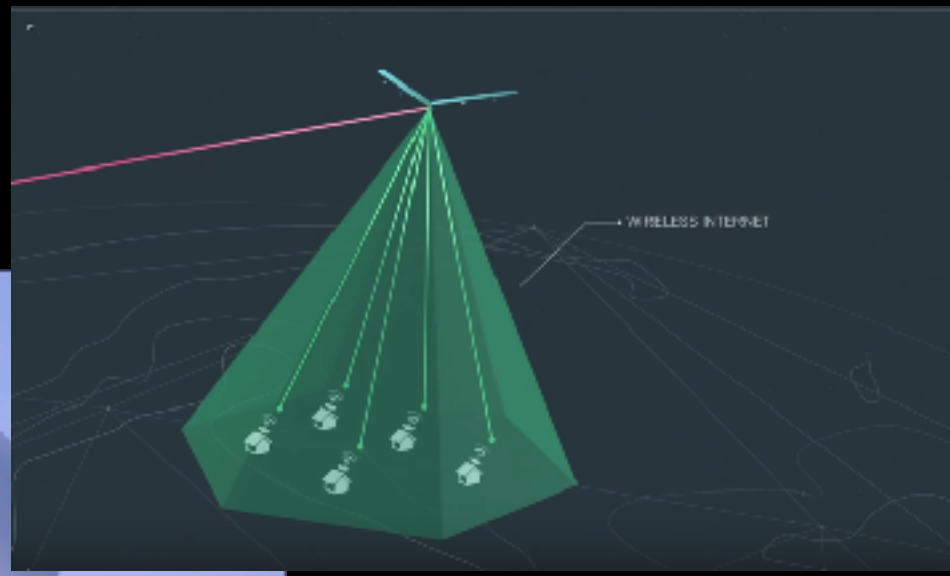
Facebook's Project Aquila

Others including Microsoft, Boeing, etc.

<u>Goal:</u> Bringing Connectivity to the Remote and Disconnected Areas of the Planet

Goal: Bringing Connectivity to the Remote and Disconnected Areas of the Planet

- Bring connectivity to rural areas



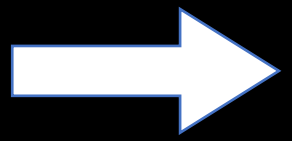
- Disaster Relief

Aquila was discontinued in 2018; Loon was discontinued in 2021

Challenges

Challenges

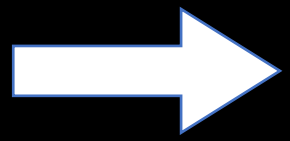
- **Power:** Constrained
  - Need to last for a long time
- **Control:** Flight paths
  - Minimal power consumption
- **Communications:** Long-range links
- **Data Rates**



Solar Energy

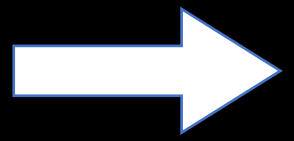
Challenges

- **Power:** Constrained
  - Need to last for a long time



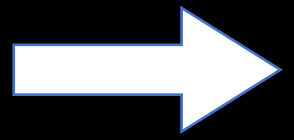
Solar Energy

- **Control:** Flight paths
  - Minimal power consumption



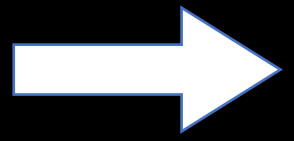
- Stratosphere
- Drone paths

- **Communications:** Long-range links



Low Frequencies

- **Data Rates**



- 10s MHz bandwidth
- Millimeter waves

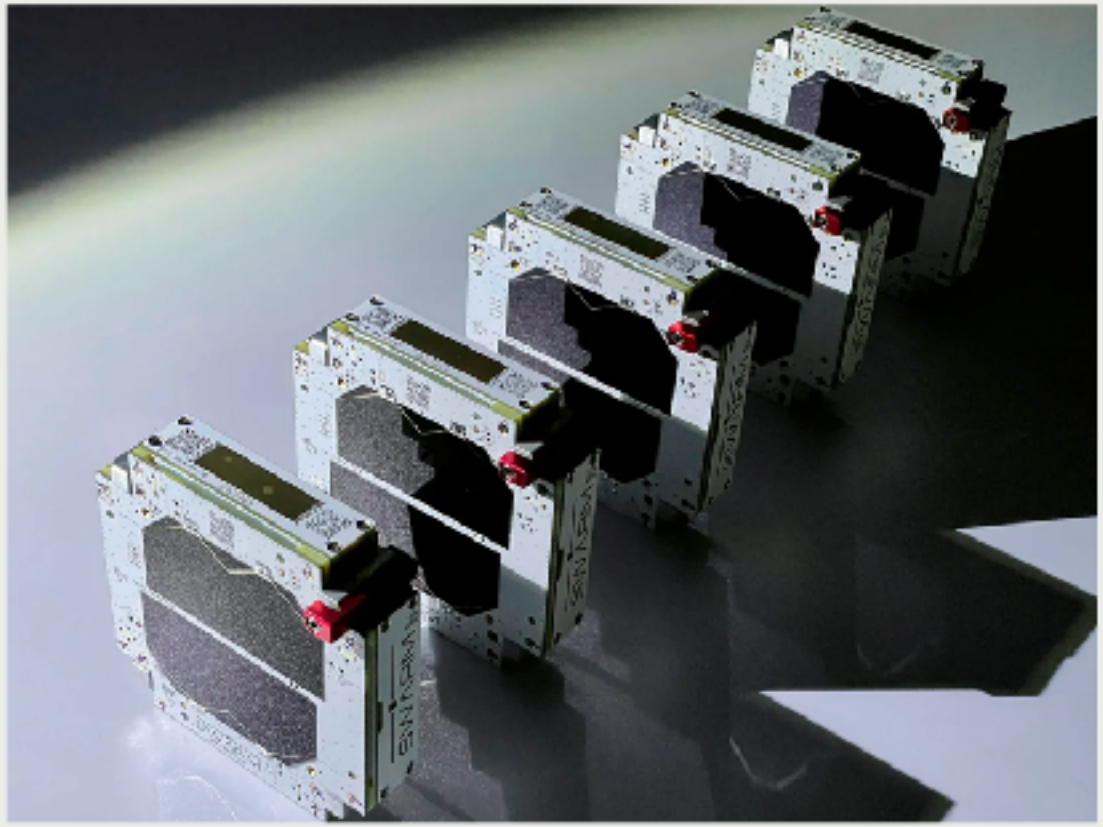
Common Opportunities: Atmospheric Conditions and Predictability

Common Opportunities: Atmospheric Conditions and Predictability

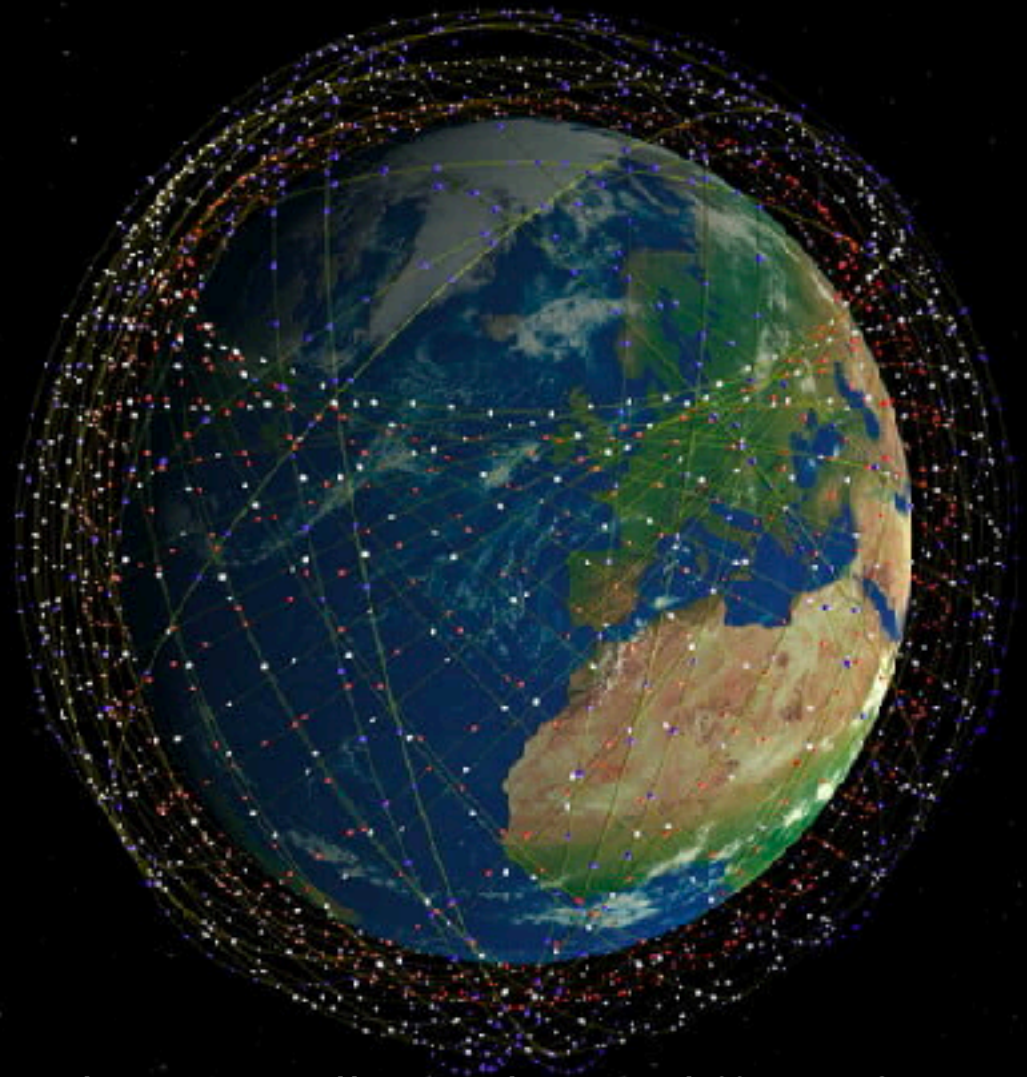
- Leverage Stratosphere in Loon/ Aquila
  - No “problematic” weather conditions (rain, winds, etc.)
  - Different stratospheric layers have different predictable currents
  - How do you move vertically?

SpaceX's Starlink

Swarm Takes LoRa Sky-High >The satellite company has adapted the popular IoT technology for use in its constellation



Each of Swarm's satellites is the size of a sandwich, but still has everything it needs to relay low-power signals from remote IoT networks to another point on the planet. PHOTO: SWARM



Satellite connectivity already exists (Iridium). Why/how are these constellations better/different ?

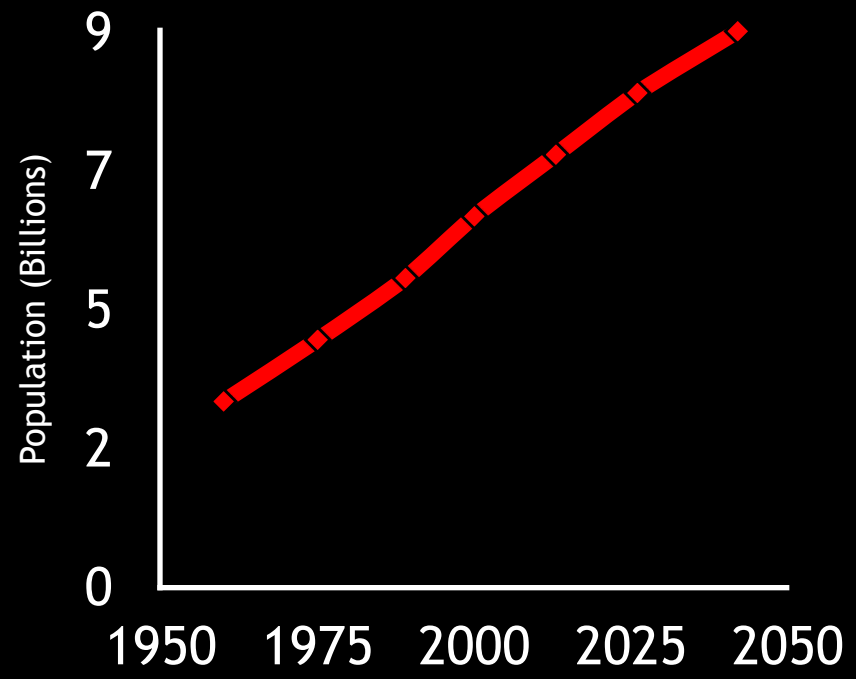
FarmBeats: An IoT System for Data-Driven Agriculture

NSDI 2017

Why Agriculture?

Agricultural output needs to double by 2050 to meet the demands

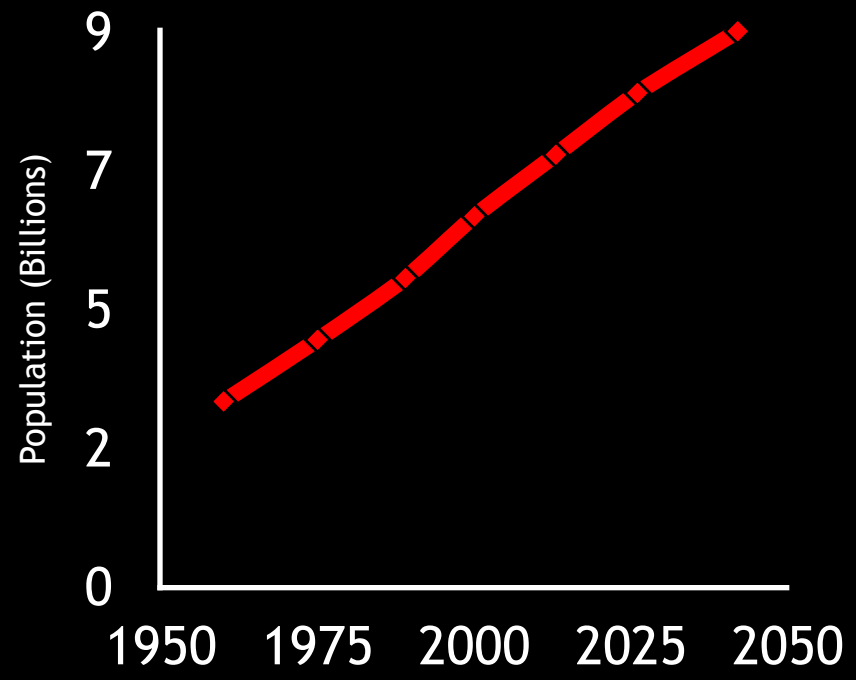
– United Nations[1]



[1]: United Nations Second Committee (Economic & Financial),

Why Agriculture?

Agricultural output needs to double by 2050 to meet the demands
– United Nations[1]



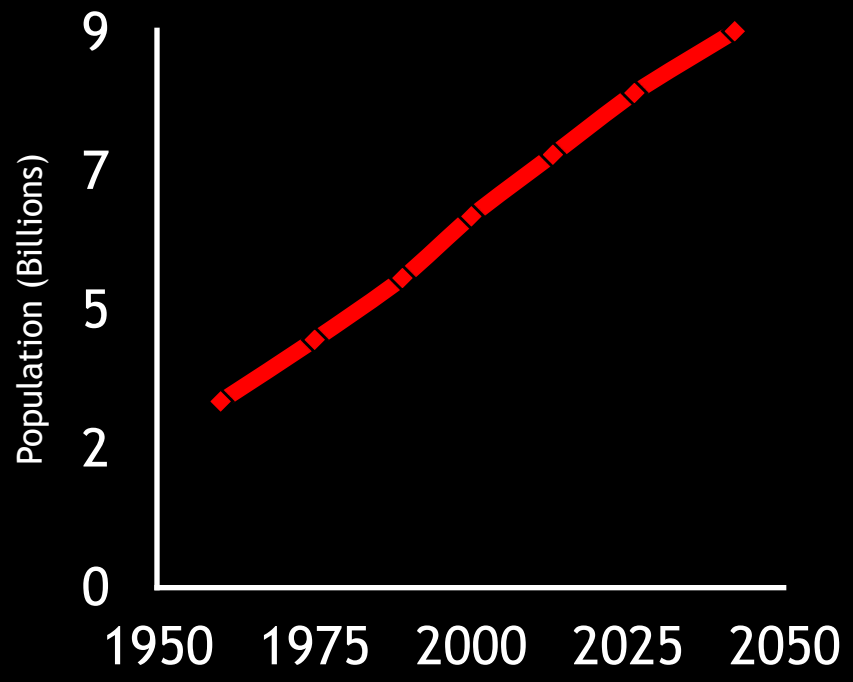
But…

- Water levels are receding
- Arable land is shrinking
- Environment is being degraded

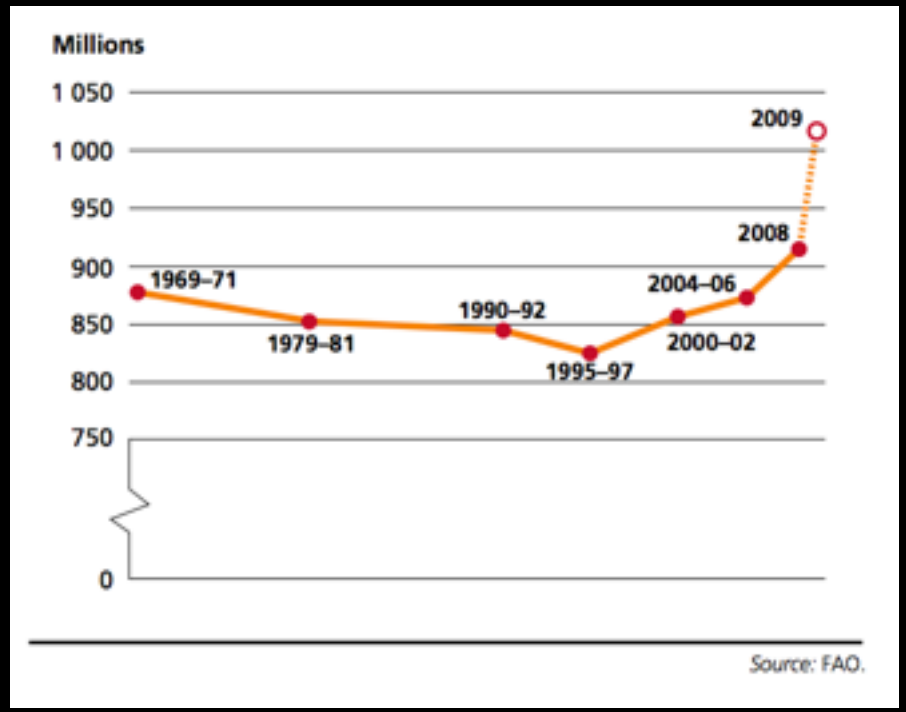
[1]: United Nations Second Committee (Economic & Financial),

Why Agriculture?

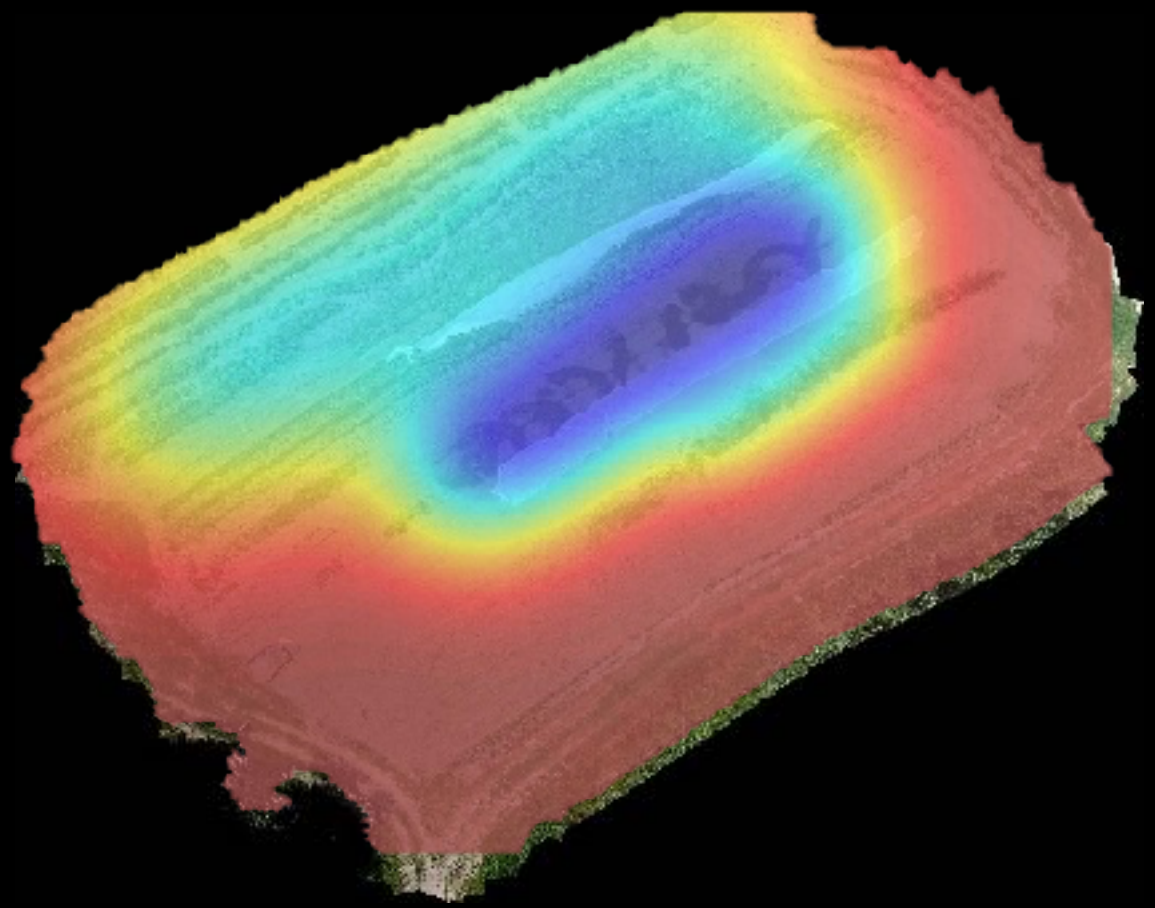
Agricultural output needs to double by 2050 to meet the demands
- United Nations



Number of World's Hungry People



Solution: Data-Driven Agriculture



Traditional vs Data-driven approach

Ag researchers have shown that it:

- Reduces waste
- Increases productivity
- Ensures sustainability

But…

According to USDA, high cost of manual data collection prevents farmers from using data-driven agriculture

IoT System for Agriculture

Microsoft Azure

Problems with this architecture?

Problem 1: No Internet Connectivity

- Most farms don’t have any internet coverage

- Even if connectivity exists, weather related outages can disable networks for weeks

Problem 2: No Power on the Farm

- Farms do not have direct power sources

- Solar power is highly prone to weather variability

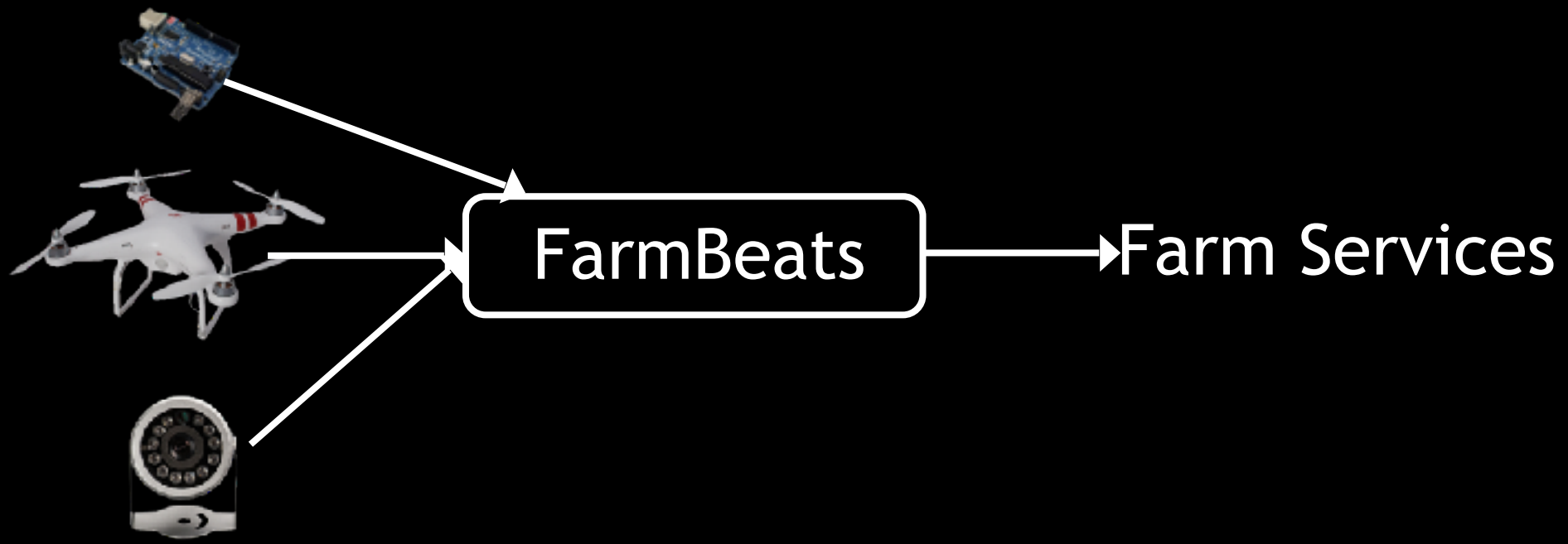
Problem 3: Limited Resources

- Need to work with sparse sensor deployments
  - Physical constraints due to farming practices
  - Too expensive to deploy and maintain

How can one design an IoT system in challenging resource-constrained environments?

Rest of this lecture

- FarmBeats: An end-to-end IoT system that enables seamless data collection for agriculture



Farmbeats System

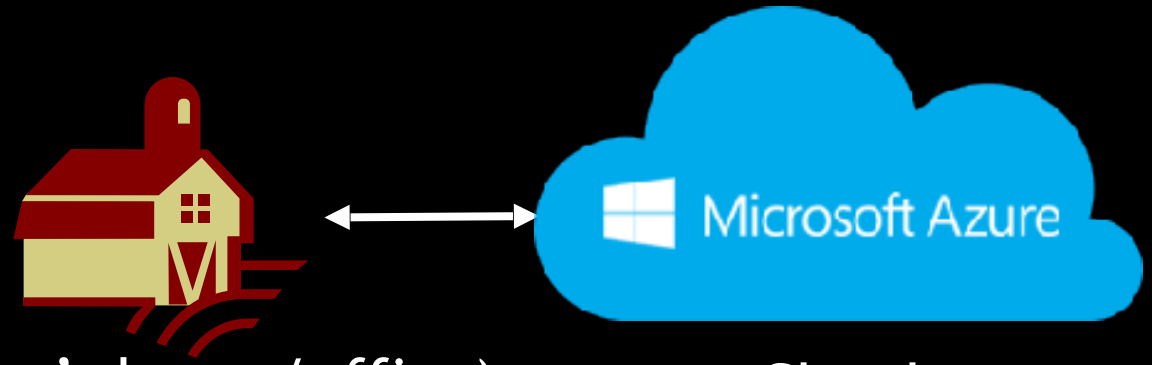
Farmbeats System

- FarmBeats: An end-to-end IoT system that enables seamless data collection for agriculture

- Solves three key challenges:
  - Internet Connectivity
  - Power Availability
  - Limited Sensor Placement

- Deployed in two farms in NY and WA for over six months

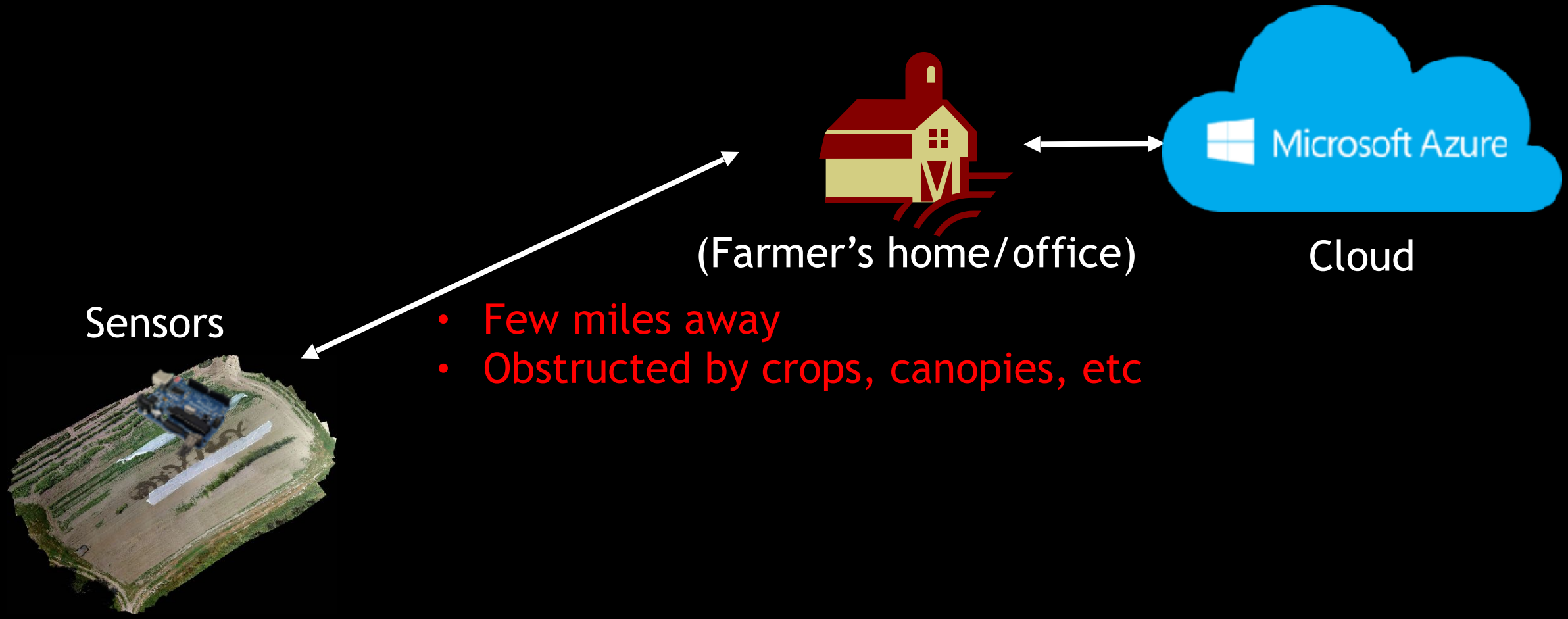
Challenge: Internet Connectivity



(Farmer's home/office)

Cloud

Challenge: Internet Connectivity



Approach: Use TV White Spaces

- Can provide long-range connectivity (10 miles)
- Can travel through crops and canopies, because of low frequencies
- Large chunks are available in rural areas=> can support large bandwidth

Idea: Use TV White Spaces

Base Station

Wi-Fi, BLE

Sensors

TV White Spaces

Few miles

(Farmer's home/office)

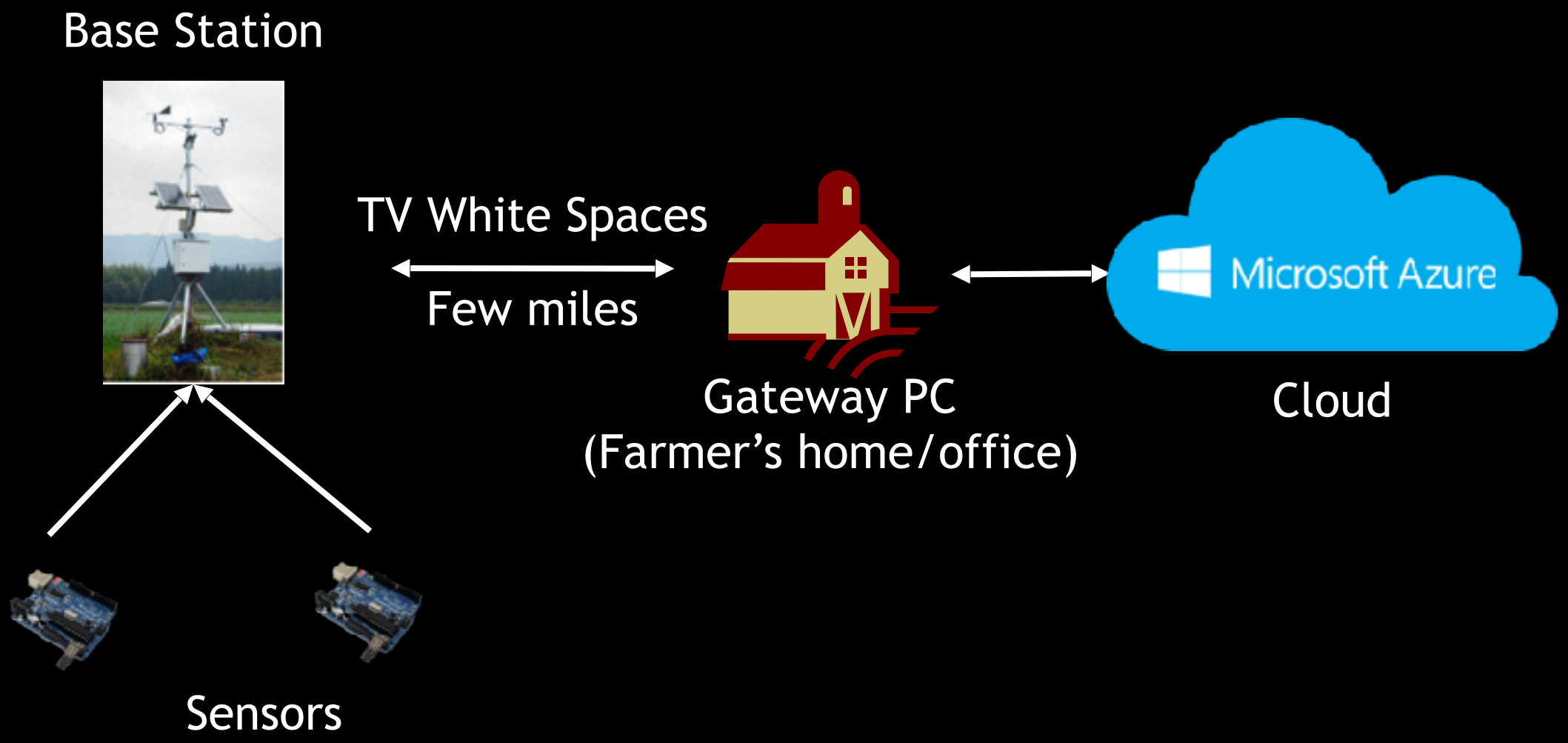
- Weak Connectivity
- Prone to outages

Cloud

Approach: Compute Locally and Send Summaries

- PC on the farm delivers time-sensitive services locally
- Combines all the sensor data into summaries
- 2-3 orders of magnitude smaller than raw data
- Cloud delivers long-term analytics and cross-farm analytics

FarmBeats Design



In this lecture

- FarmBeats: An end-to-end IoT system that enables seamless data collection for agriculture

- Solves three key challenges:
  - ✓Internet Connectivity
  - Limited Sensor Placement
  - Power Availability

- Deployed in two farms in NY and WA for over six months

Challenge: Limited Resources

- Need to work with sparse sensor deployments
  - Physical constraints due to farming practices
  - Too expensive to deploy and maintain
- How do we get coverage with a sparse sensor deployment?

Approach: Use Drones to Enhance Spatial Coverage

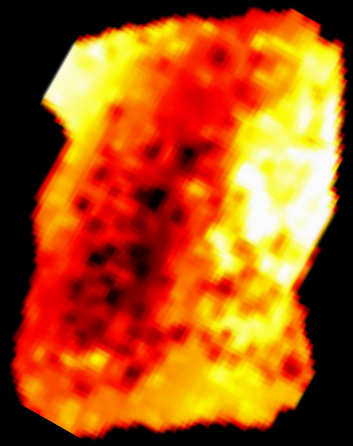
- Drones are cheap and automatic
- Can cover large areas quickly
- Can collect visual data

Combine visual data from the drones with the sensor data from the farm

Idea: Use Drones to Enhance Spatial Coverage

Drone Video

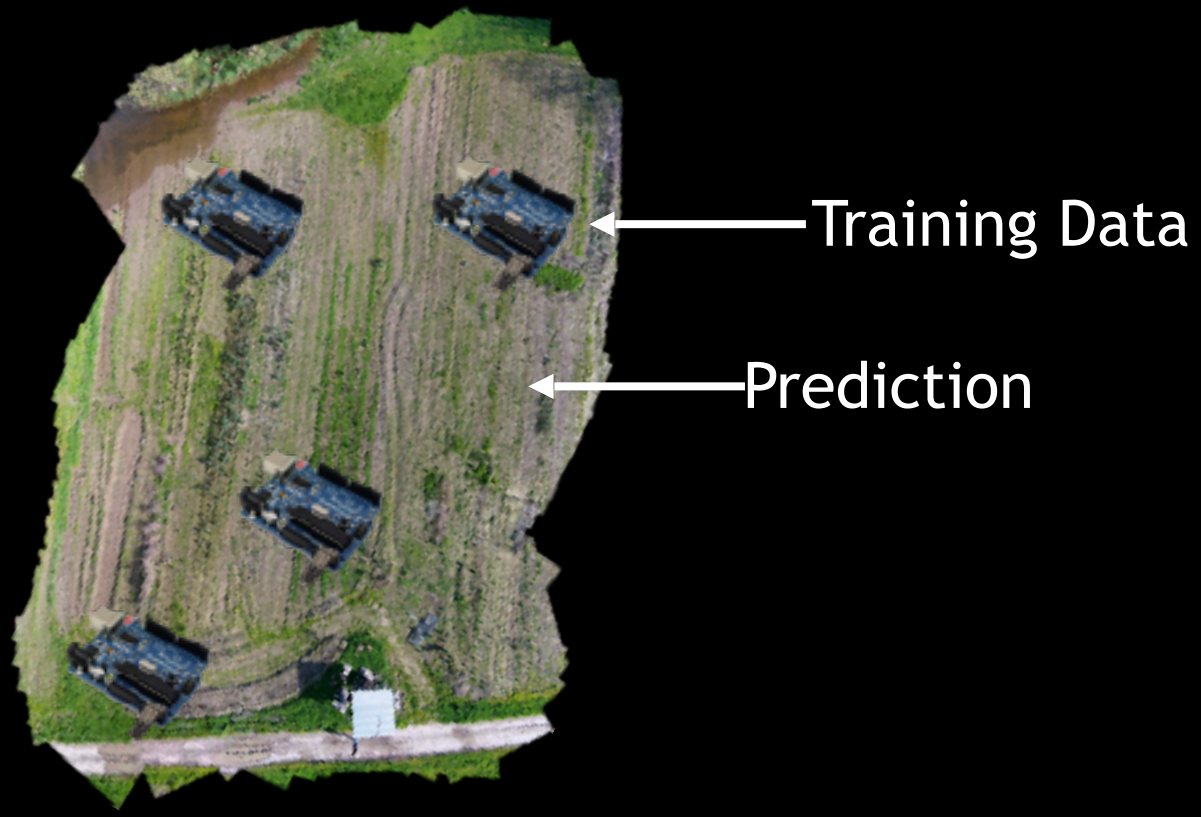
Panoramic Overview



Precision Map

Sparse Sensor Data

Formulate as a Learning Problem



Panoramic Overview

Model Insights

- **Spatial Smoothness:** Areas close to each other have similar sensor values

- **Visual Smoothness:** Areas that look similar have similar sensor values values

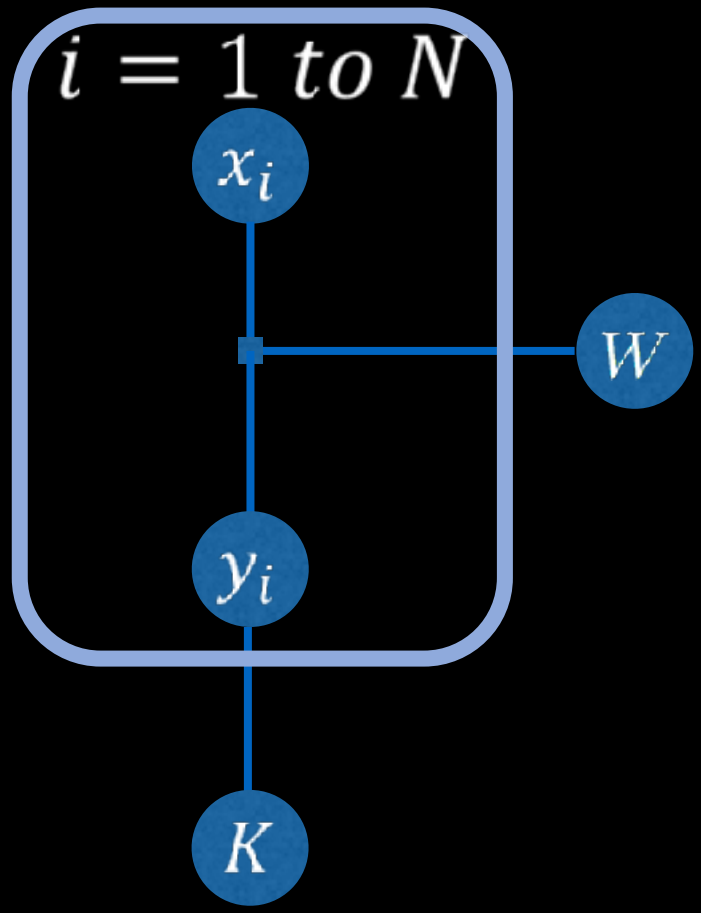
Model: Gaussian Processes

Features (visual)

Kernel (Model visual similarity)

Output (say, moisture)

Spatial Smoothness

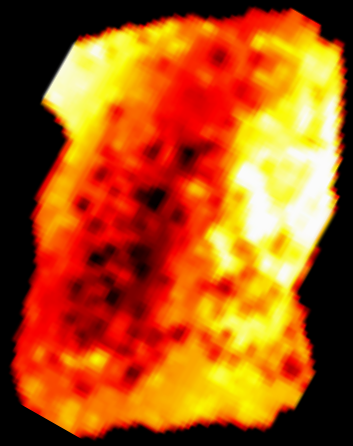


- **Training Phase:** Learn K and W
- **Test Phase:** Generate outputs for unknown areas

Using Sparse Sensor Data

Drone Video

Panoramic Overview



Precision Map

100 kB summary

FarmBeats can use drones to expand the sparse sensor data and create summaries for the farm

Farmbeats Paper

- FarmBeats: An end-to-end IoT system that enables seamless data collection for agriculture

- Solves three key challenges:
  - ✓Internet Connectivity
  - ✓Limited Sensor Placement
  - Power Availability

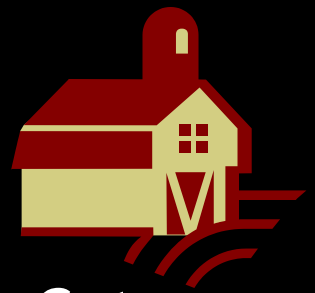
- Deployed in two farms in NY and WA for over six months

Challenge: Power Availability is Variable

Farm

Battery dies due to cloudy/rainy/snowy weather

TV White Spaces



Gateway
(Farmer's home/office)

Cloud

Challenge: Power Availability is Variable

- Solar powered battery saw up to 30% downtime in cloudy months
- Miss important data like flood monitoring

How do we deal with weather-based power variability?

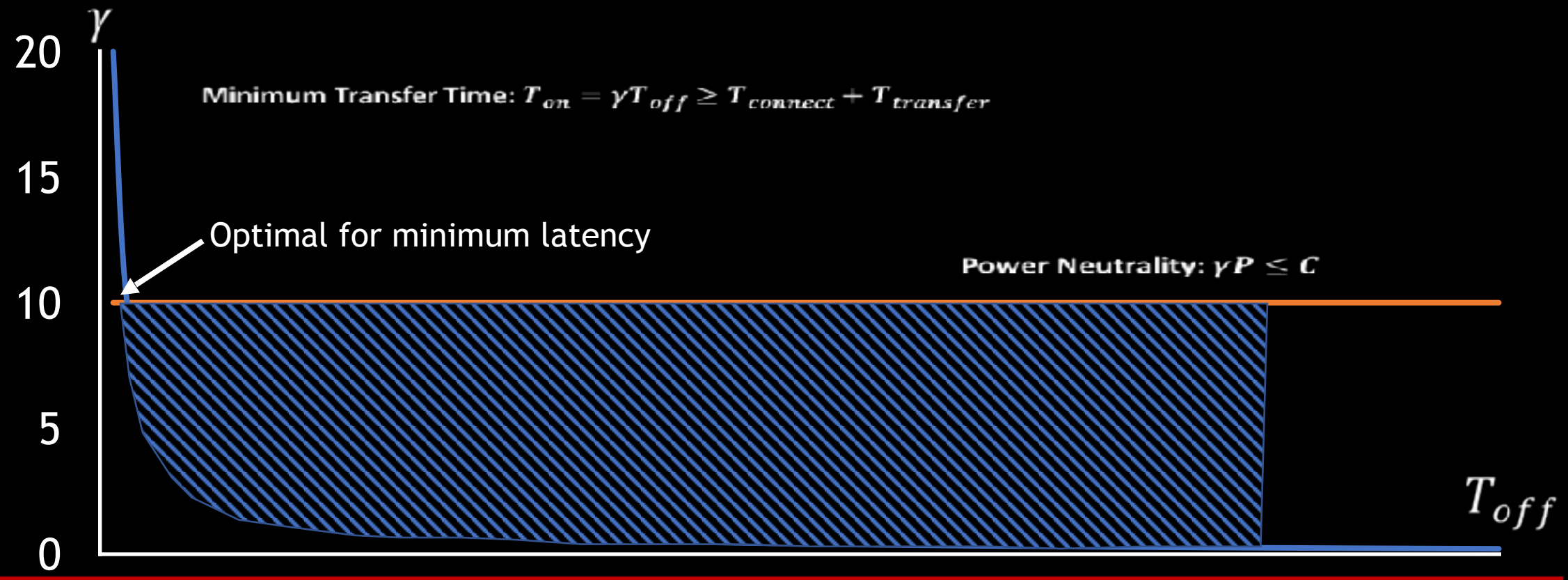
Approach: Weather is Predictable

- Use weather forecasts to predict solar energy output
- Ration the load to fit within power budget

Idea: Weather is Predictable

- γ: Duty Cycle ratio, T_{on}: On time in each cycle, T_{off}: Off time
- $\gamma = \frac{T_{on}}{T_{off}}$ Gamma's denominator is T_total = T_on + T_off, but T_on << T_off
- Constraints:
  - **Power Neutrality:** $\gamma P \leq C$
  - **Minimum Transfer Time:** $T_{on} \geq T_{connect} + T_{transfer}$

Solution: Weather is predictable



FarmBeats can use weather forecasts to duty cycle the base station, with minimum latency

How would you design the sensors?

How would you design the sensors?

- Low-power — backscatter
  - problems: intermittent, or base station runs out of power
  - Limited range
- Semi-passive?
- Power decays with 1/d^2 (Sphere) => waste less energy by multiple harvesters
- Can even harness power from whitespace emissions

Farmbeats

- FarmBeats: An end-to-end IoT system that enables seamless data collection for agriculture

- Solves three key challenges:
  - ✓Internet Connectivity
  - ✓Limited Sensor Placement
  - ✓Power Availability

- Deployed in two farms in NY and WA for over six months

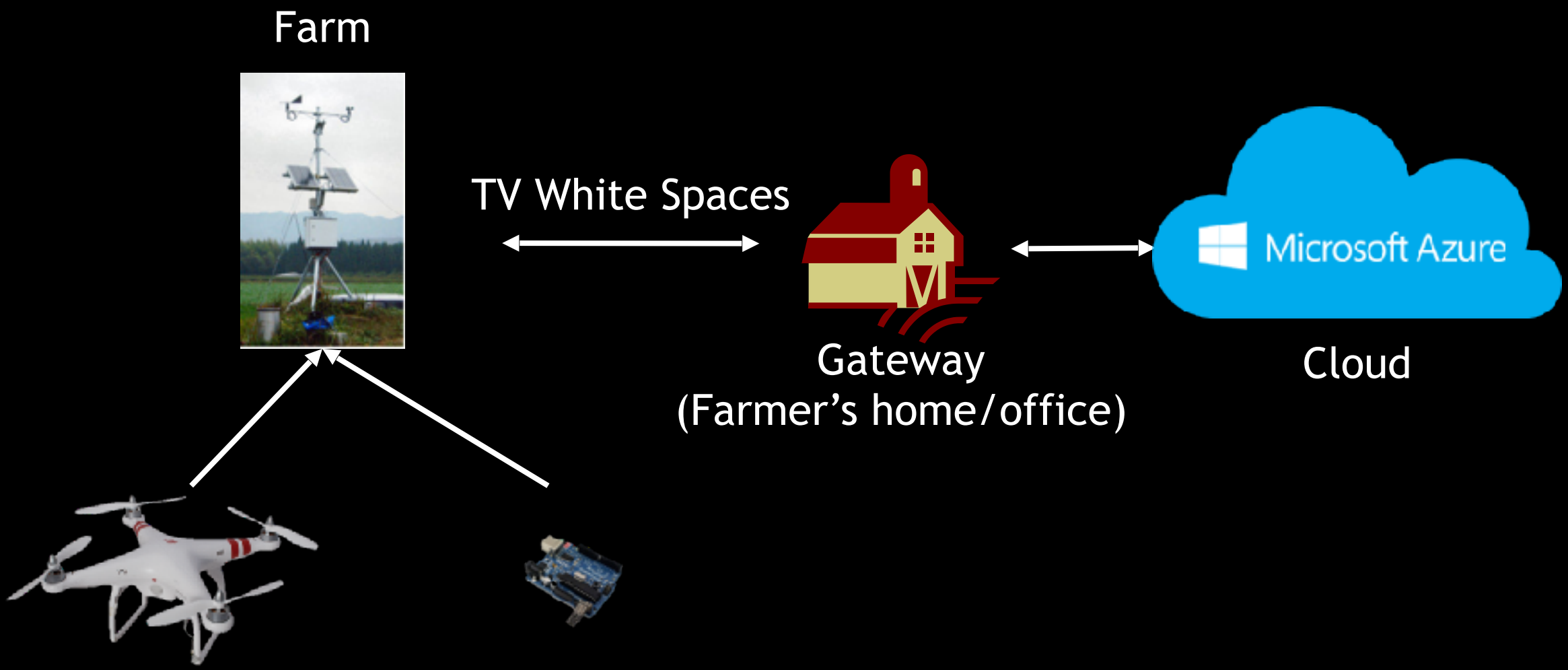
Deployment

- Six months deployment in two farms: Upstate NY (Essex), WA (Carnation)
- The farm sizes were 100 acres and 5 acres respectively
- Sensors:
  - DJI Drones
  - Particle Photons with Moisture, Temperature, pH Sensors
  - IP Cameras to capture IR imagery as well as monitoring
- Cloud Components: Azure Storage and IoT Suite

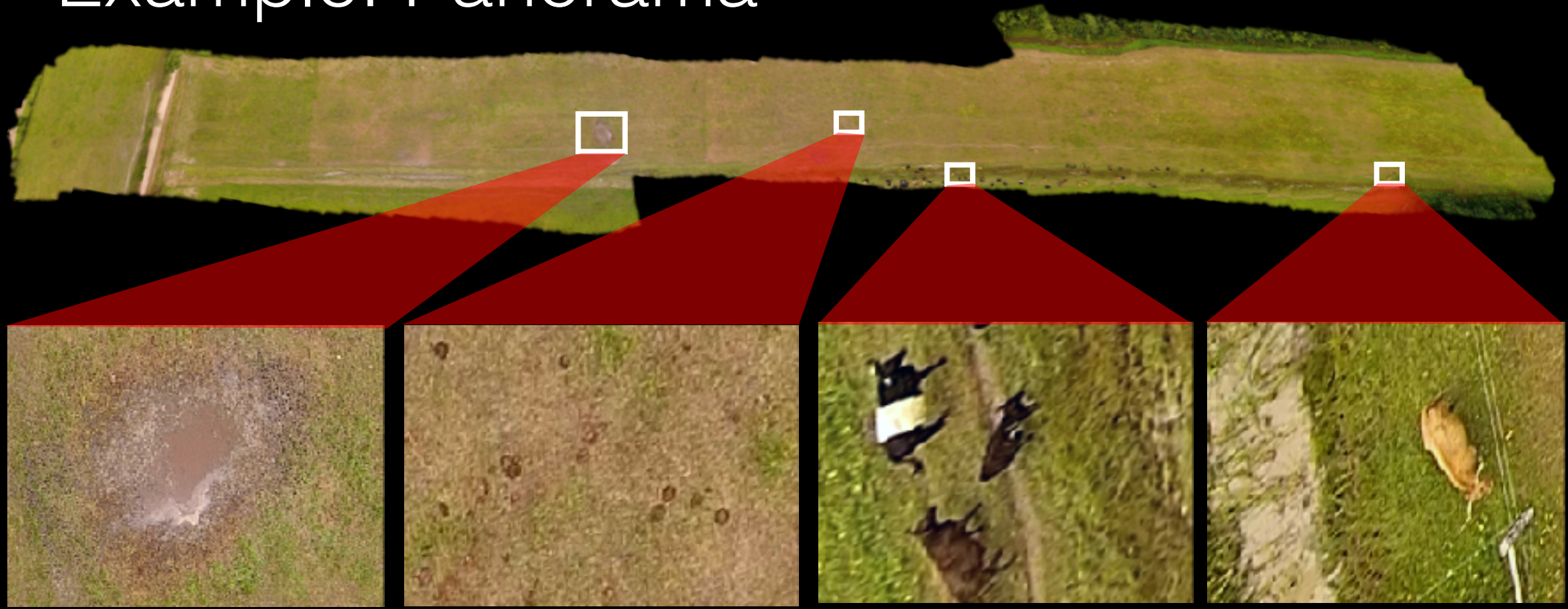
Deployment Statistics

- Used 10 sensor types, 3 camera types and 3 drone versions
- Deployed >100 sensors and ~10 cameras
- Collected >10 million sensor measurements, >0.5 million images, 100 drone surveys
- Resilient to week long outage from a thunderstorm

FarmBeats: Usage



Example: Panorama



Water puddle

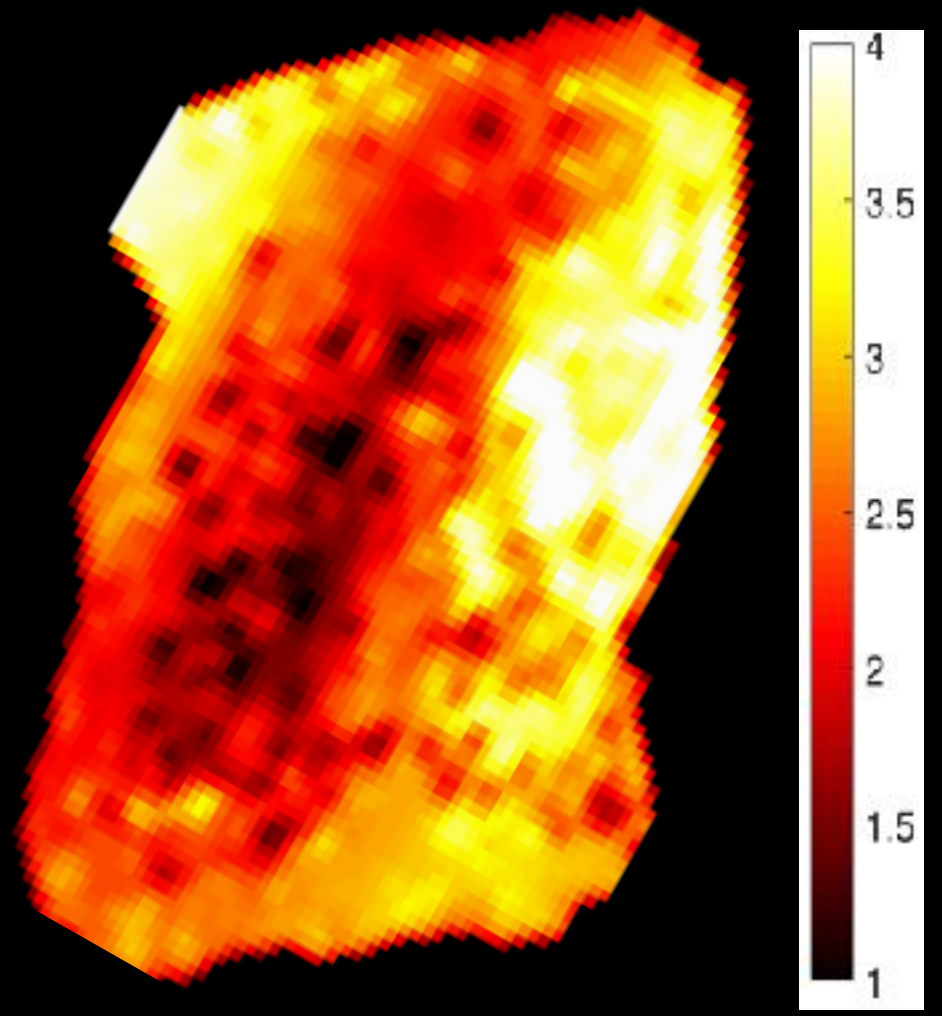
Cow excreta

Cow Herd

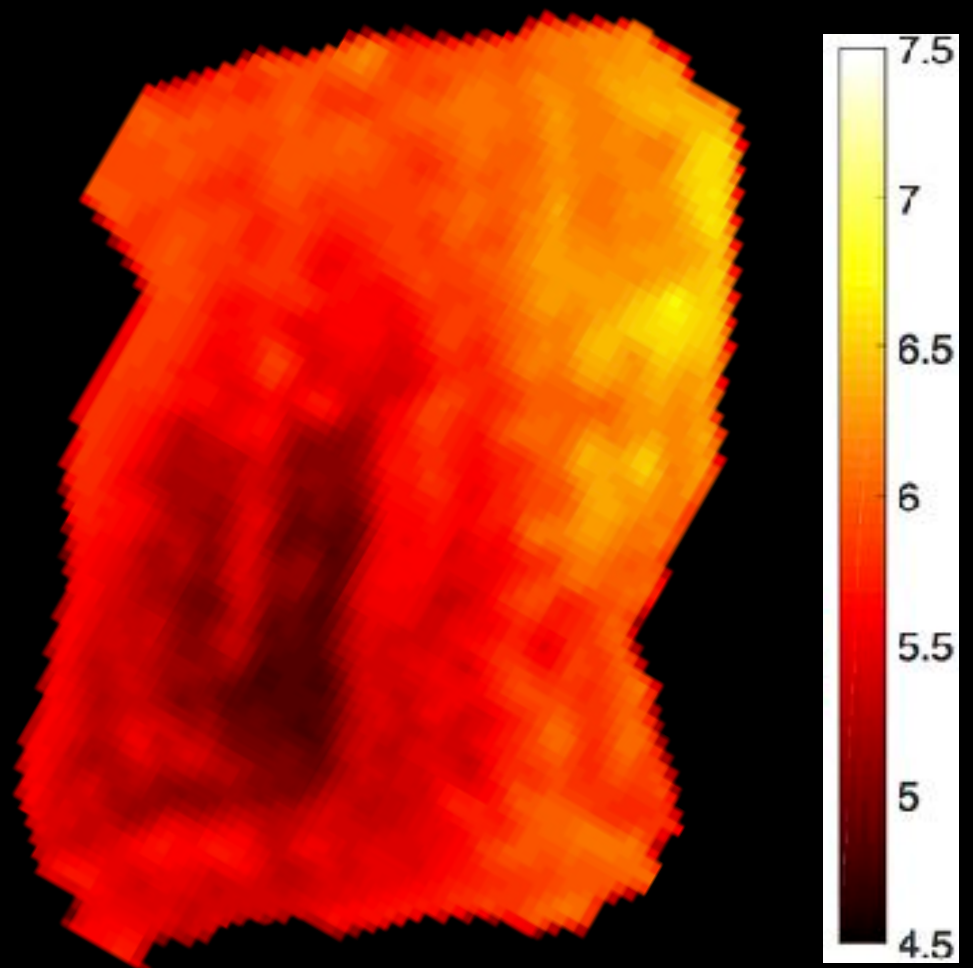
Stray cow

Precision Map: Panorama Generation

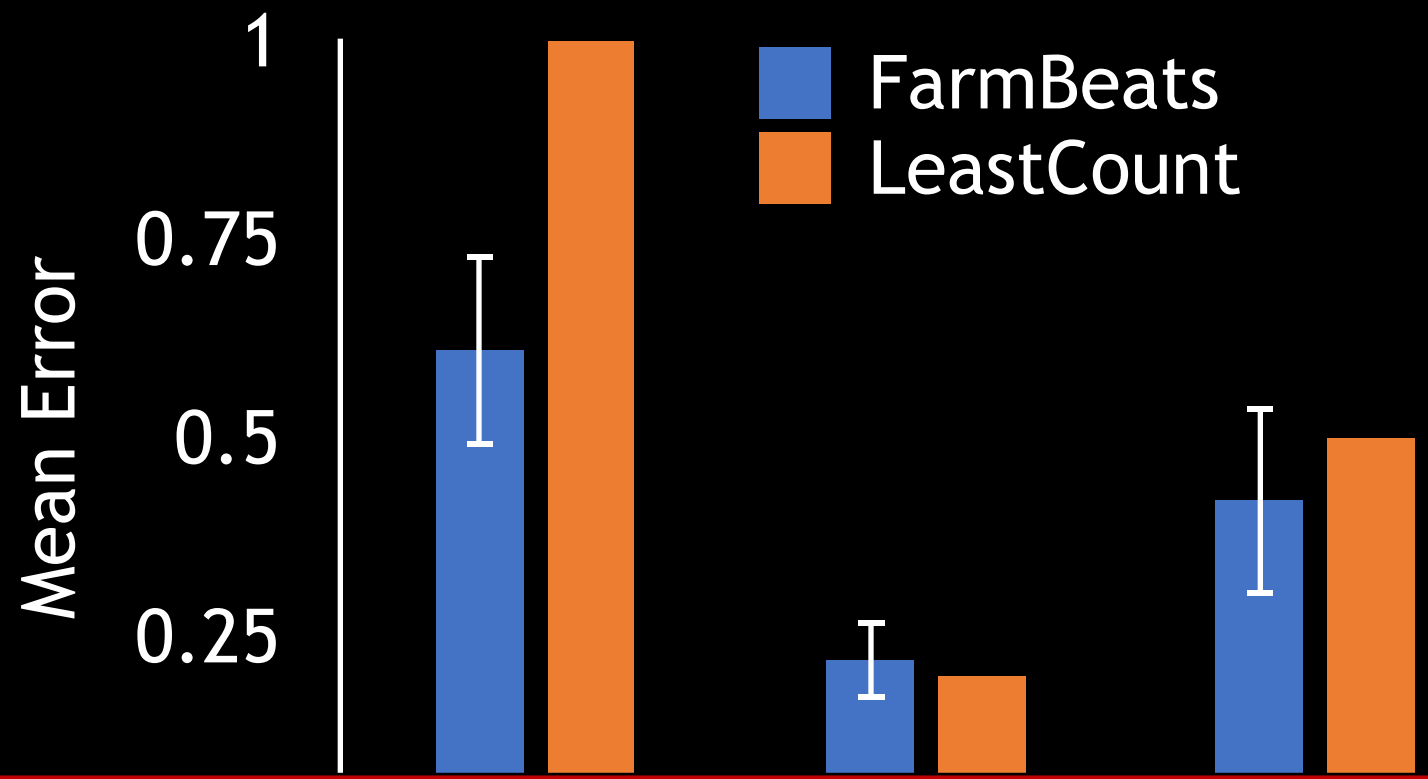
Precision Map : Moisture



Precision Map : pH

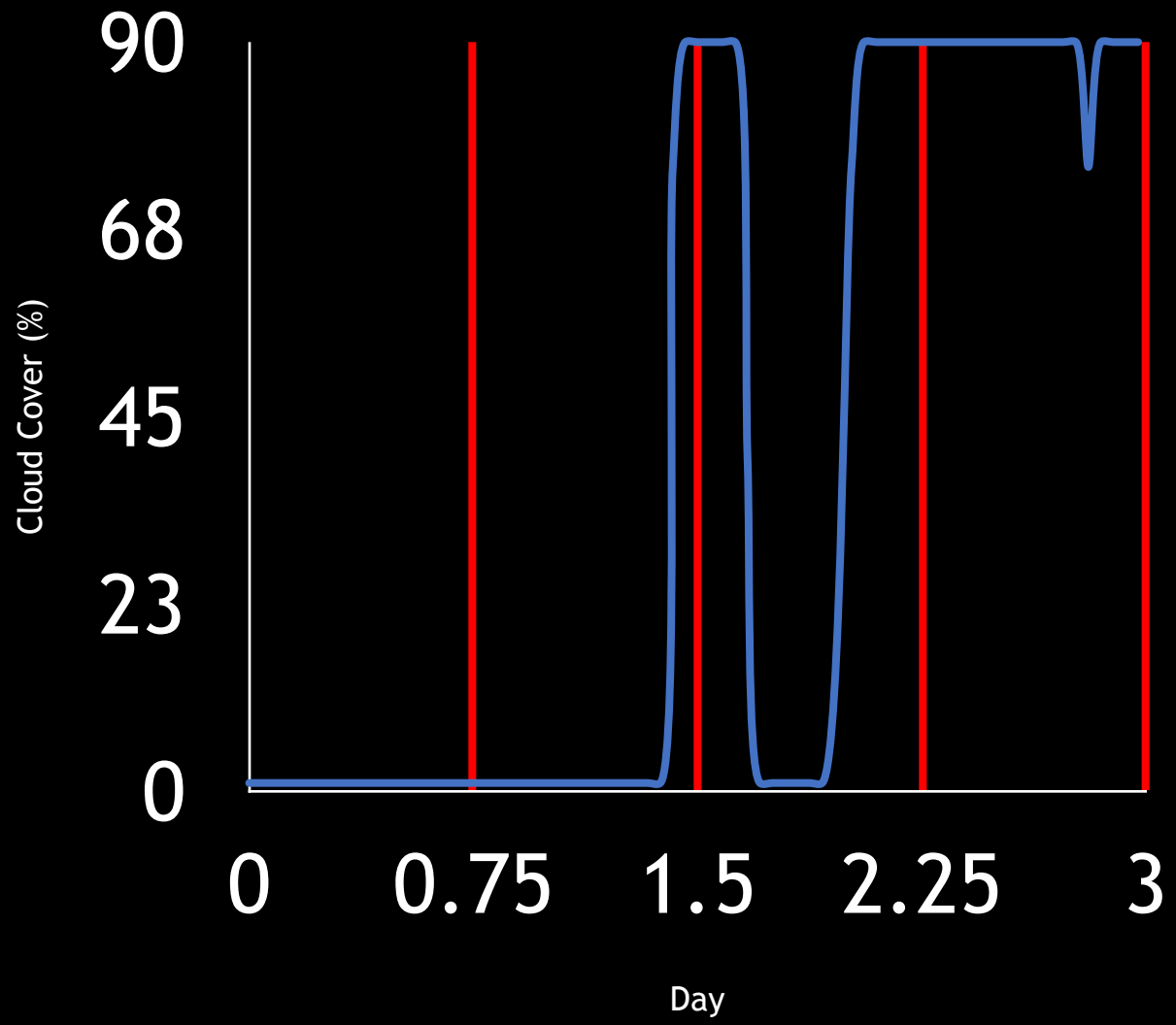


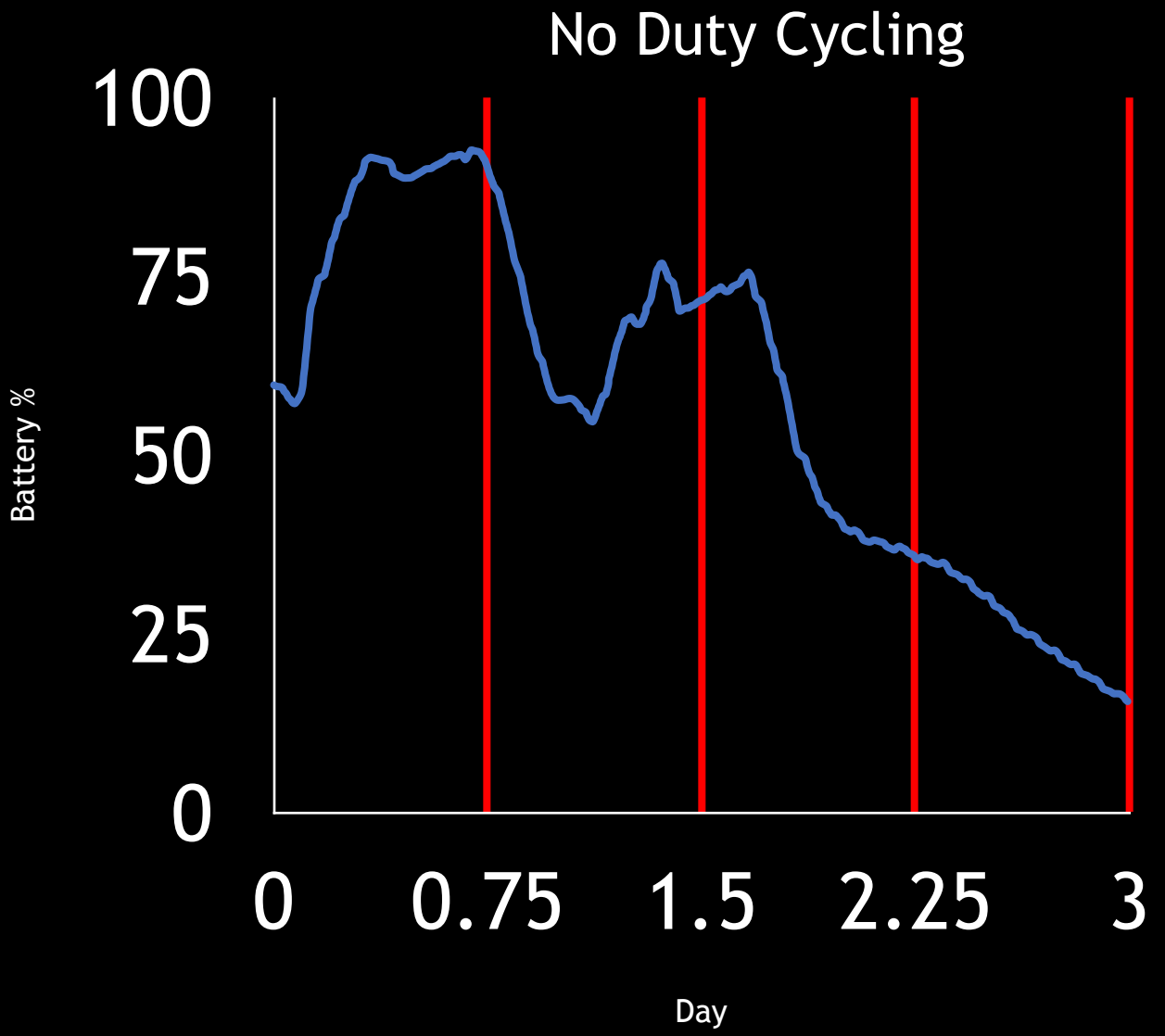
Precision Map: Accuracy



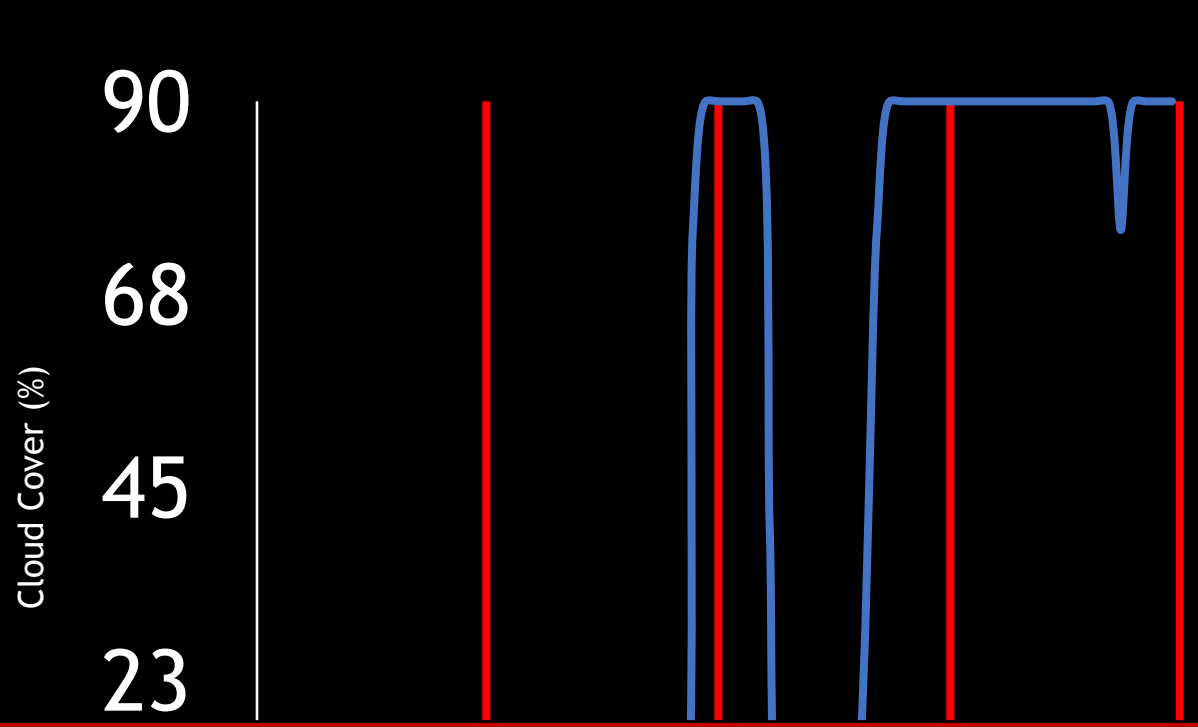
FarmBeats can accurately expand coverage by orders of magnitude using a sparse sensor deployment

Weather-Aware Duty Cycling

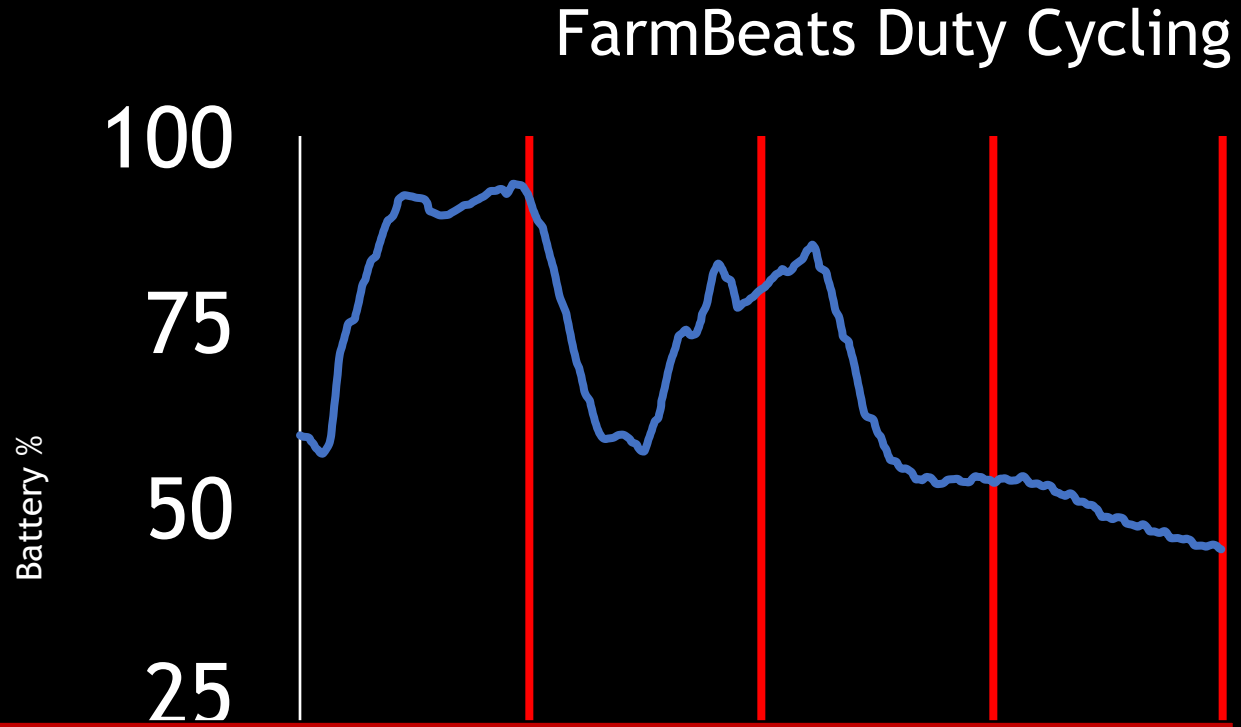




Weather-Aware Duty Cycling



FarmBeats Duty Cycling

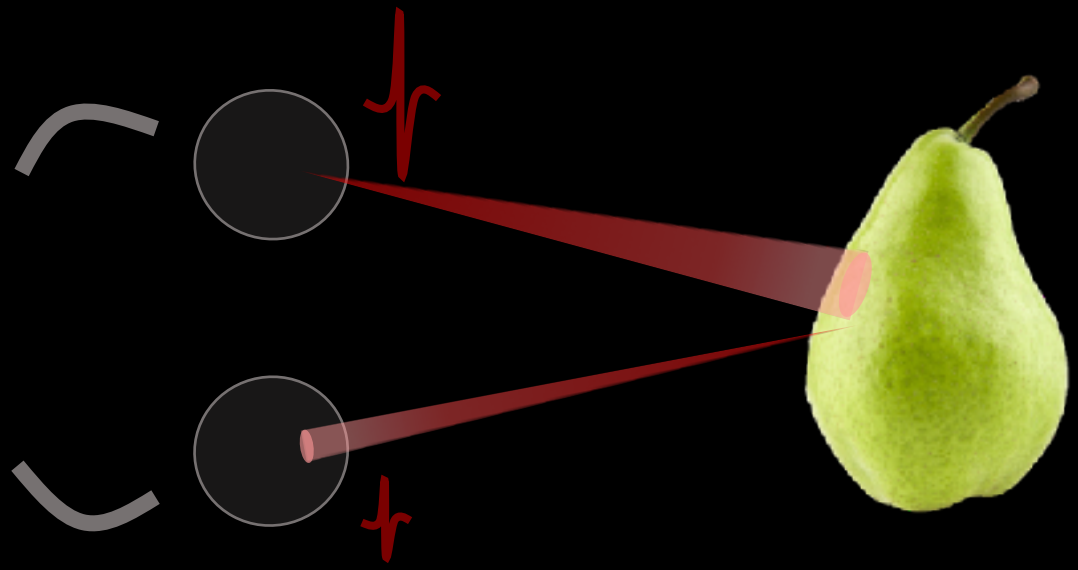


Reduced downtime from 30% to 0% for month long data (September)

Objectives of Today's Lecture

- Learning about aerial-based Connectivity (Loon, Aquila)
- Agriculture IoT
  - The IoT Challenges
  - An IoT System solution
- Wireless sensing for agriculture

AgriTera: Accurate Non-Invasive Fruit Ripeness Sensing via Sub-Terahertz Wireless Signals



MobiCom 2023

Can we detect the ripeness of fruit beneath its peel non-invasively?

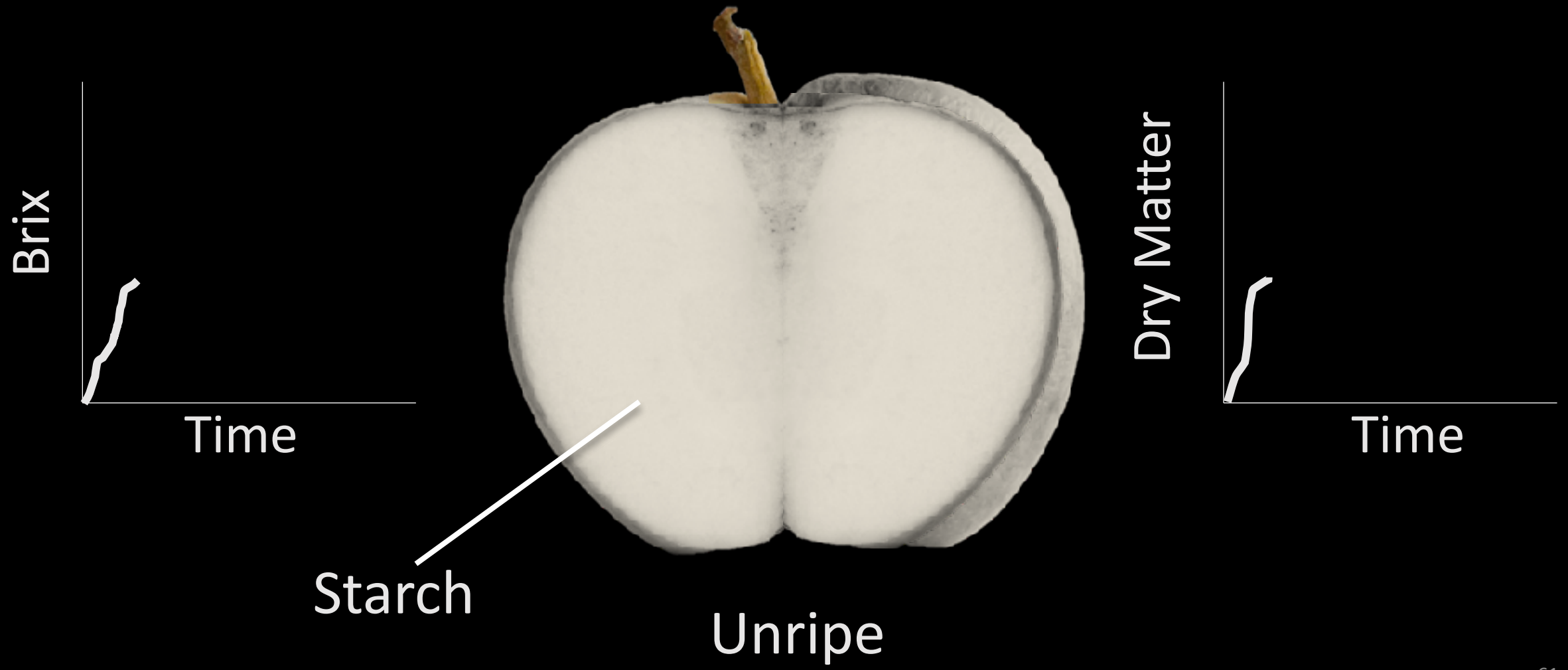
Is it ripe?

Does it feel firm?

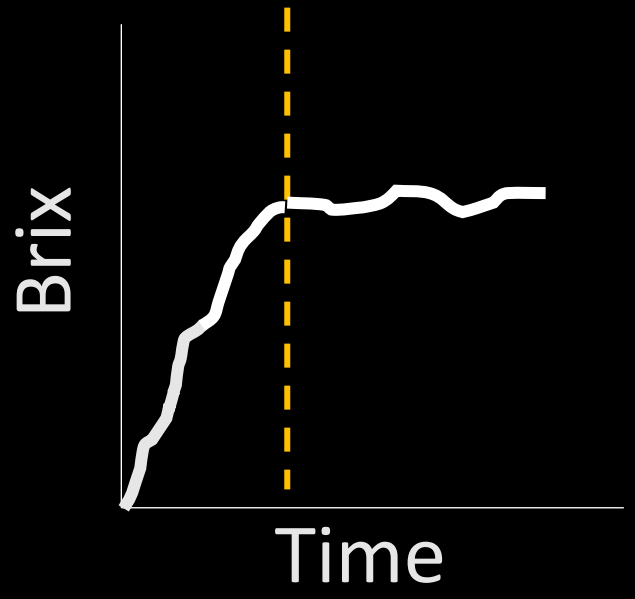
Has it rotten?

Nearly *50%* of the fruits and vegetables produced worldwide are wasted each year

Quantifying fruit ripeness

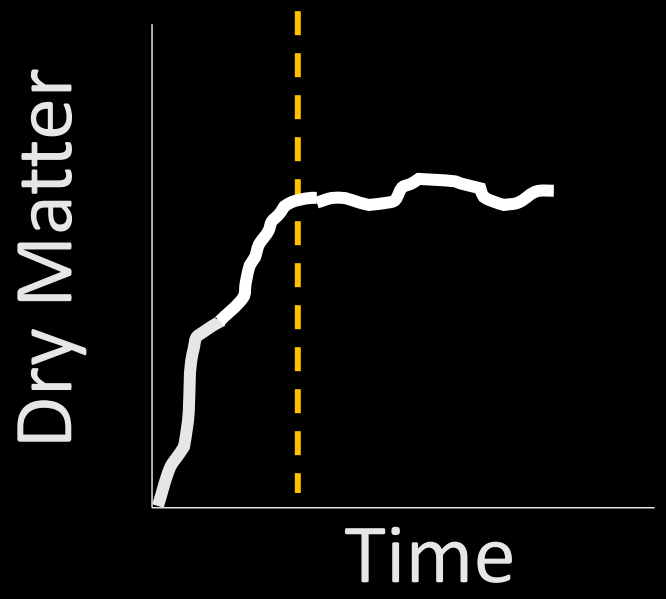


Quantifying fruit ripeness



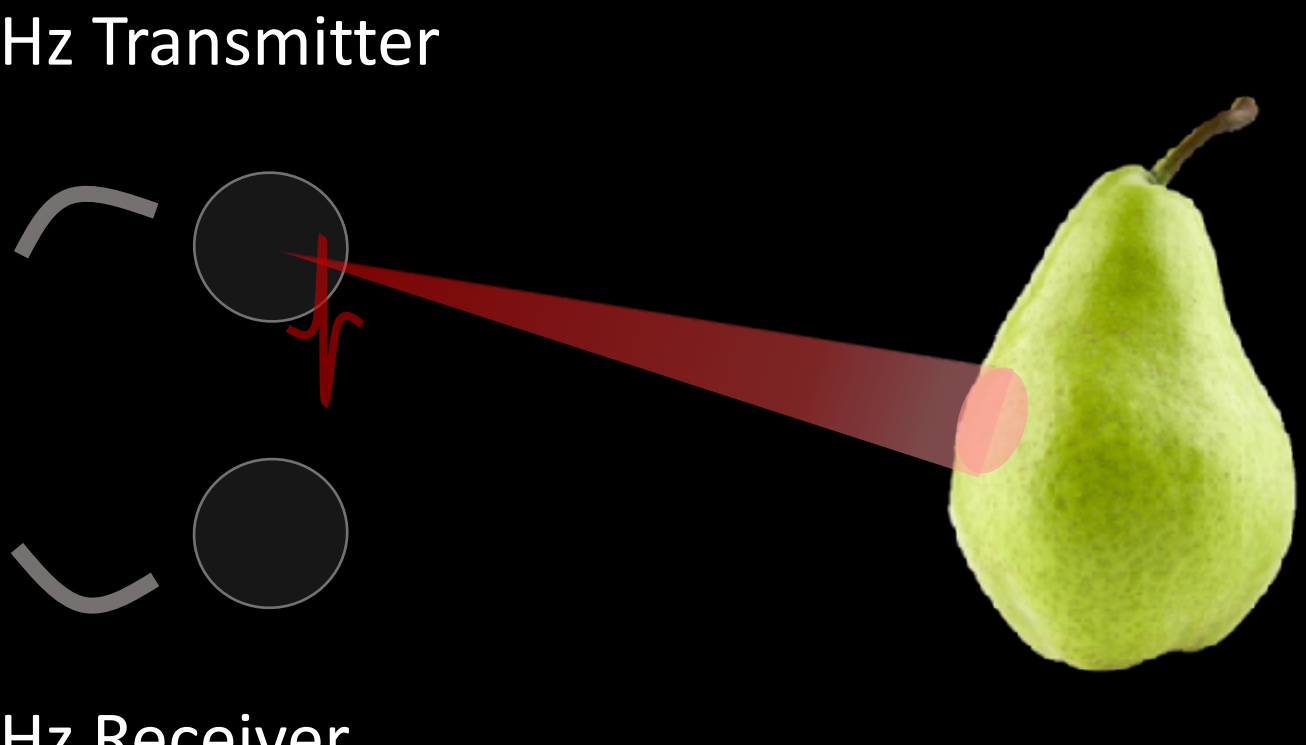
Ripe

Sugar

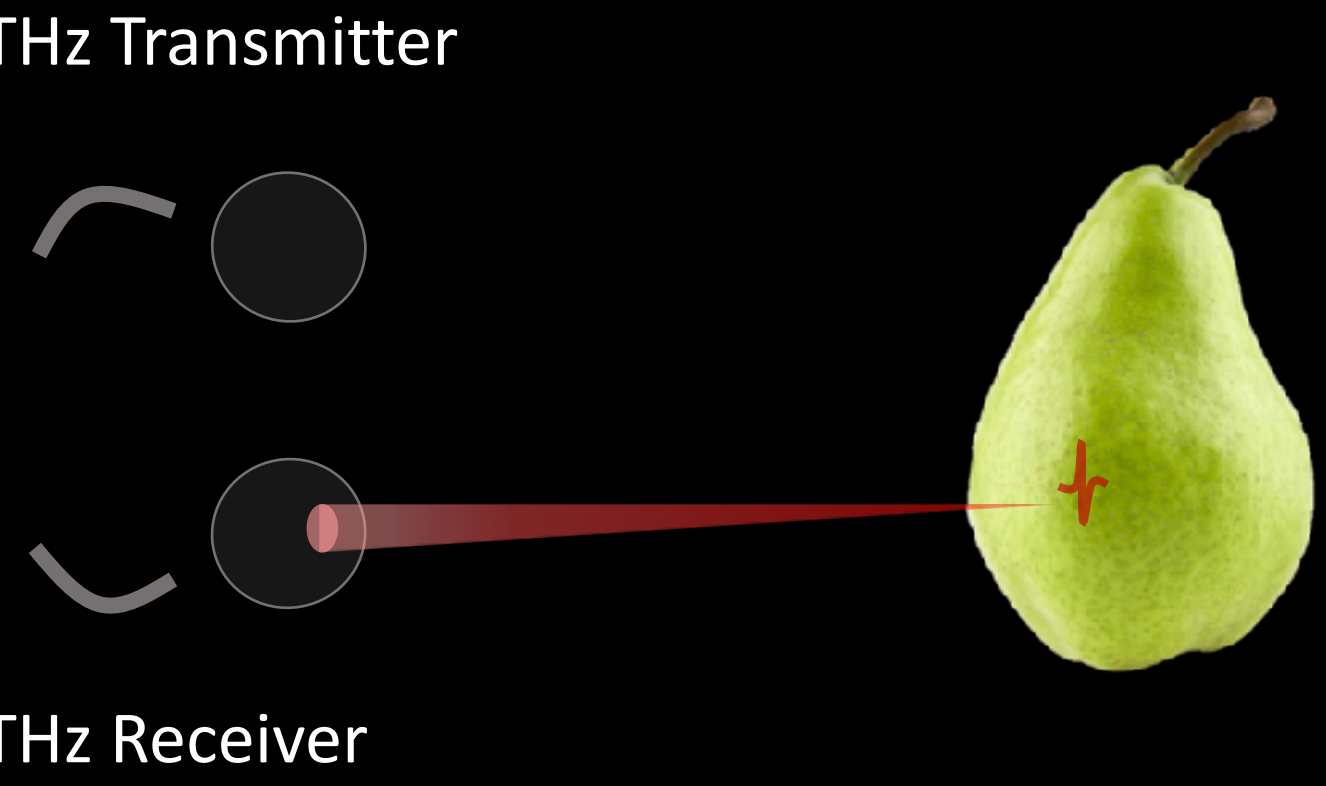


How can we measure Brix and Dry-Matter non-invasively and without contact?

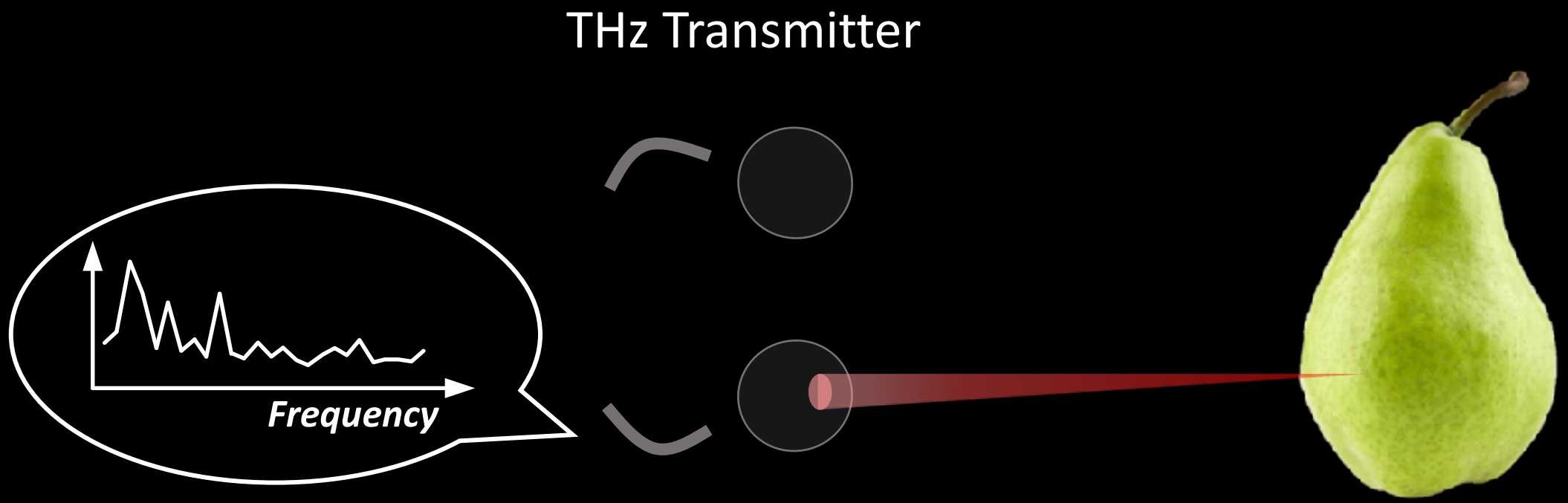
Approach : Exploit the sub-THz band to determine Ripeness Metrics



Approach : Exploit the sub-THz band to determine Ripeness Metrics

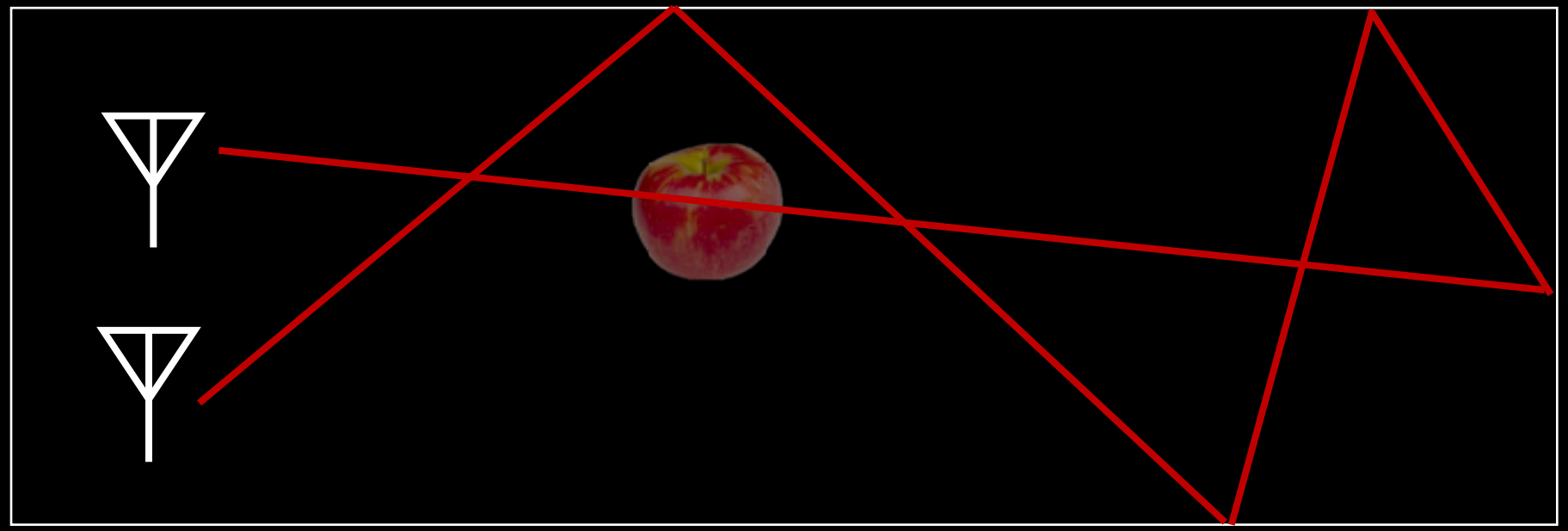


Approach : Exploit the sub-THz band to determine Ripeness Metrics



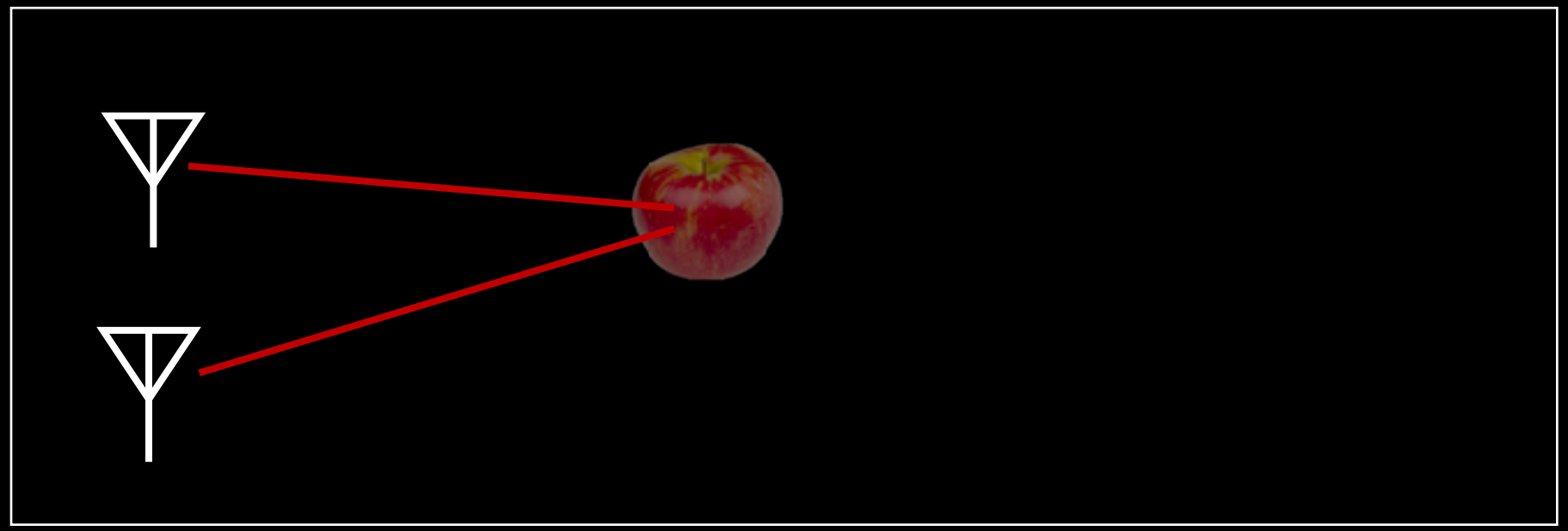
Changes in refractive-index leave a footprint in the sub-THz band

Why Sub-THz bands?



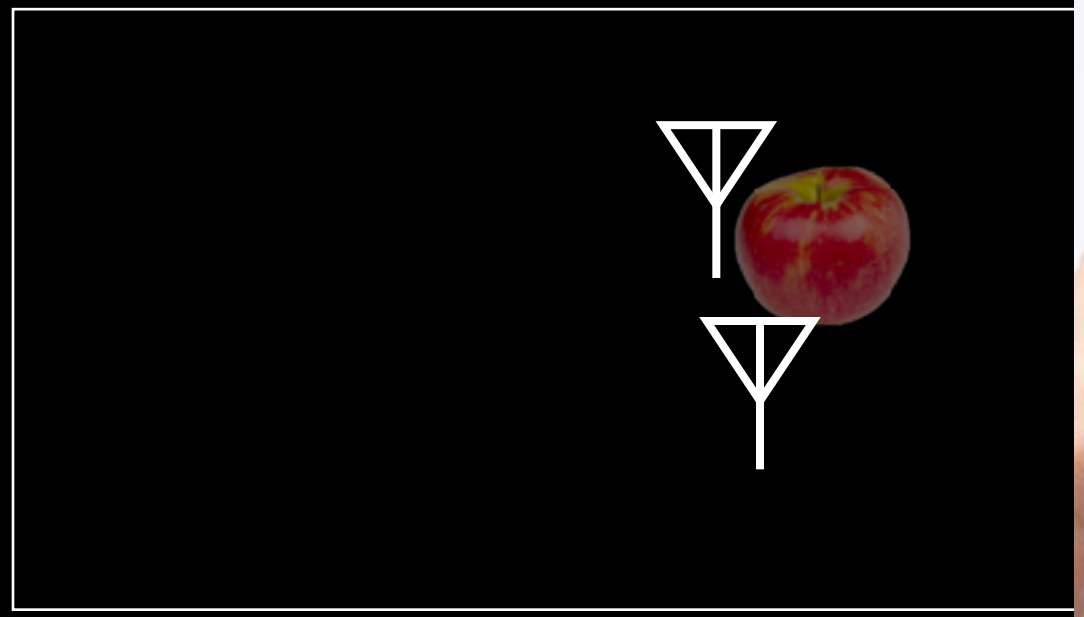
Wi-Fi mmWave sub-THz NIR Visible

Why Sub-THz bands?



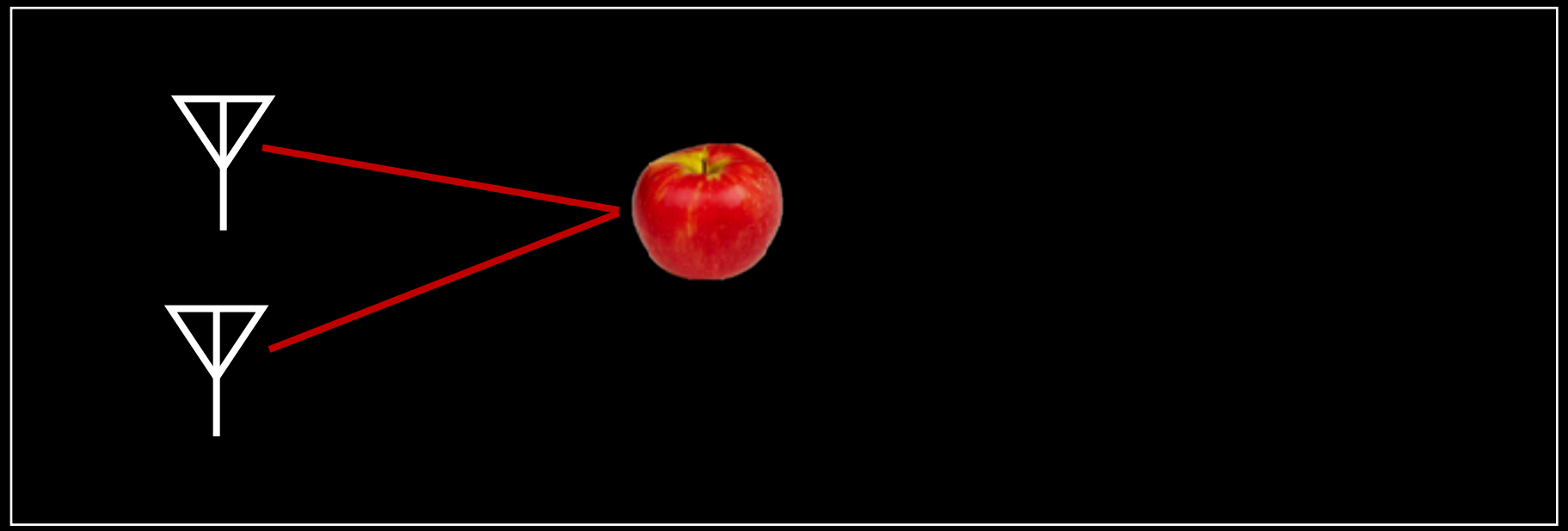
Wi-Fi mmWave sub-THz NIR Visible

Why Sub-THz bands?



Wi-Fi mmWave sub-THz NIR Visible

Why Sub-THz bands?

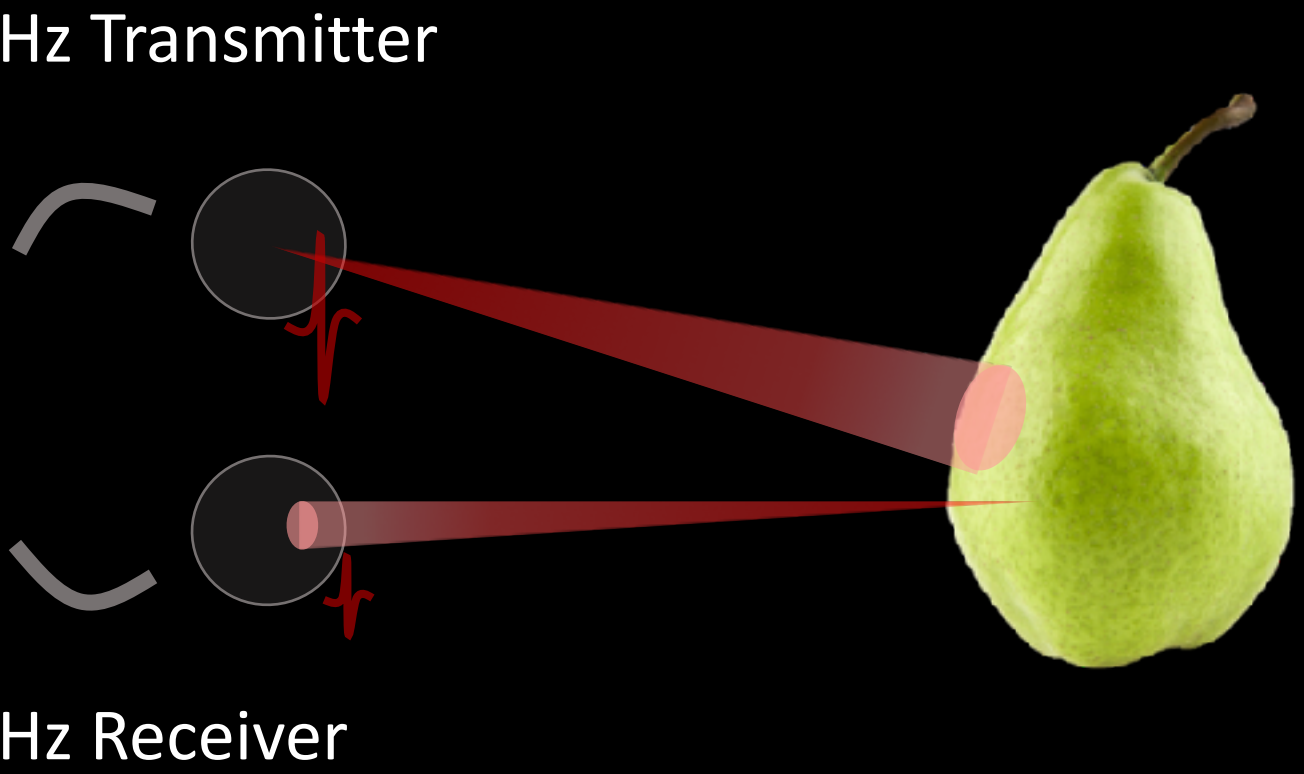


Wi-Fi mmWave sub-THz NIR Visible

AgriTera

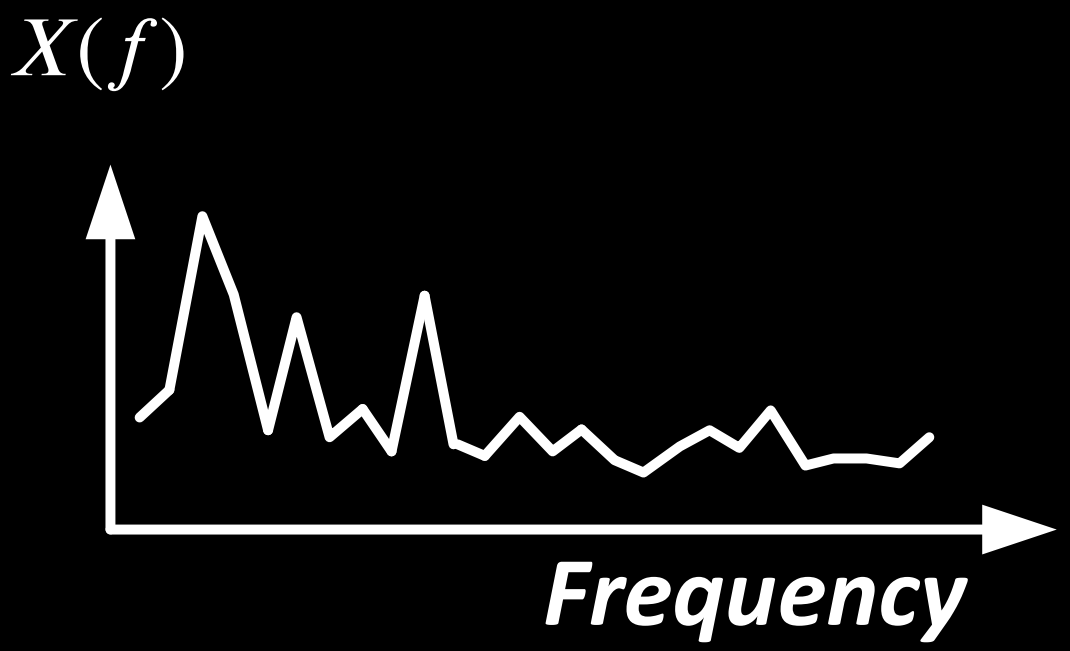
- Estimates fruit ripeness metrics such as Brix and Dry-Matter without contact
- Works accurately with different types of fruits with different structures, surface properties, peel thickness and pulp types.
- Implemented and evaluated in practical environments with an average NRMSE error of 0.55%

Key Idea : Exploit the sub-THz band to determine Ripeness Metrics



How can we map sub-THz spectra to Brix and Dry-Matter?

Approach: Chemometric Analysis for Extracting Ripeness Metrics



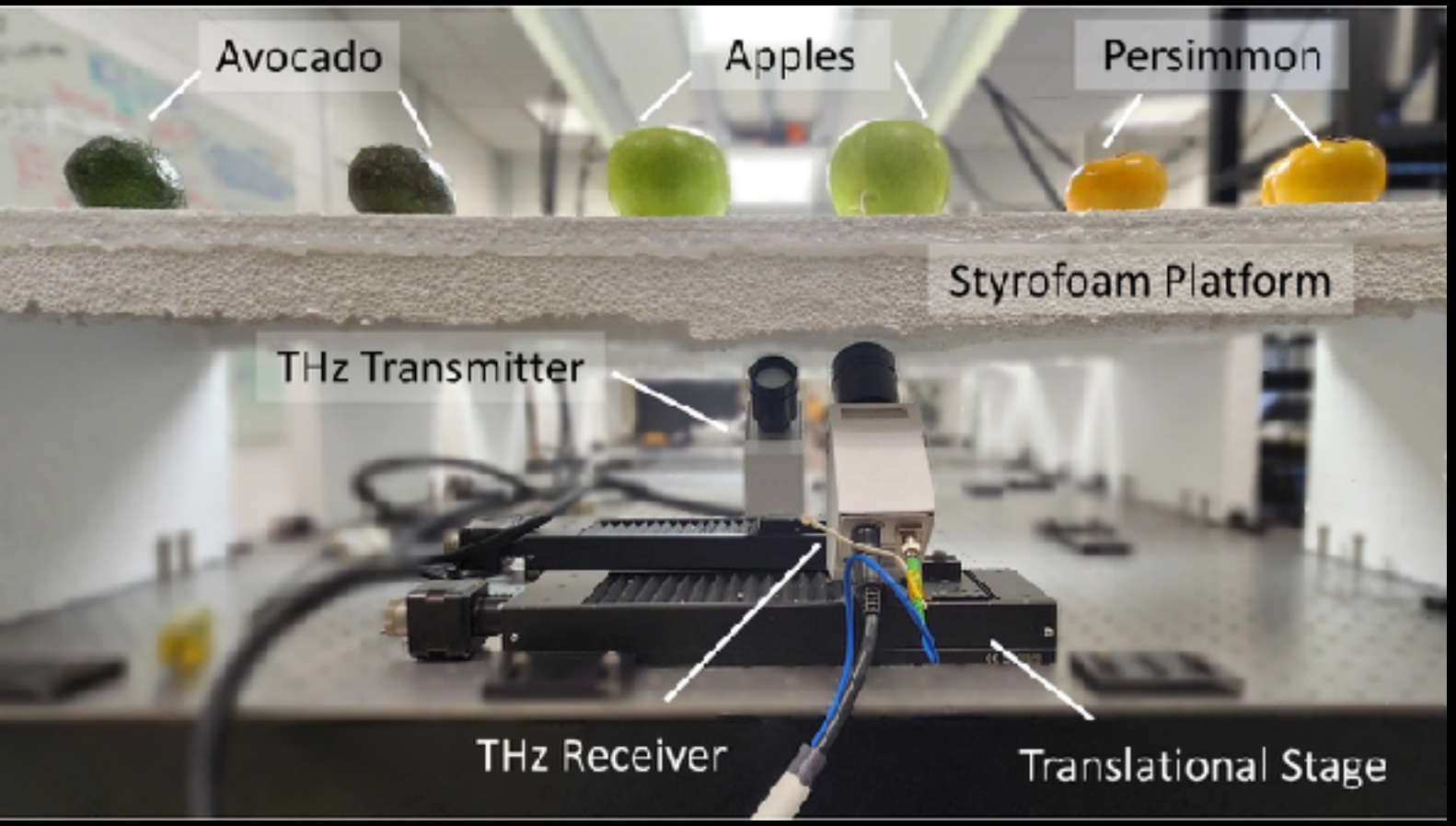
$$< X(f),\ P >$$

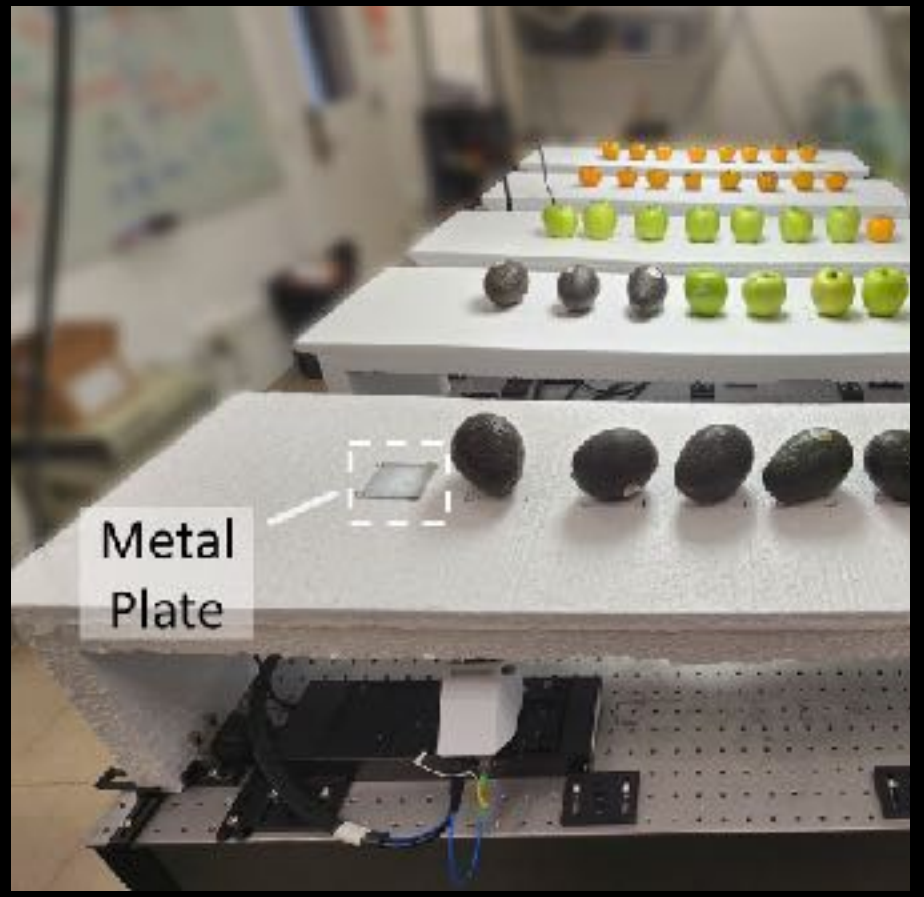
$$Frequency \quad Subspace$$

N Measurements

N Projections

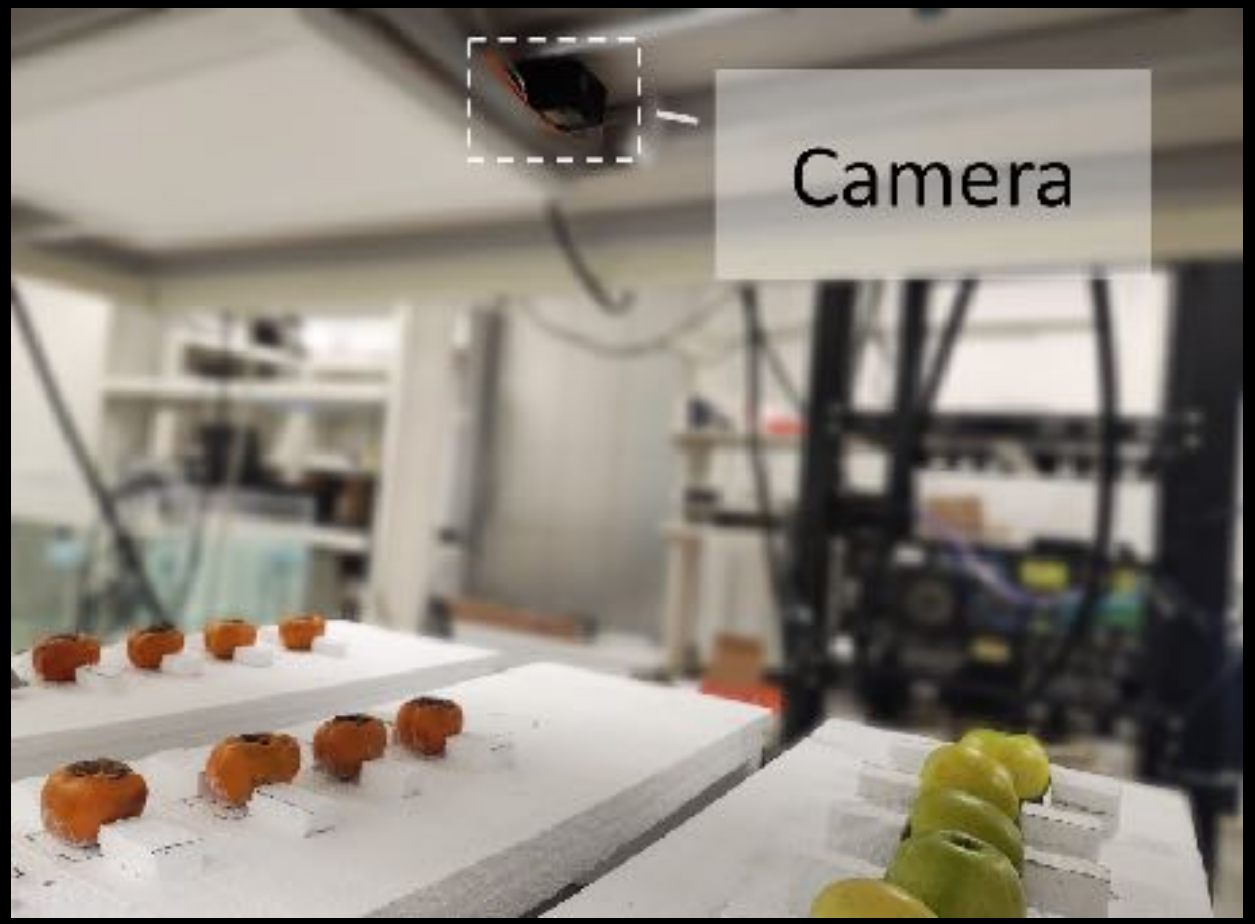
Implementation





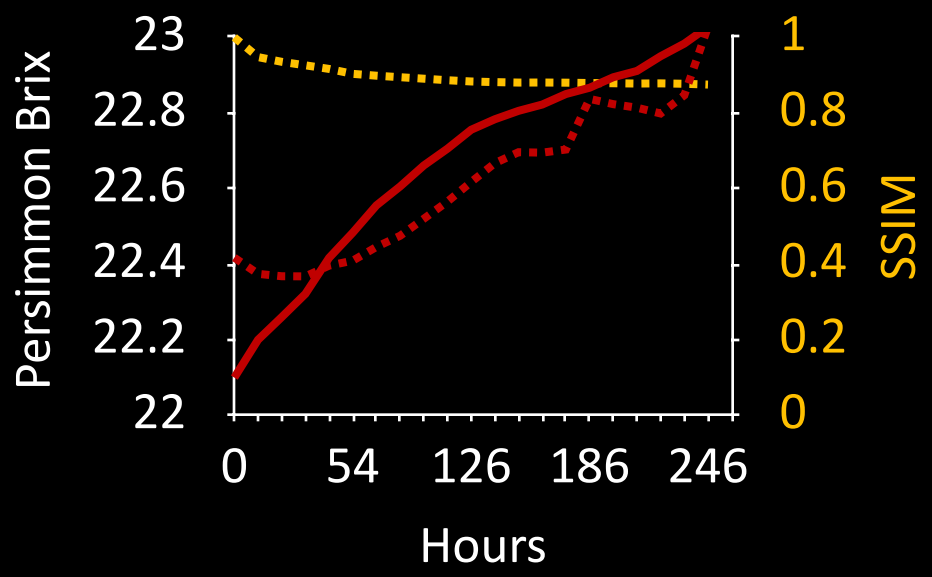
Implementation

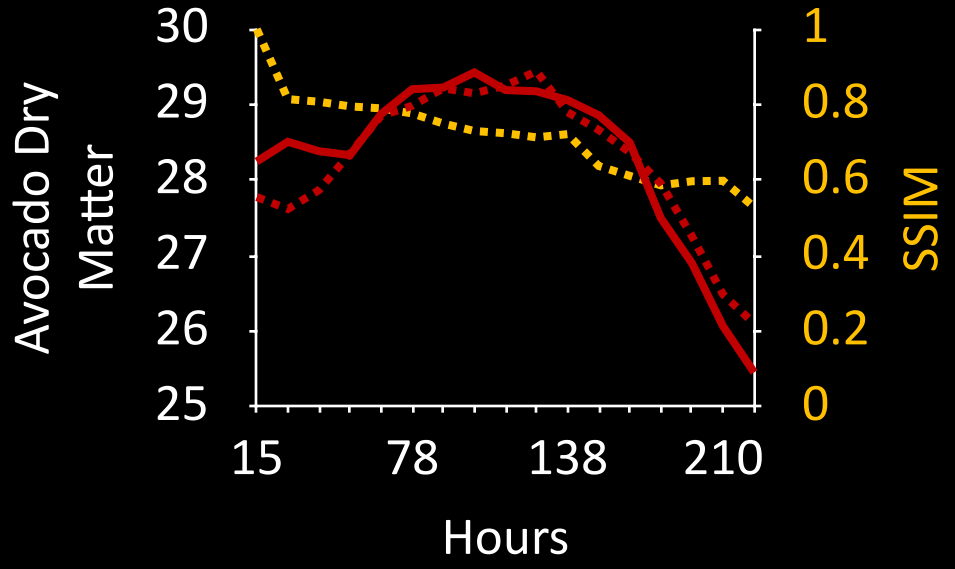
Ground Truth

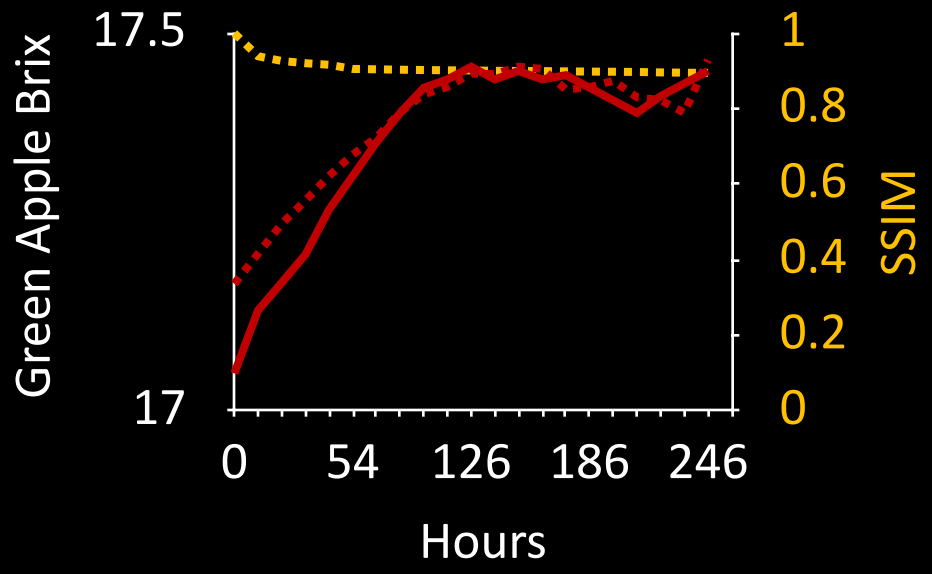


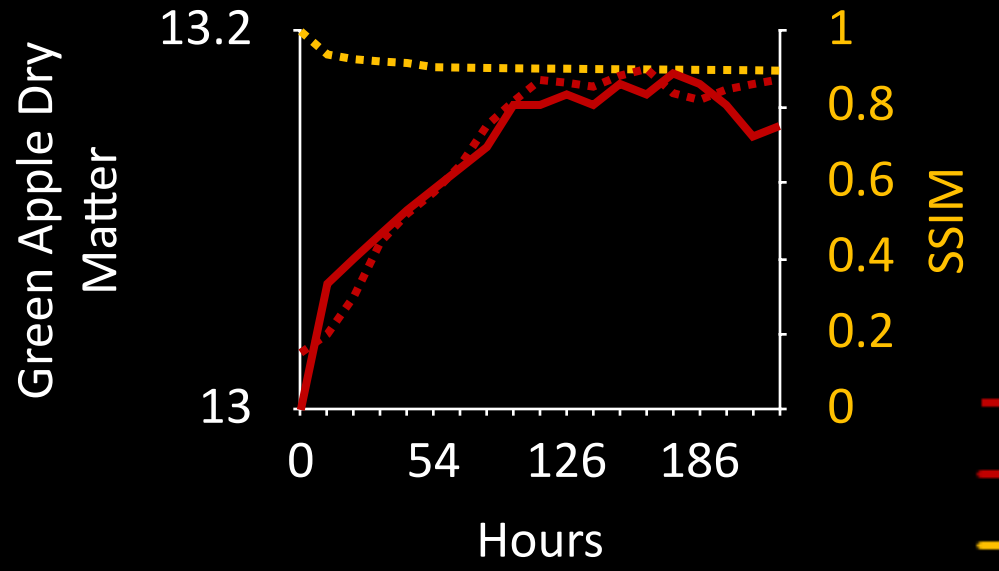
Baseline

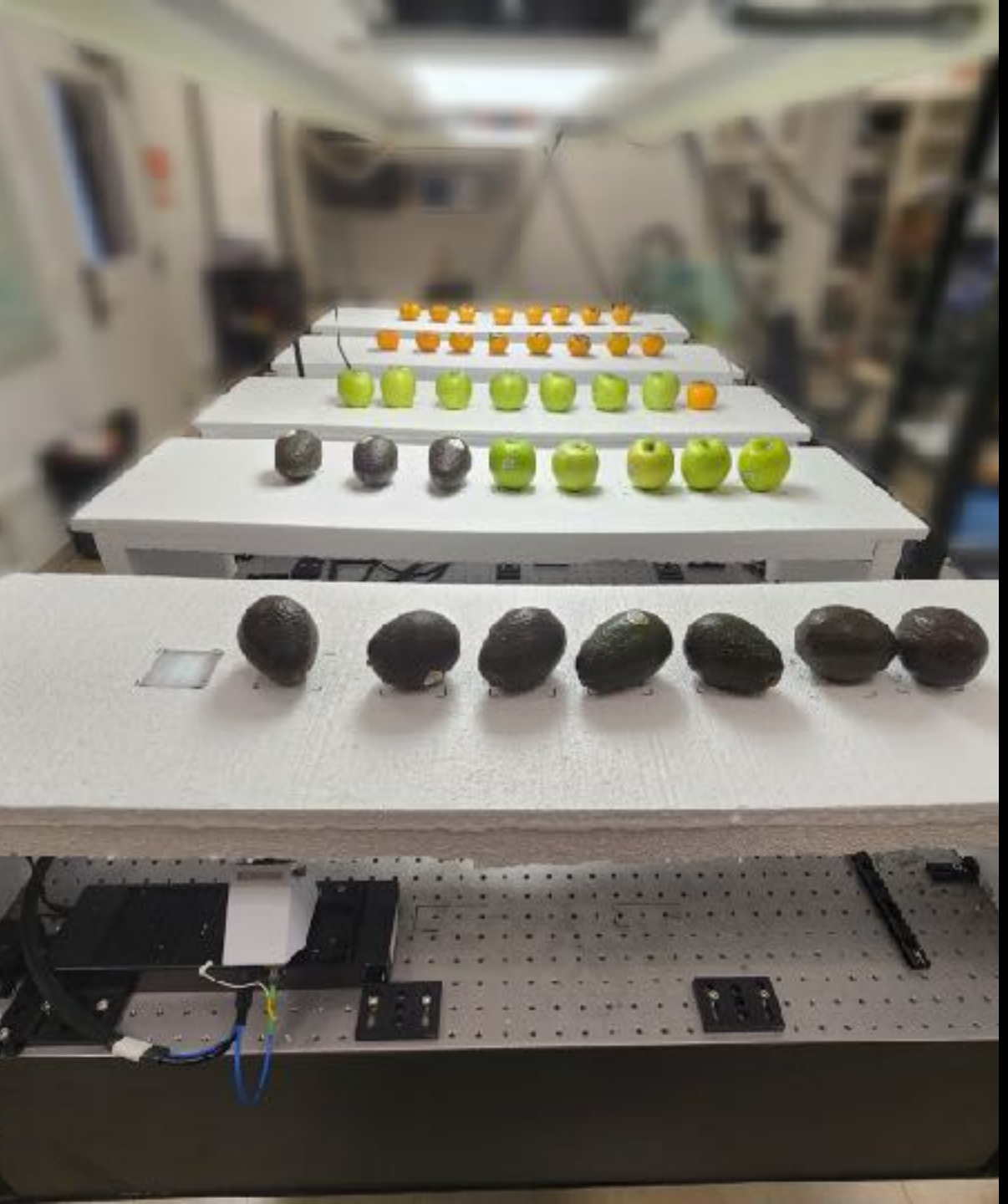
AgriTera Ripeness Prediction during Ripening Cycle











Conclusion

- Agri-Tera utilizes the sub-THz band to infer about ripeness metrics of fruits
- It can accurately determine Dry Matter/ Brix for a variety of different types of fruits
- Future work: Enabling a mobile system for fruit sensing using AgriTera

Lecture Recap

- Learning about aerial-based Connectivity (Loon, Aquila)
- Agriculture IoT
  - The IoT Challenges
  - An IoT System solution
- Wireless sensing for agriculture