

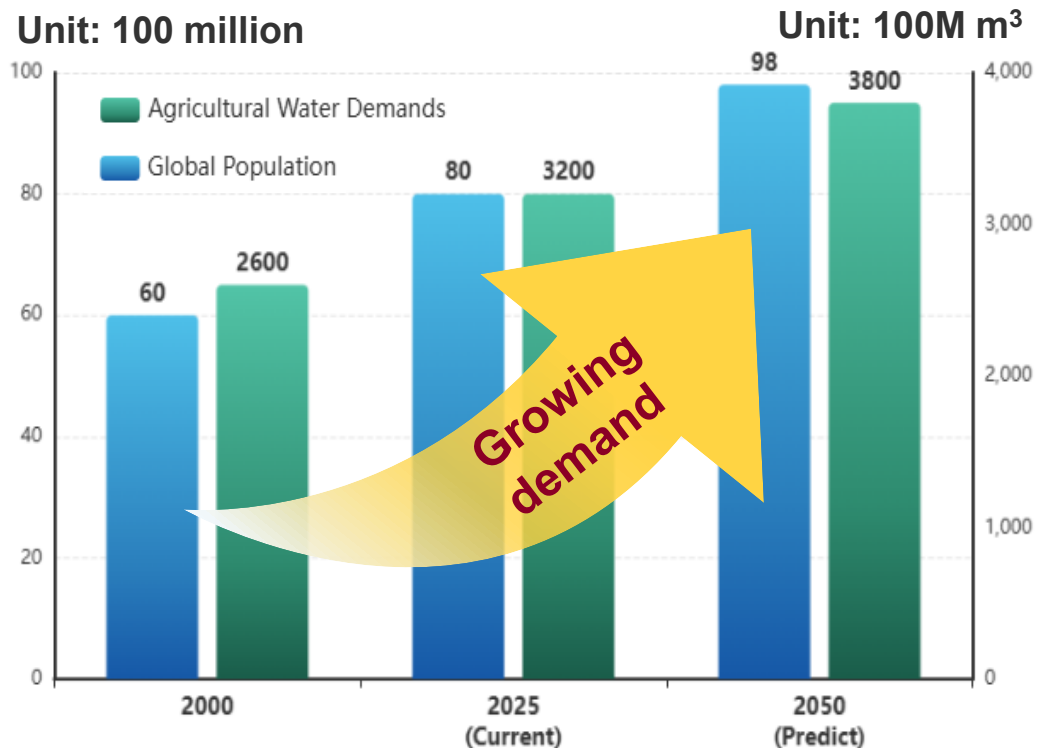


GPSoil: Towards Low-Cost Soil Moisture Sensing Using GNSS Signals

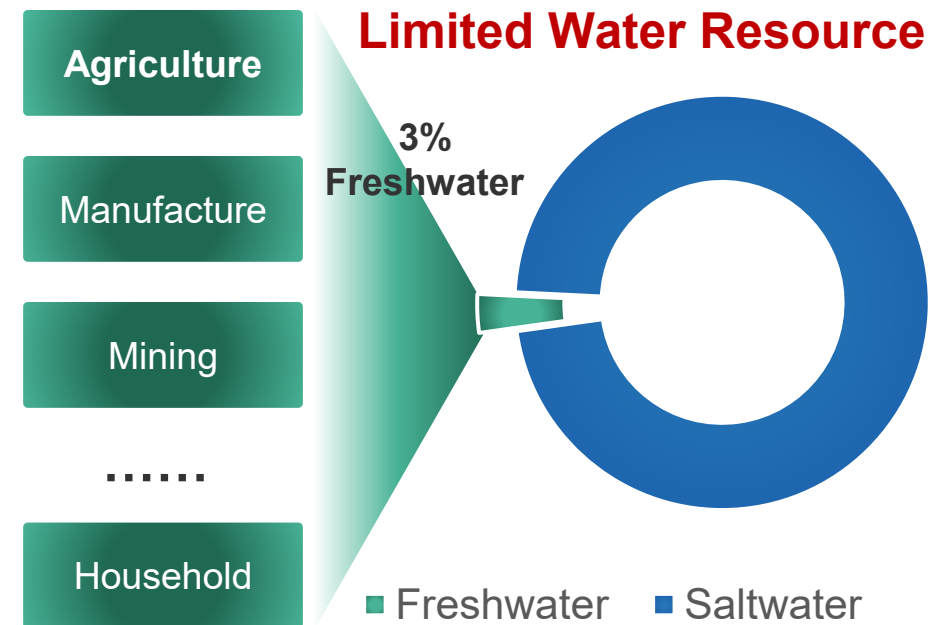
Huixin Dong, Jingqi Lin, Minhao Cui, Serena Zhang,
Lili Qiu, Jie Xiong and *Wei Wang*

Problem: Feeding a growing world with limited water resource

Growth Population & Agricultural Water Demands



Global Freshwater Distribution & Use



*Data source:

[1] Global Landscapes Forum, How to feed 9.8 billion people by 2050, thinklandscape.globallandscapesforum.org.

[2] Shang, S., Gabriel, H.F., & Zhang, Q. (2024). Editorial on Hydrology and Water Resources in Agriculture and Ecology. *Remote Sensing*, 16(2), 238.

Inefficient irrigation



40%

of freshwater is **wasted**
due to inefficient irrigation



Wide-spread Soil Sensing methods are urgently needed

Low Cost

Affordable for
agricultural
fields

Long-term

Durable in
challenging
field conditions

Easy-to-deploy

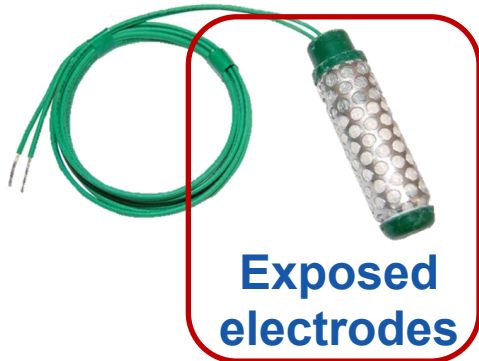
Simple
installation
process

*Data source:

High Tide Technologies. 2021. "Water Usage in the Agricultural Industry." Accessed May 23, 2024. <https://htt.io/water-usage-in-the-agricultural-industry/>.

Commercial soil moisture sensors

Gypsum Block based Soil Sensors



Capacitance-Resistance based Sensors



Limitations of Electrode-exposed Sensors



Difficult Long-term Deployment

Maintaining reliable sensor networks over extended periods is challenging due to maintenance requirements, environmental factors, and the need for frequent recalibration in changing soil conditions.



Short Lifespan Corrosion

Electrodes degrade quickly due to soil corrosion and chemical reactions, requiring frequent replacement and increasing long-term costs.

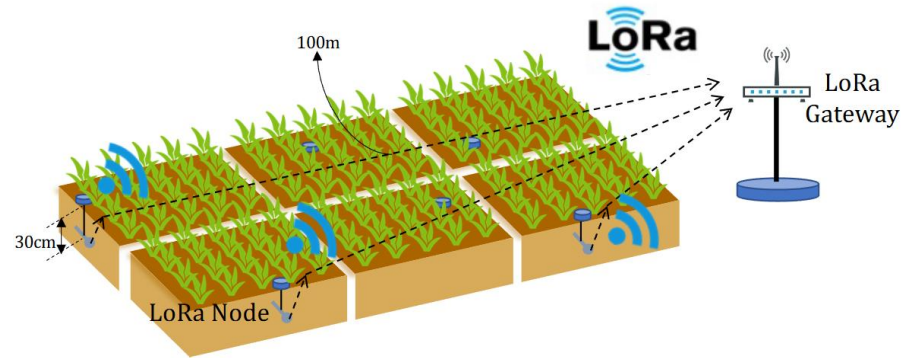


High Cost

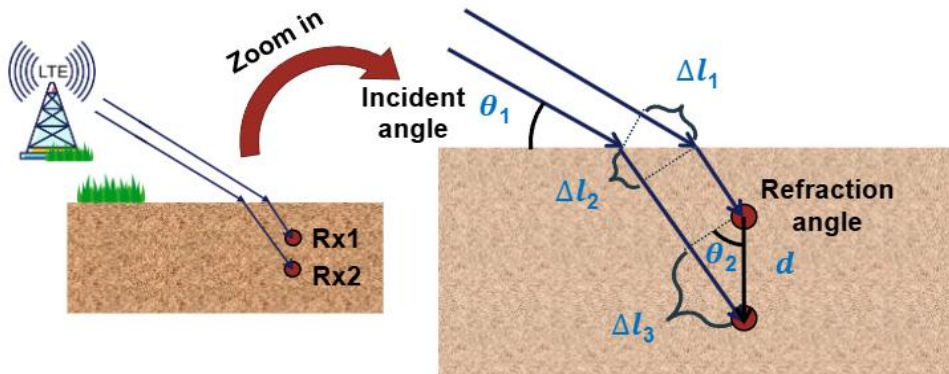
Commercial electrode sensors are expensive, making large-scale deployment economically unfeasible for most agricultural applications.

Promising wireless soil sensing approaches

LoRa Soil Moisture Sensing



LTE Soil Moisture Sensing

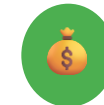


Wireless Sensing Advantages



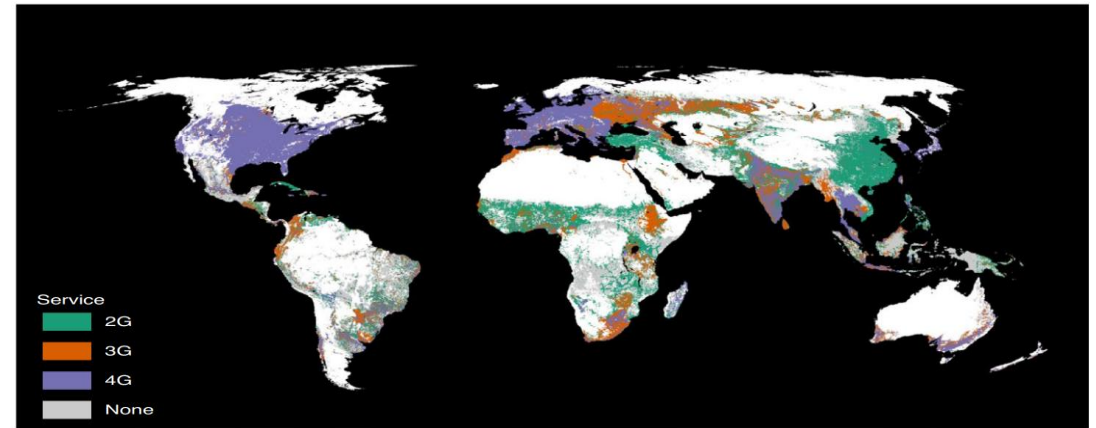
No Direct Soil Contact

Eliminates electrode corrosion and degradation issues, enabling long-term monitoring.



Lower Overall Cost

Reduced sensor complexity and elimination of frequent replacement lower costs.

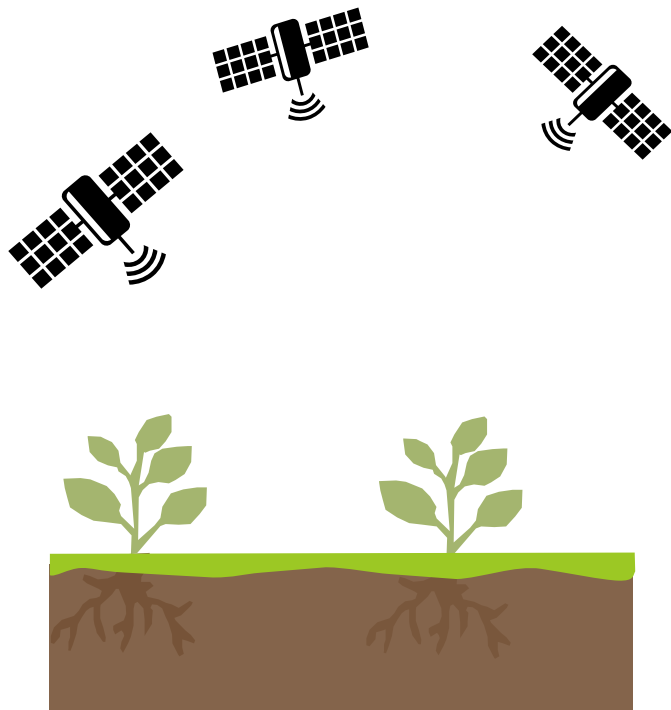


Only 24–37% of farms of <1 ha in size are served by third generation (3G) or 4G services.

- [1] Chang Z. et al. Sensor-free soil moisture sensing using LoRa signals. Proc. ACM IMWUT, 6(2).
- [2] Feng Y., et al. LTE-based low-cost and low-power soil moisture sensing. Proc. SenSys ' 22.
- [3] Mehrabi Z. et al. (2021). The global divide in data-driven farming. Nature Sustainability, 4(2).

**Can we leverage truly pervasive signals to
enable low-cost soil moisture sensing**

Our idea: Sensing with pervasive GNSS signals



No Blind Spots

24/7 Accessibility

No Interference

Advantages

With over 100 GNSS satellites providing global coverage, GPSoil requires no additional infrastructure;

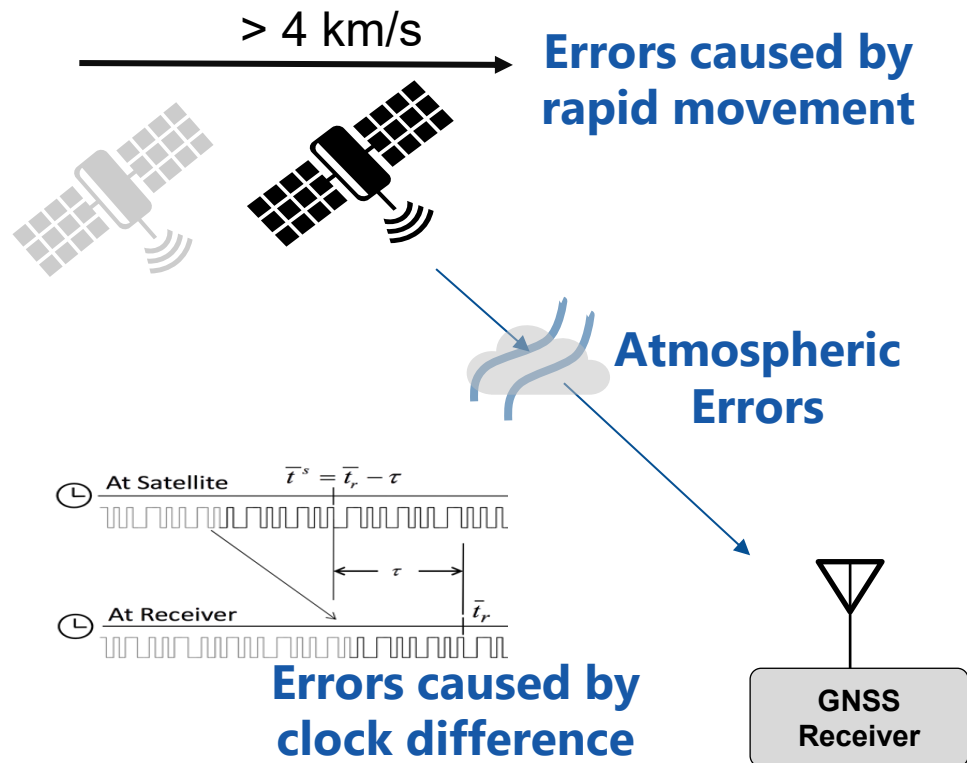
GNSS signals are always available, with satellites transmitting continuously;

GNSS signals are transmitted within a dedicated spectrum, ensuring that GNSS-based soil moisture sensing does not interfere with other communications.

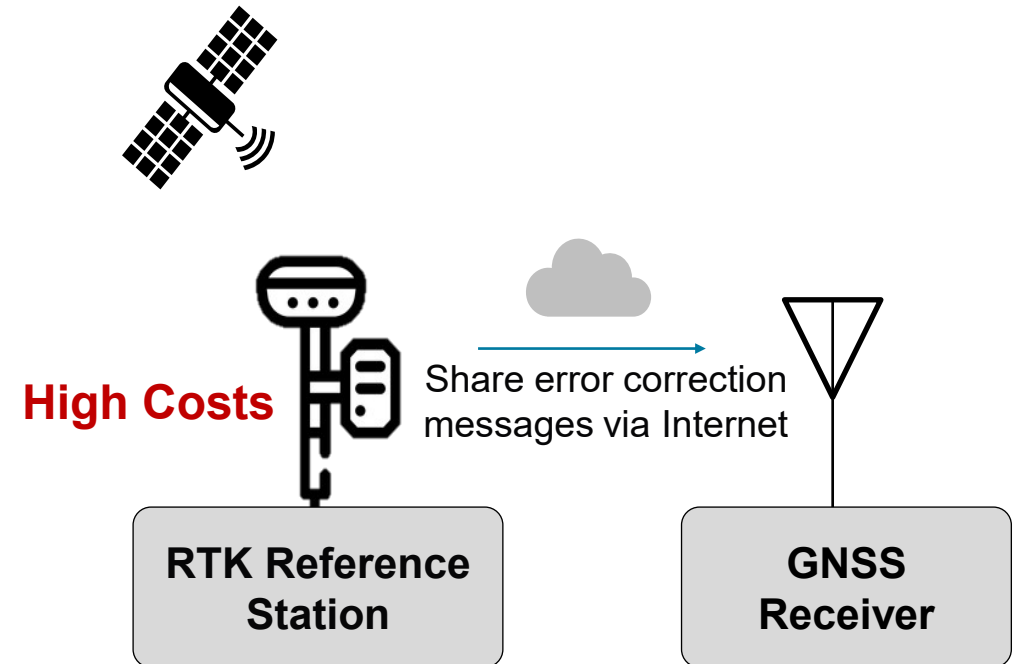
Challenges and Solutions

Challenge 1: Large propagation errors

Km-level propagation errors vs. centimeter-level requirements



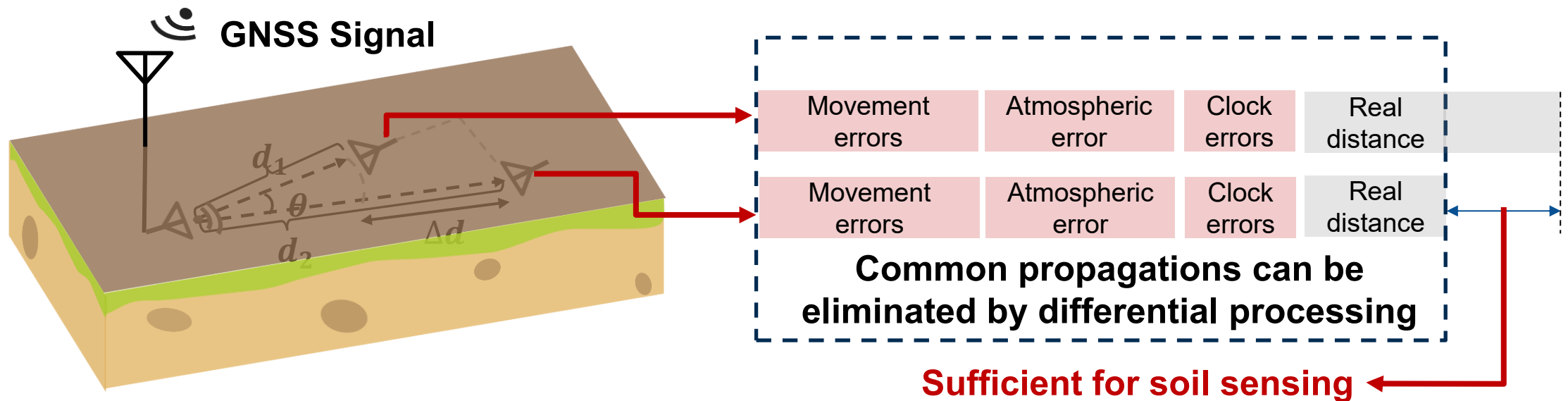
Current DGPS is too expensive for agriculture



Solution 1: Low-cost differential GNSS

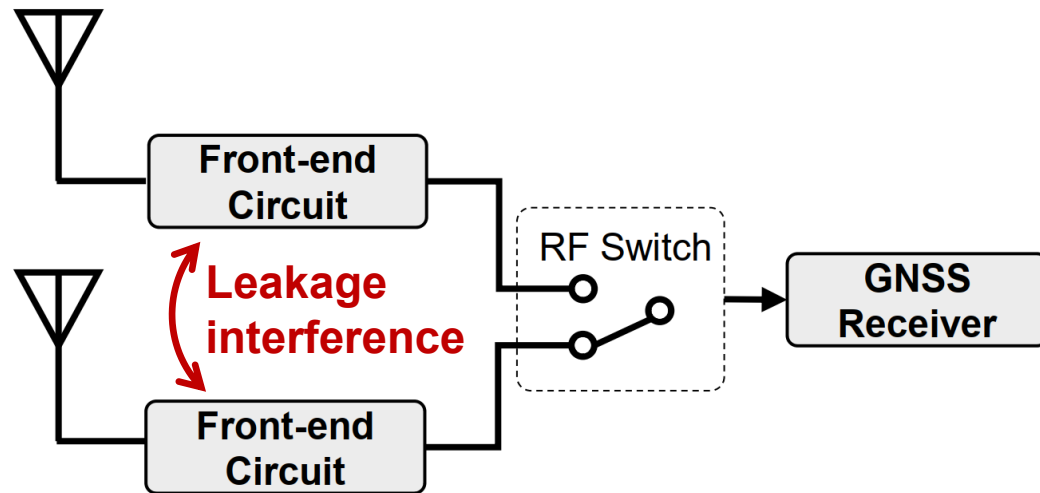
Key insight

We only need to sense the speed changes rather than across the entire path from the satellite to the GNSS receivers

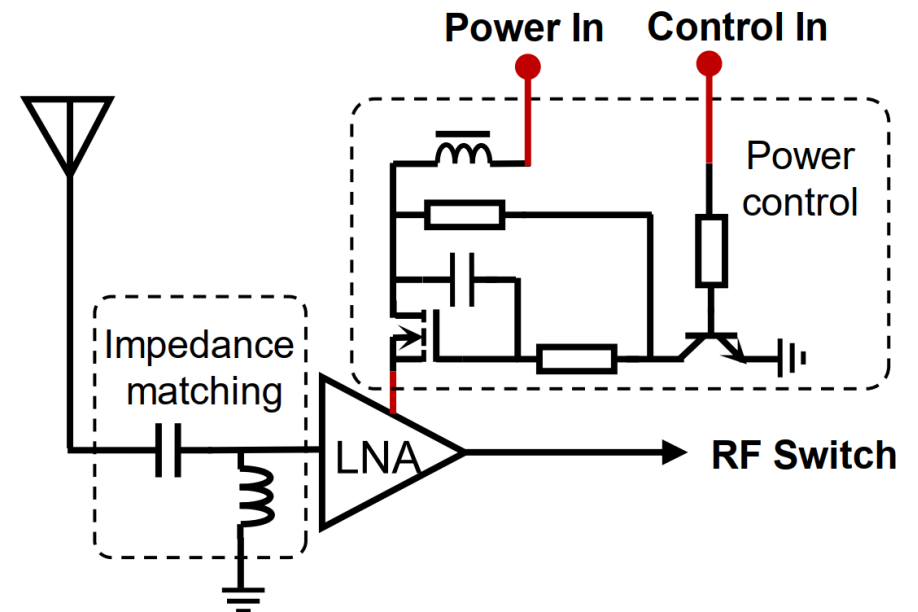


Solution 1: Low-cost differential GNSS

Leakage interference between two antennas



Independent power control for high isolation front end



Challenge 2: Weak received Signals

Soil sensing depth requirements



Celery

Root depth: ~30 cm



Corn

Root depth: ~50 cm



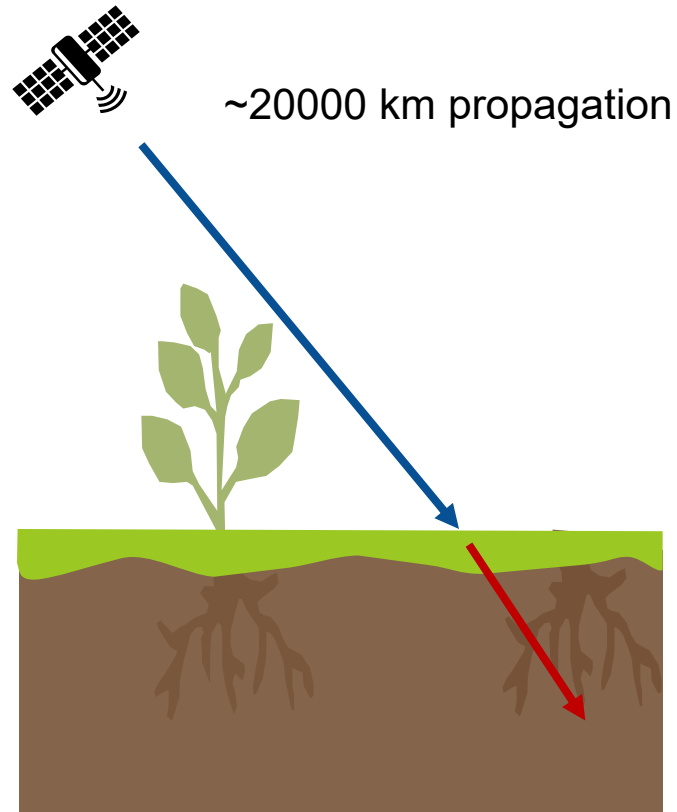
Tomato

Root depth: ~70 cm



Cotton

Root depth: ~90 cm



Hard to sense
in deep soil



Long propagation
attenuation (-125 dBm)

11–18 dB attenuation every
10 cm wet soil

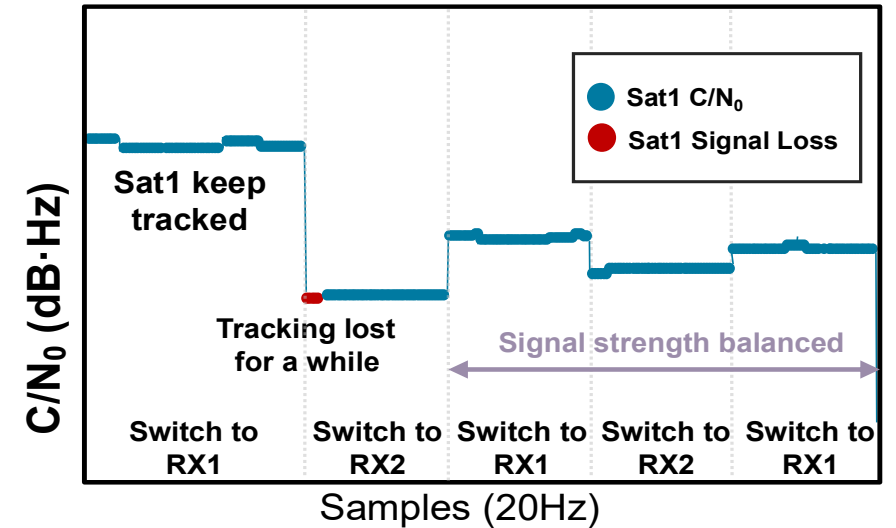
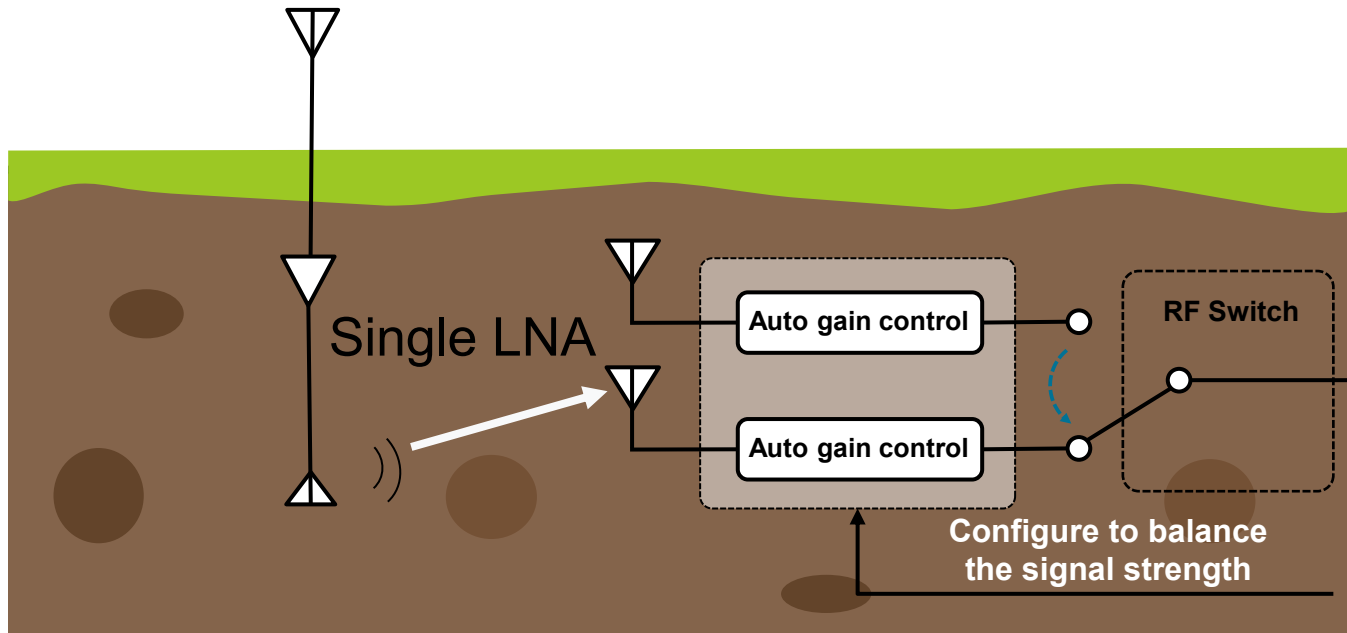
Solution 2: Enhancing GNSS signals underground

Step 1

Retransmit the GNSS signals underground

Step 2

Auto gain control to balance the strength of received signals



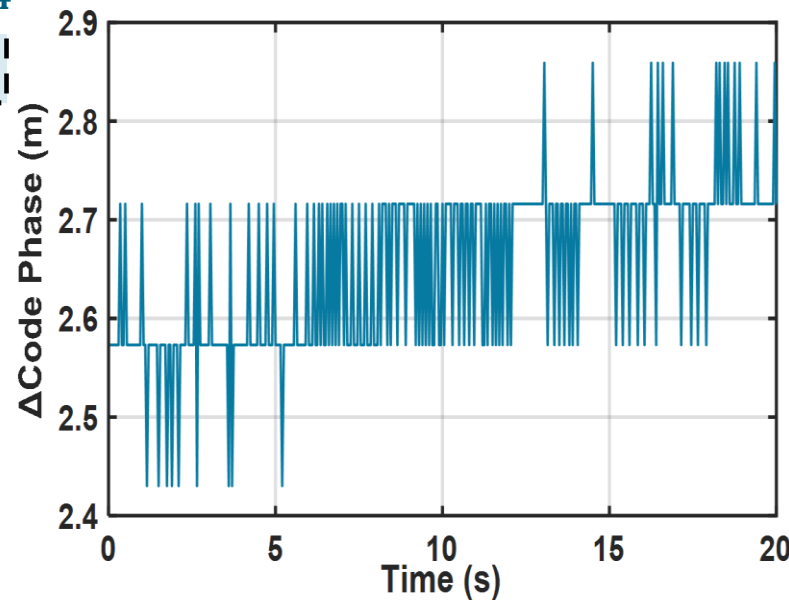
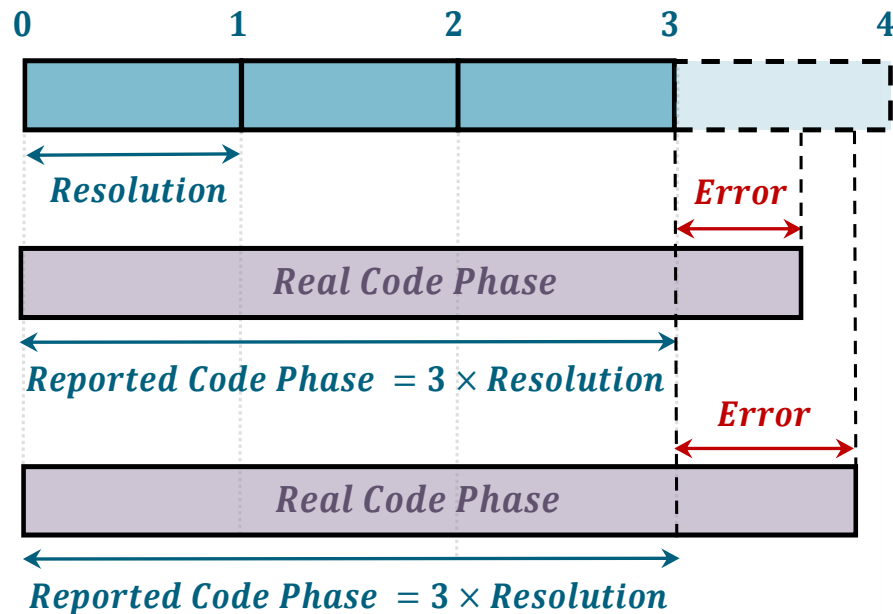
Unbalanced signal strength
Easy to lose track

Balanced signal strength

Challenge 3: Limited sensing resolution

Code Phase resolution of UBX – M8N (Widely used meter-level GNSS sensors)

$$R_{\Delta T} = 2^{-21} \text{ ms} \longrightarrow 0.46 \text{ ns} \longrightarrow 0.144 \text{ m}$$



Measurements ambiguity

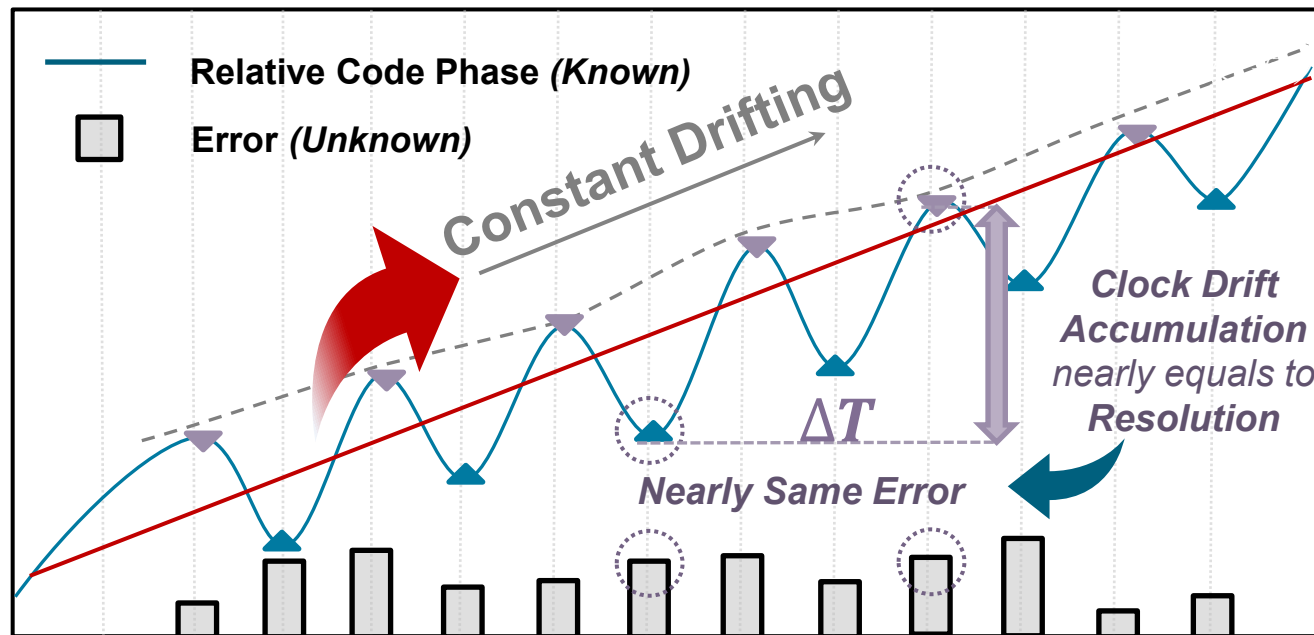


Challenge for accurate sensing

Solution 3: Resolution enhancement

Observation

Clock drift of the receiver is almost constant during a short period



$$\Delta P = \delta t_d \cdot \Delta T + (Q_{E,t+\Delta t} - Q_{E,t})$$

$$Q_{E,t+\Delta T} \approx Q_{E,t}$$

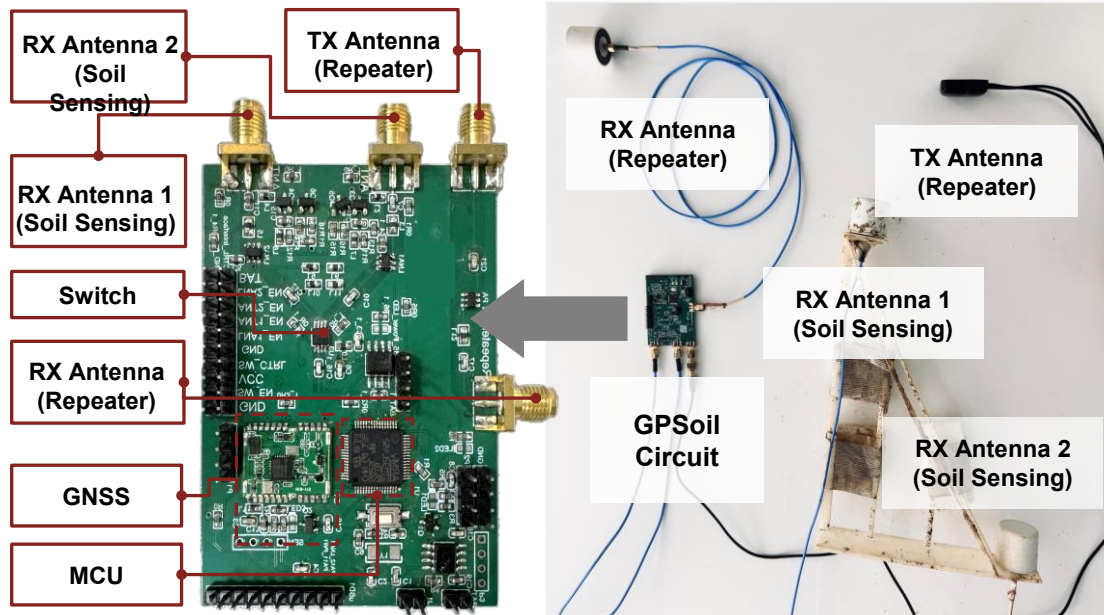
$$\Delta T = \arg \min_{\Delta T} \| \delta t_d \cdot \Delta T - \Delta Res \|$$

Combine multiple satellites

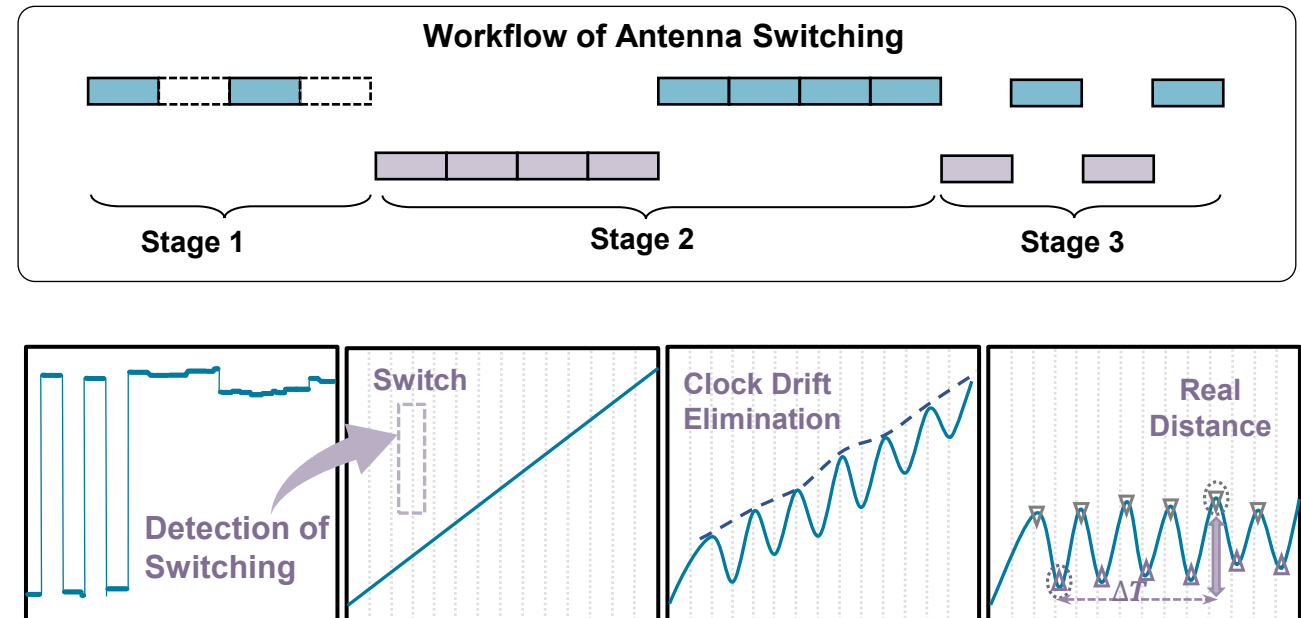
$$\Delta d = c_0 \sum_{i=1}^n \frac{w_i}{n \sum_{i=1}^n w_i} \sum_{j=1}^m \frac{(\Delta P_{t+j\Delta T} - \Delta P_{t+(j-1)\Delta T})}{m}$$

GPSoil implementation and workflow

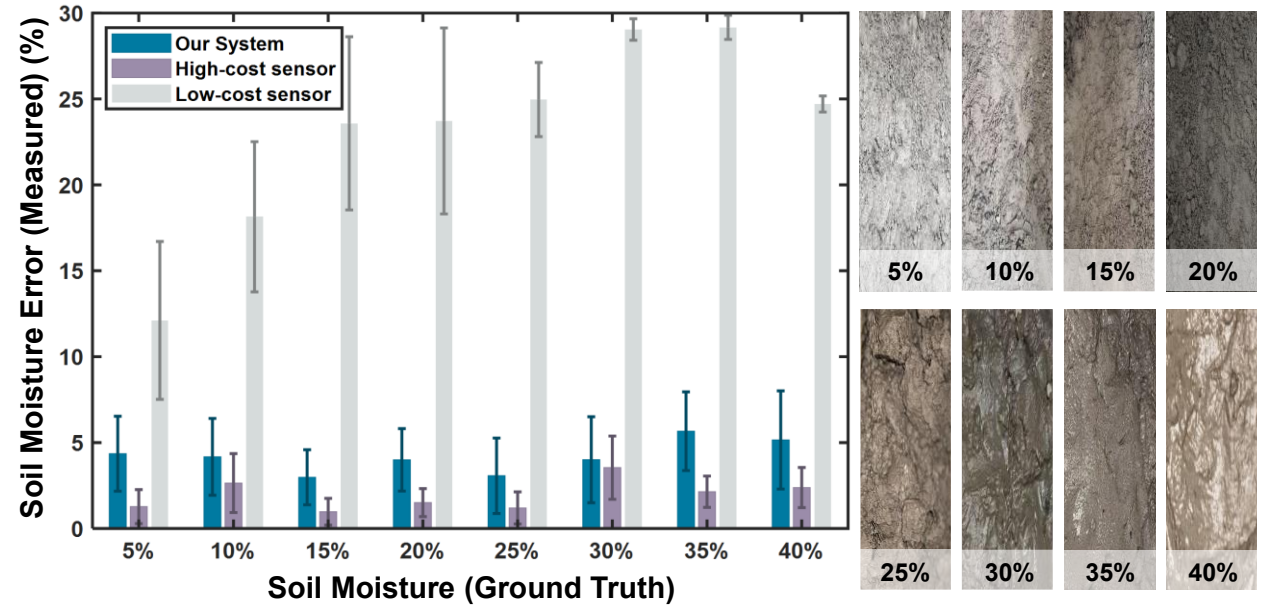
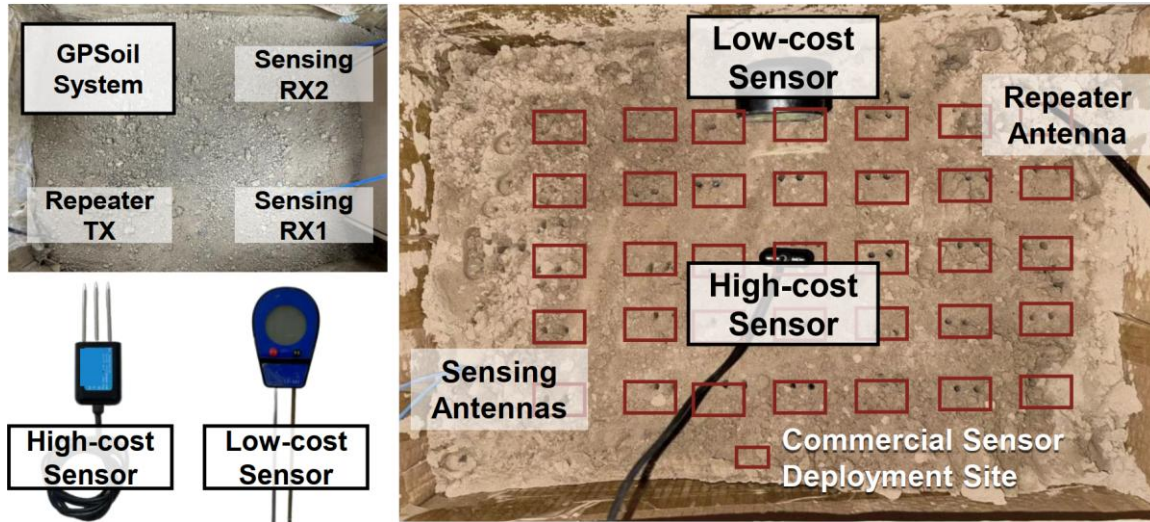
Implementation



GPSoil Embedded Workflow



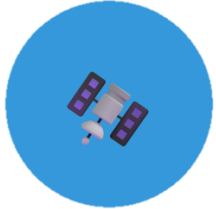
Evaluation



In-lab experiment setup

GPSoil achieves overall sensing accuracy of approximately 5.2%

Contribution



Wide-area deployable

Using GNSS signals for soil moisture, eliminating the need for dedicated infrastructure.



Cost-Effective Design

Single-chip dual-antenna system reduces hardware costs while maintaining accuracy.



Innovative Error Elimination Methods

Transforming clock drift into a tool for enhancing sensor resolution.

Thanks!