Soil moisture measurements using reflected GNSS signals – a recent Australian quest

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Outline

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- Introduction
- Current status
- Methodology
- Field experiments and results
- Conclusion

GNSS Atmosphere Sounding

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GNSS atmosphere sounding is a new technique to measure the physical properties of the atmosphere such as

- ✓ pressure, temperature, water vapour, wind speed and direction, liquid water contents, …
- ✓ Using global navigation satellite signals

- **GNSS meteorology**
  - ✓ Space-borne technique - radio occultation (John Le Marshall's talk in Session 8)
  - ✓ Ground-based technique – national positioning infrastructure (NPI), e.g. CORS (Witold Rohm's talk in Session 10)

- **GNSS-Reflectometry**
  - ✓ "Trash for treasure" - signal from noise for soil moisture, wind speed/direction and wave motion etc.

GPS Meteorology

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A name given to the body of science and technology which makes use of GPS for active remote sensing of the Earth's atmosphere

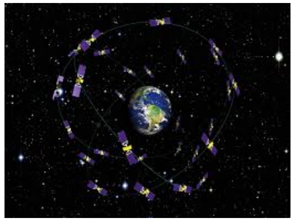
GPS Meteorology

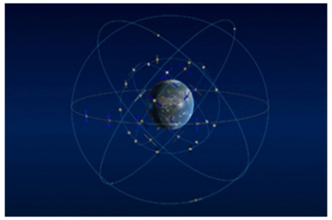
- Ground Based — Measure signal delays from fixed points on ground
  - ✓ Gives total precipitable water vapor (PWV) with an accuracy of ~1mm
  - ✓ Incepted 1992 and become a valuable tool for determining WV
  - ✓ NPI/CORS networks based
  - ✓ Used for NWP and climate monitoring with various degrees of success
  - ✓ Possible severe weather events
- Space-Based radio Occultation (RO) — Measure signal delays from LEO satellites with global coverage
  - ✓ Provides profiles of integrated refractive index
  - ✓ Space-borne - satellite to satellite tracking
  - ✓ Many unique/special characteristics
  - ✓ Used for NWP with a great success

Introduction

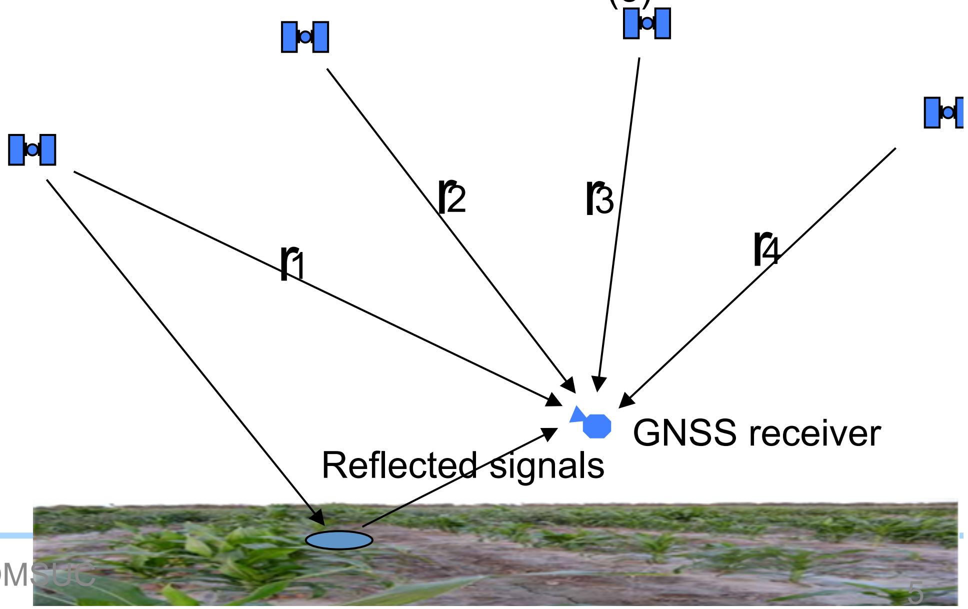
- **Global Navigation Satellite System (GNSS)**
  - ✓ **Global Navigation Satellite Systems (GPS + Glonass + Galileo + Beidou + QZSS + …)**
  - ✓ **~70 satellites available, ~150 SVs by 2020**
- **GNSS reflectometry**
  - ✓ **GNSS signals reflected off surrounding terrain, buildings, … due to multipath**
  - ✓ **Most of the reflected signals change polarizations**
  - ✓ **"Trash for treasure"**


GPS(30)


Glonass (24)


Beidou (35)

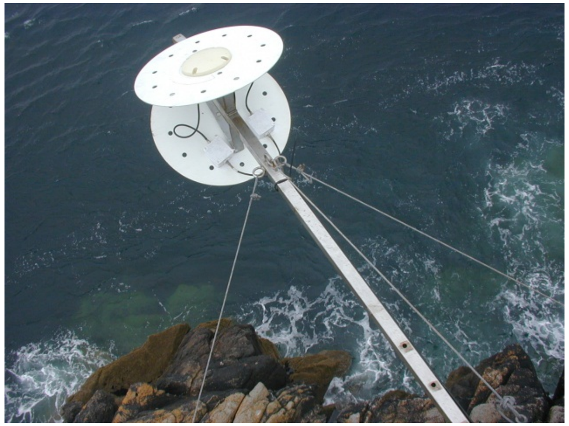

QZSS
(3)



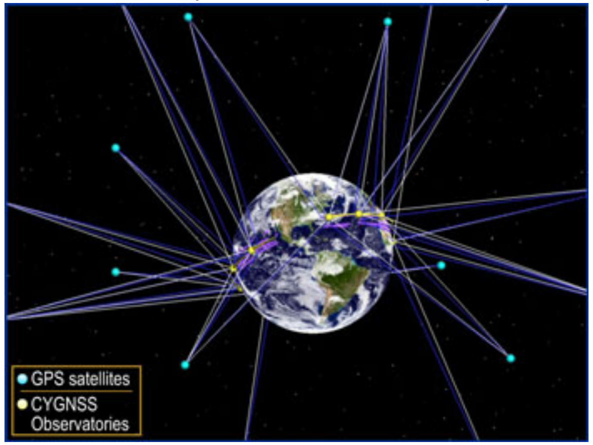
Potential applications - Ocean

- **Ocean surface altimetry**
- **Wind speed & direction estimation**
- **Significant wave height estimation**

GPS Tide Gauge
(K.M.Larson,2013)



OceanPal for sea monitoring
(Starlab/Spain, 2009)



CYGNSS
(NASA, 2013)

Potential applications - Land

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- Forest change detection
- Soil moisture retrieval
- Snow depth
- Ice thickness

Soil moisture (K.M.Larson,2013)

Sea-ice sheet measurement (ESA, 2011)

Snow depth measurement
by GPS reflectometry (USA ,2012)

Advantages and Disadvantages

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- **Advantages**
  - ✓ Large coverage
  - ✓ L-band signals and sensitive to soil moisture
  - ✓ GNSS as a critical global infrastructure
    - ➢ both space-borne and
    - ➢ ground-based
  - ✓ Multi-signal and multi-frequency
  - ✓ System of systems
  - ✓ Microwave remote sensing technology, good penetration characteristics
  - ✓ Signals are high-accuracy and free (passive technique)

- **Disadvantages**
  - ✓ A relatively complex technique
  - ✓ Weak reflected signals
  - ✓ Incoherent signals (caused by rough surfaces)
  - ✓ Poor resolution and accuracy, caused by low sampling rate
  - ✓ Large computation load
  - ✓ Influenced by surface roughness

GNSS-R for soil moisture in world

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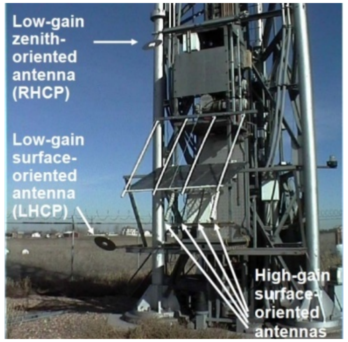
- **GNSS-R first introduced in 1993**
  - ✓ Martin-Neira, 1993
- **Various experiments conducted based on different platforms across the world, e.g.**
  - ✓ Tower-based experiments (US, V. Zavorotny, 2003)
  - ✓ Air-borne experiments (US, SMEX02, SMEX03, SMEX04)
  - ✓ Space-borne experiments (Surrey Satellite Technology Limited, UK-DMC satellite, 2003)
  - ✓ Ground-based: The LEiMON project (Starlab, Spain) (Alejandro Egido, 2012)



Tower based experiment (USA 2003)

(UK-DMC satellite, 2003)

US Air borne experiments (SMEX02/SMEX03/SMEX04)

CYGNSS (USA)

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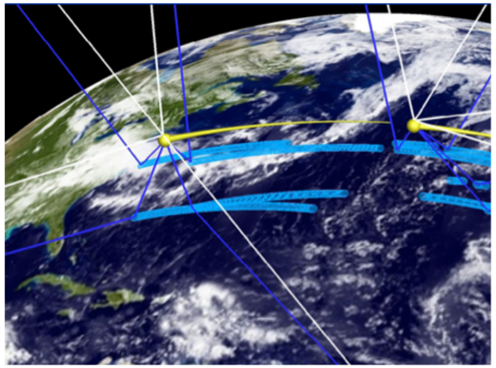
- CYGNSS - The Cyclone GNSS
- Typical satellite-borne GNSS-R
  - ✓LEO-based receivers to obtain both direct and reflected signals from GPS satellites
  - ✓A constellation of 8 LEO satellites, to be launched in 2016
- Key objectives:
  - ✓Measure ocean surface wind speed in all precipitating conditions, including those experienced in the TC eyewall
  - ✓Measure ocean surface wind speed in the TC inner core with sufficient frequency to resolve genesis and rapid intensification
  - ✓Support the operational TC forecast community by producing/providing ocean surface wind speed data products, and helping them assess the value of these products for use in their retrospective studies of potential new data sources



GNSS-R for soil in world

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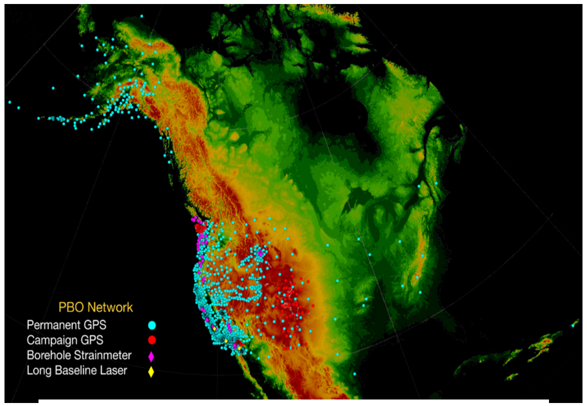
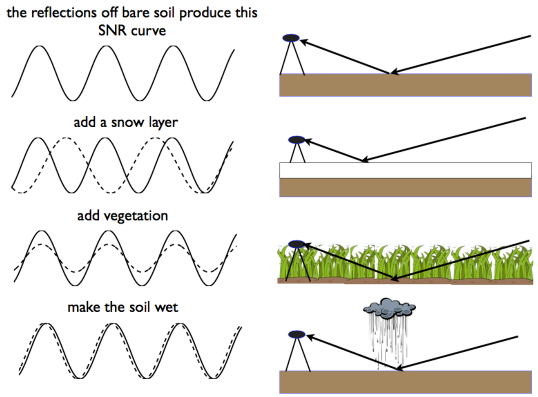
- **Plate Boundary Observatory (USA)**
  - ✓ **Part of the EarthScope project**
  - ✓ **Instrumentation involves GPS, seismometers, strainmeters, borehole titlmeters, InSAR and LiDAR**
  - ✓ **1,100 ground GPS tracking stations**
  - ✓ **Multipath reflected signals used soil moisture retrievals**

GPS Station for soil moisture, USA



PBO Stations, USA



Different waveforms at different case

GNSS-R for soil in Australia

- **Soil moisture important in Australia**
- **National Airborne Field Experiment (NAFE05 NAFE06)**
  - ✓ **Aim: to provide access to a wide range of airborne and ground-based monitoring data (Jeffrey Walker & Rocco Panciera, University of Melbourne, 2005)**
  - ✓ **2005-2006**
  - ✓ **No reflected signals were used**

GNSS-R in Australia

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- **Australian GNSS-R**
  - ✓ Multipath signals were simulated (Queensland Univ of Technology, 2001)
  - ✓ Air target detection using GPS bistatic radar was initially discussed in 2006 (E. P. Glennon, A. G. Dempster and C. Rizos, 2006)
  - ✓ Airborne experiments for GNSS-Based Altimetry was conducted recently (Kegen Yu, Chris Rizos and Andrew Dempster, 2011)
  - ✓ Ground-based soil moisture field experiments carried out by SPACE, RMIT (2012-2013)

Australian Centre for Space Engineering Research (ACSER)

SPACE Research Centre (RMIT)

Methods for soil moisture retrieval

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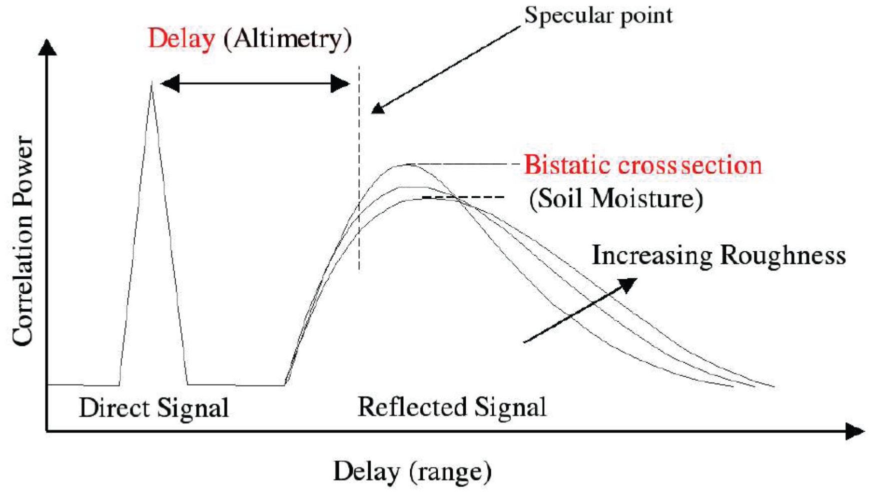
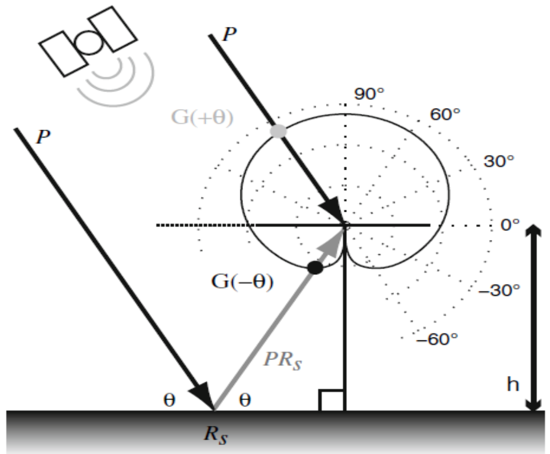
- **Normalised power method (NPM)**
  - ✓Different soil moistures lead to different powers of the reflected signals
  - ✓The power of the reflected GPS signals needs to be <u>normalised</u> by the power of direct signals
  - ✓Dielectric constant is a function of soil moisture



- **Interference technology method (ITM)**
  - ✓Direct and reflected signals form an interference pattern waveform
  - ✓ Soil moisture affects the characteristics of the interference waveform (notch position amplitude, etc.)
  - ✓The moisture estimation is realized through identifying the interference characteristics



Our device - hardware

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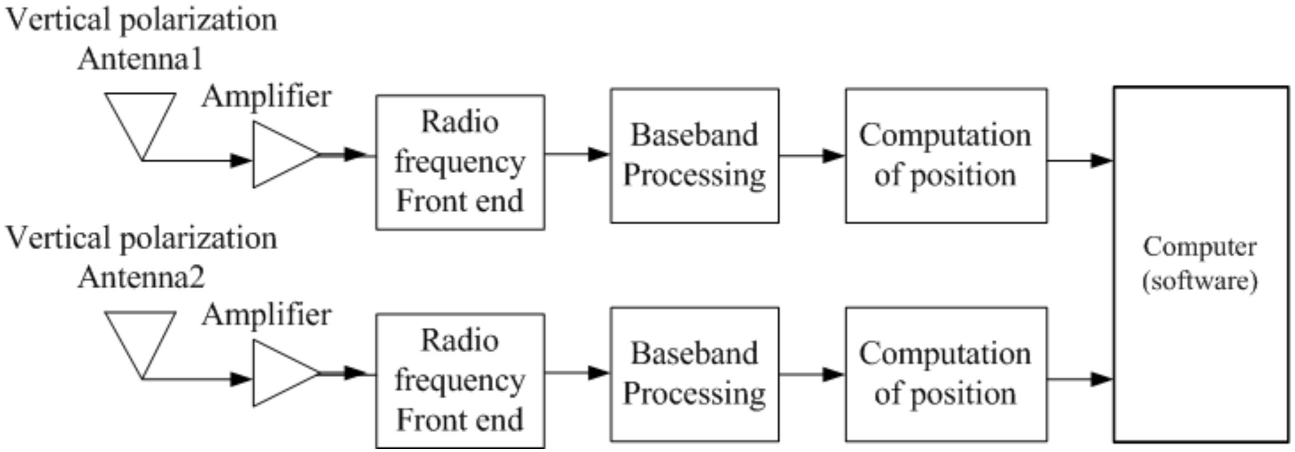
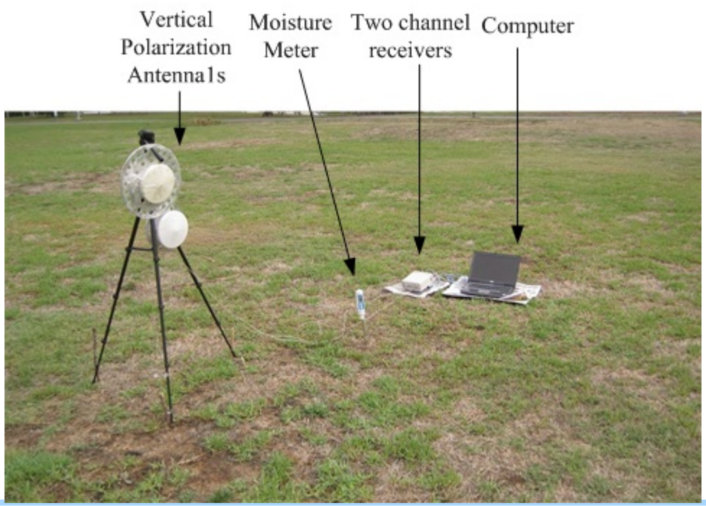
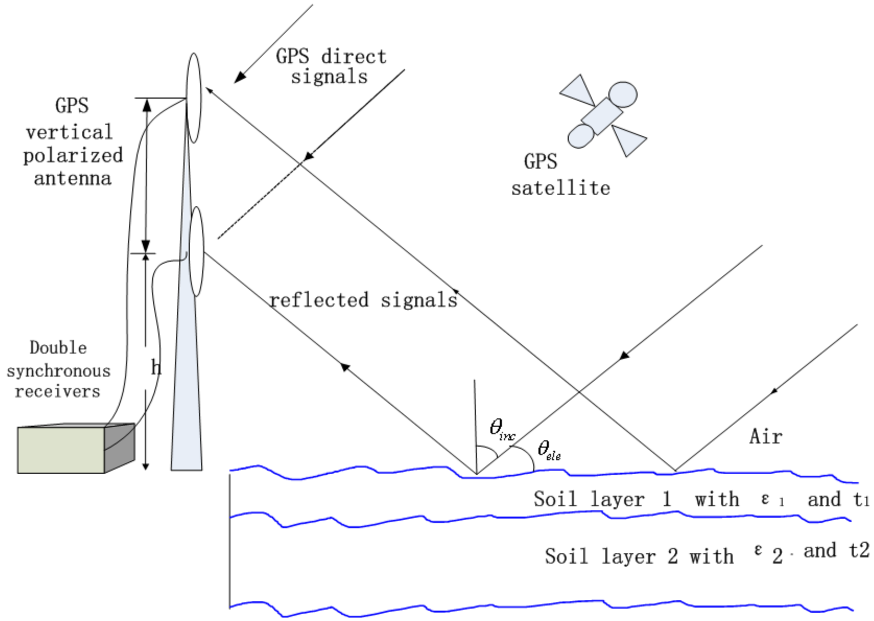
- **A new method - interference difference technique (IDT) (improved ITM) developed which is also hardware related**

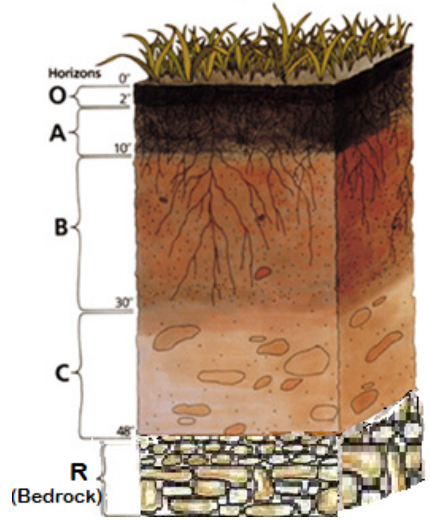




Our Method

- **GNSS-R interference different signal**
  - ✓ Two antennas are used to receive the reflected signals





ε_i	**dielectric constant of the i-th layer**
t_i	**thickness of the i-th layer**
h_j	**height of the j-th antenna**
θ_{inc}	**incidence angle of the direct signal (complementary angle of elevation)**
$\theta_{reflected}$	**reflected angle of the reflected signal**

Our Method

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- **Interference difference**
  - Differential technique to remove unknown parameters and improve the accuracy of the retrieval

$$D = S_1 - S_2 = \sqrt{\mathrm{k} \cdot G(\theta, \varphi)} \cdot R[(e^{j\phi_{i1}} - e^{j\phi_{i2}})] \quad i = 1, 2$$

$$\phi_1 = \frac{4\pi}{\lambda} \cdot H \cdot \cos(\theta_{inc})$$

$$\phi_2 = \frac{4\pi}{\lambda} \cdot (H + \Delta H) \cdot \cos(\theta_{inc})$$

D is a function of mv G H

mv	Soil moisture	k	Means the linear relationship
H	Height of the first antenna	R	Reflection coefficient
G	Antenna gain	ϕ	Excess phase of reflected signals

Key steps in signal processing

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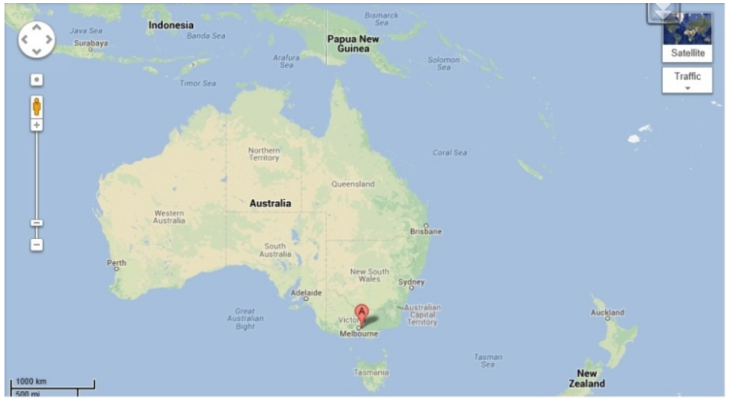
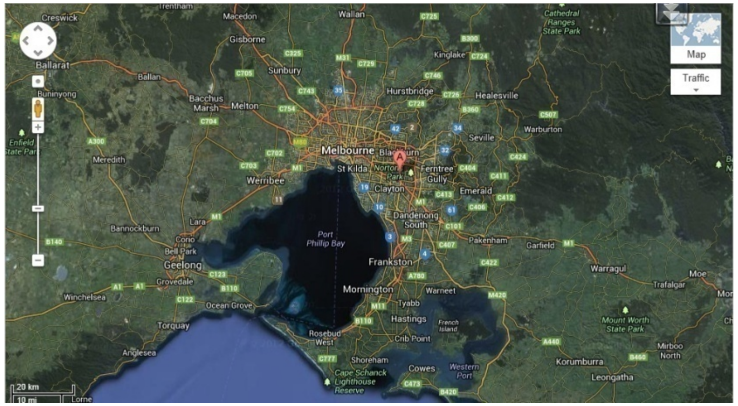
- **Record data series by two receivers**
- **Sort the data series according to elevation angles**
- **Obtain the difference of the two data series**
- **Generate "theoretical" data series according to the double layer soil model and radio reflection theory**
- **Matching:**
  - ✓ Calculate the Euclidean/direct distance btw the measured and the model-based info;
  - ✓ Identify the minimum distance of the two vectors for matching

Field tests



Field experiment in Melbourne



Experiment Location in Google map

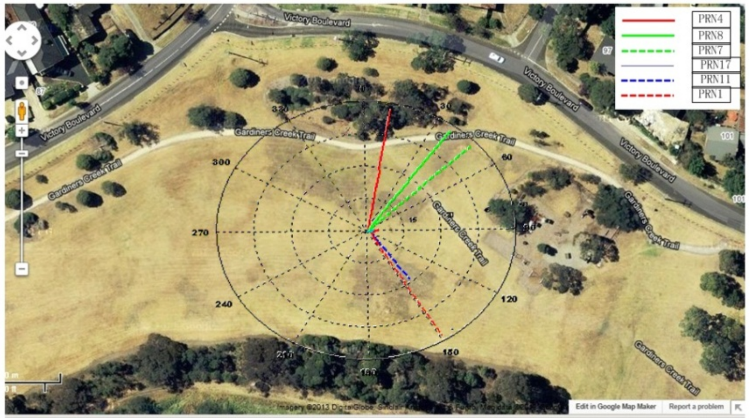
Soil morphology

Horizon	Depth (m)	Colour	Mottles	Texture
A1	0.00–0.20	dark brown (10YR 3/3)	–	sandy loam
A2	0.20–0.35	sporadically bleached	–	light sandy loam
B21	0.35–0.80	yellowish brown (10 YR 5/4)	yellowish brown (10YR 5/6) and red (2.5YR 4/6)	light medium clay
B22	0.80–1.20	light grey (10YR 7/1)	yellowish brown (10YR 5/8) and red (2.5YR 4/6)	light medium clay

Near Cranbourne, south-east of Melbourne

Soil model for Melbourne

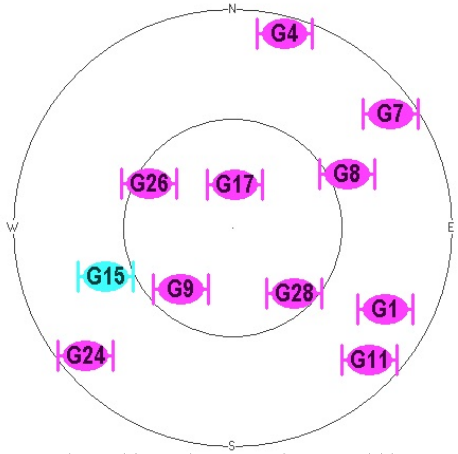
(Australian soils and Landscapes, 2004)



Site: Gardiners Creek

Field tests

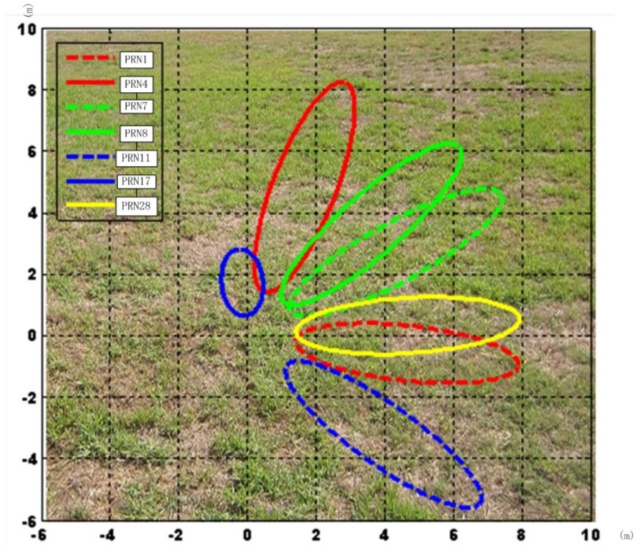
- **Antenna (towards east)**
- **Distribution of satellites**
- **Footprint of satellites**
    - ✓ **The *in situ* soil moisture is 0.14**
    - ✓ **The mean (average) of 50 samples by a soil moisture meter**



Distribution of satellites

Antennas

Moisture meter: PMS-714



Footprints

Experiment

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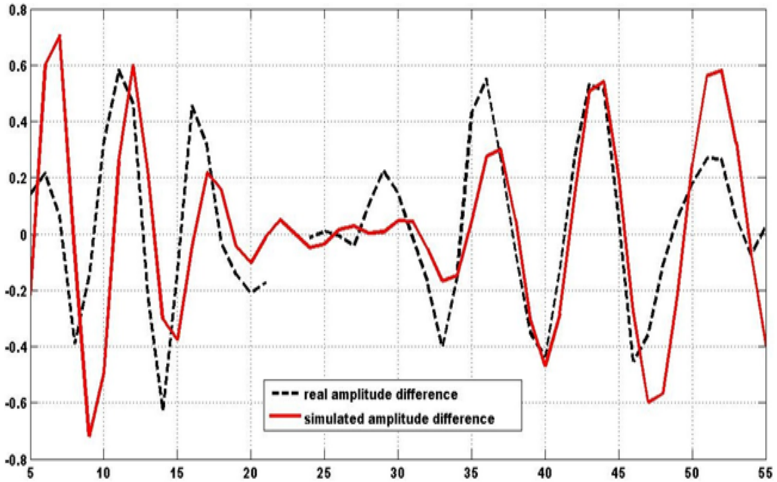
- **Match with Euclidean distance**

$$D_j = \left\| S_r - S_j \right\| = \sqrt{\sum_{i=1}^{N} (s_{r\_ei} - s_{j\_ei})^2}$$

- **Two steps**
  - ✓Search for the optimal H (antenna height)
  - ✓Search for the optimal mv (soil moisture)

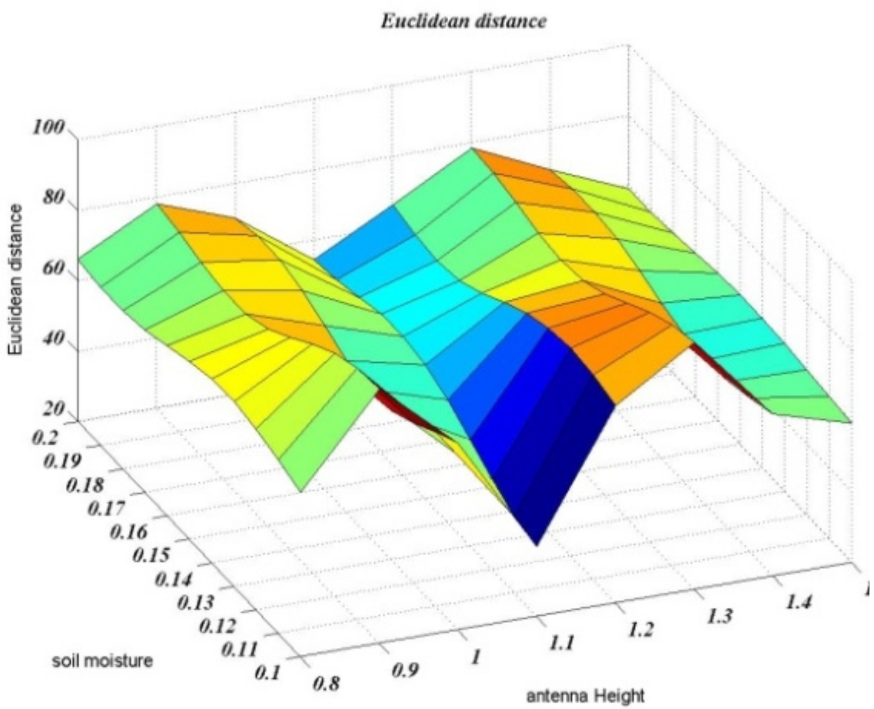
- **Optimal results**
  - ✓Smallest distance
  - ✓Waveform matched well

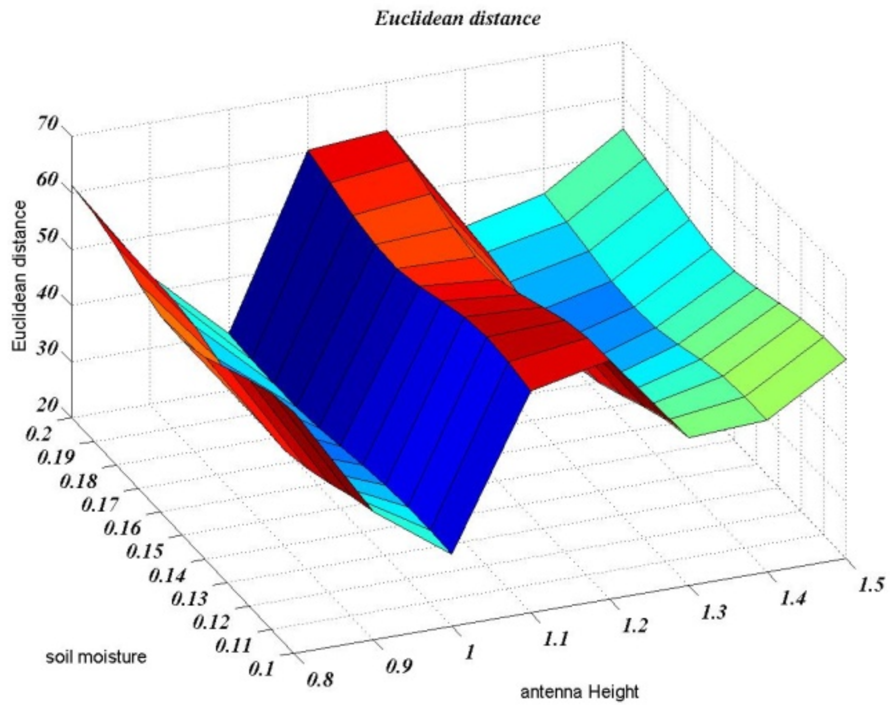


matched waveform

Experiment

- **First step: search the optimal antenna height H**
  - ➢(due to the terrain effects at the reflected point)





PRN1
optimal antenna H1=1.1m

PRN4
optimal H1=1m

These estimated heights are close to the real height

Experiment

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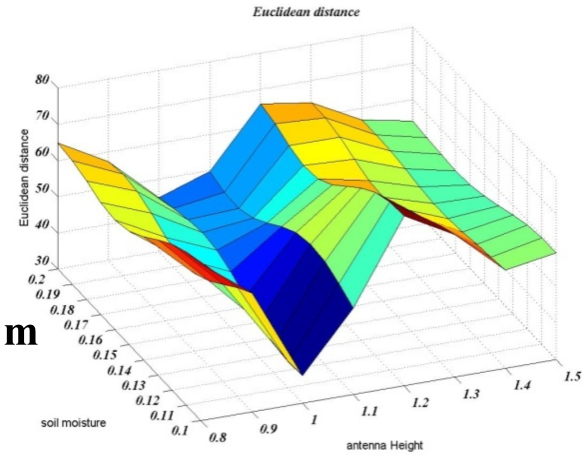
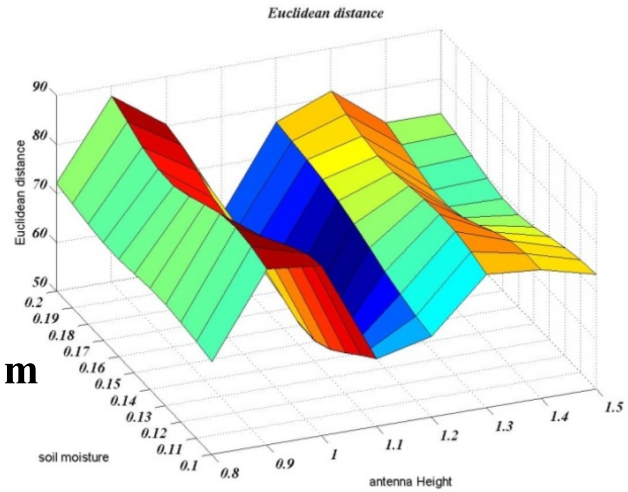
- **Search the optimal antenna height H for various satellites**

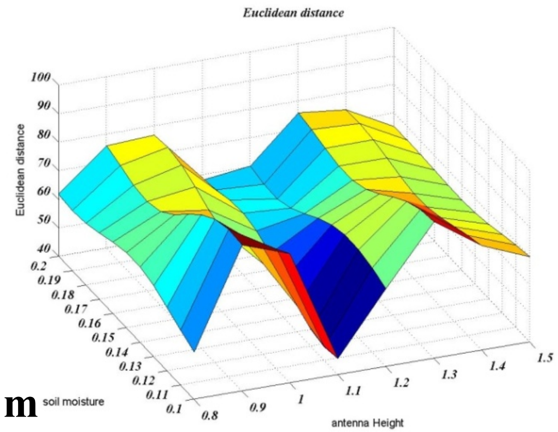
PRN7
optimal H1=1m



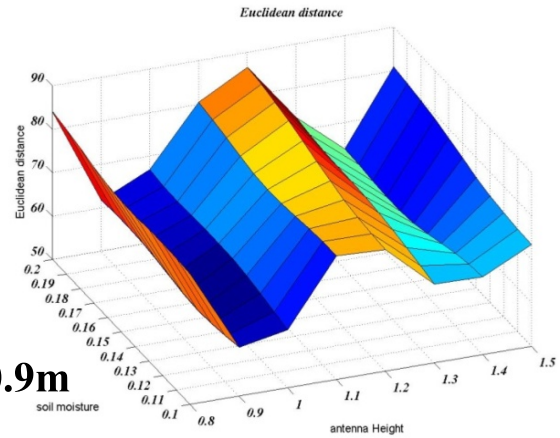
PRN8
optimal H1=1m



PRN11
optimal H1=1.1m



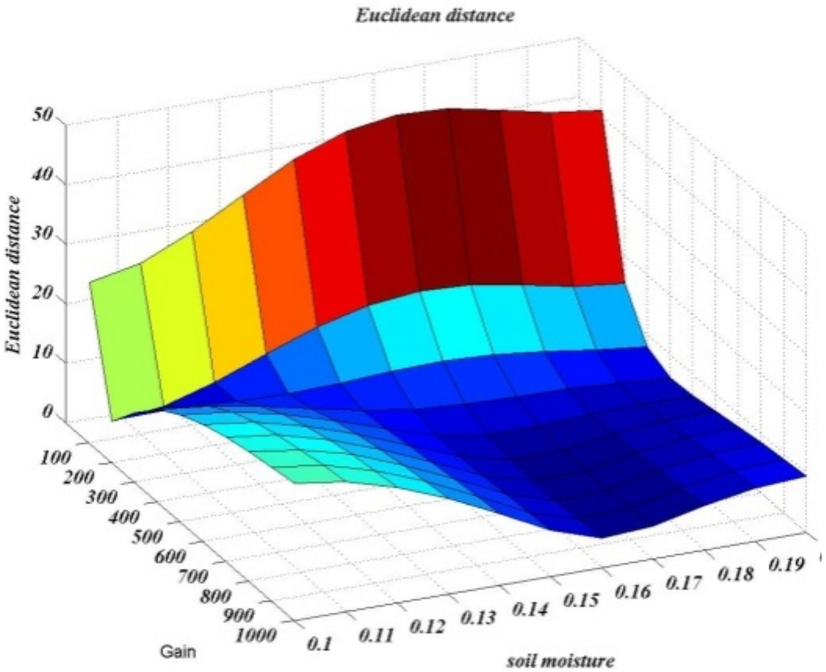
PRN28
optimal H1=0.9m



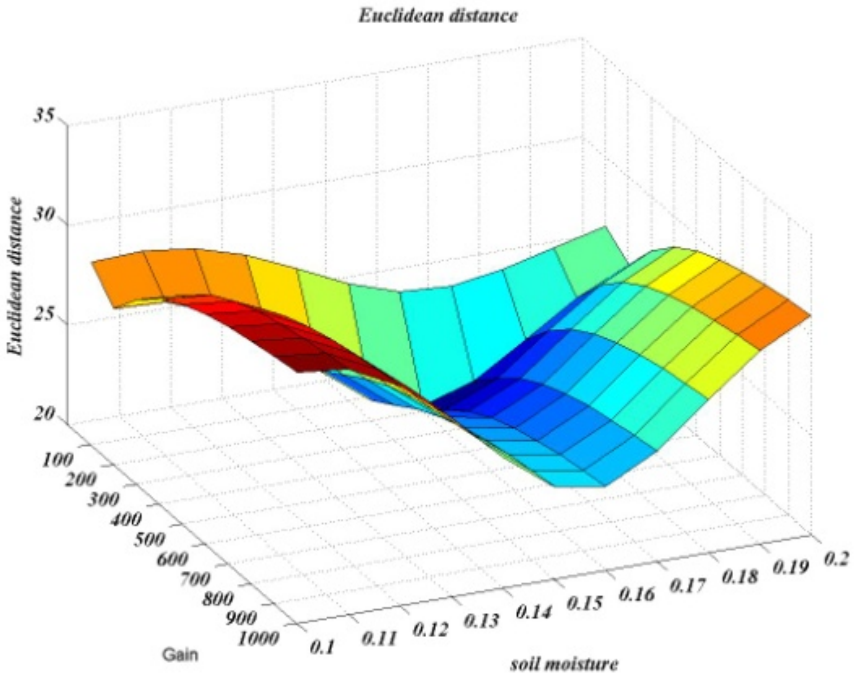
These estimated heights are close to the real height

Experiment

- Second step: search the optimal moisture (mv) measurements for various satellites



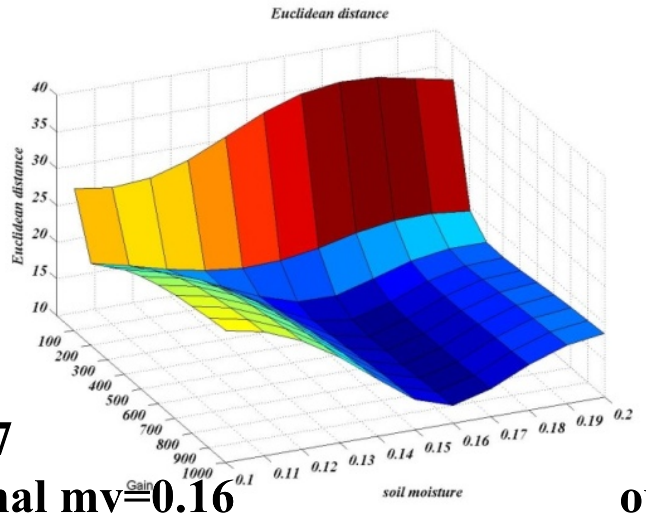
PRN1
optimal gain=1000
optimal mv=0.16



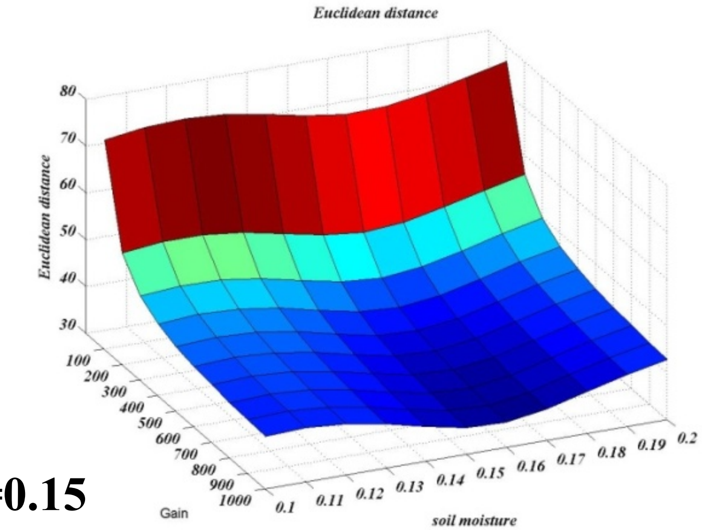
PRN4
optimal gain=200
optimal mv=0.15

These estimated soil moistures are close to the real value (0.15)

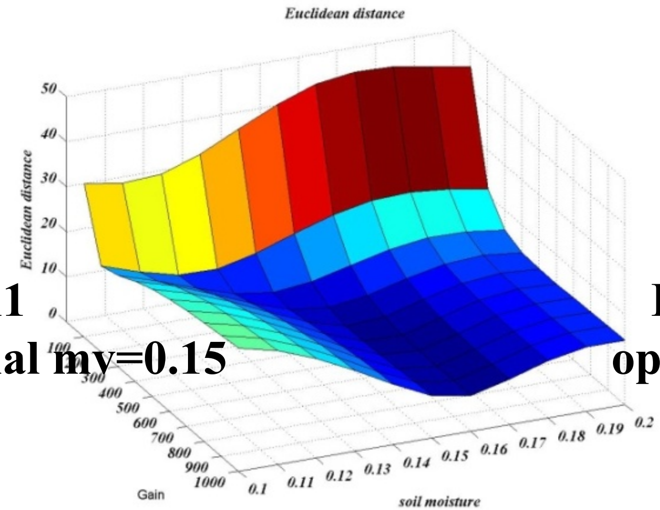
Experiment



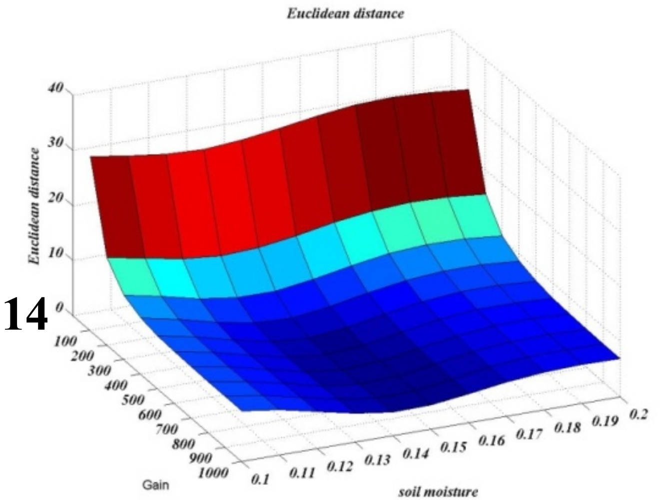
PRN7
optimal mv=0.16



PRN8
optimal mv=0.15



PRN11
optimal mv=0.15



PRN28
optimal mv=0.14

These estimated soil moistures are close to the real value (0.15)

Conclusion

- **Recent Australian effort in GNSS-R is introduced along with the current status of the technology**
- **A new soil moisture retrieval method (IDT) is presented**
- **Experiments show the new method is valuable/effective**
- **GNSS-R is an emerging and promising satellite RS technology for soil moisture measurements that is under significant international development**
- **Lots of challenges need to be resolved**
  - ✓e.g. roughness of the parcel, different vegetation cover, second or more times of signal reflections
- **Our future efforts include retrieval theory and algorithms, device/hardware for data collection and more validation tests**
- **Exploit the full spectrum of GNSS atmospheric sounding**

Thank you

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SPACE at a Glance

RMIT UNIVERSITY
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- Formed in 2010 as part of the Australian Space Research Program
- One of only 6 officially recognised research centres (and the largest) at RMIT
- Skills and expertise developing new methods, new algorithms and frontier technologies for satellite PNT, space situation awareness (including space object and debris monitoring and tracking), space weather, weather and climate change modelling and severe weather event modelling and prediction
- Research facilities on the RMIT City and Bundoora campuses
- The first comprehensive GNSS tracking station in Australia
- More than 20 full time Research and Academic and 10 higher degree by research students affiliated with the centre
- Large range of international collaborative arrangement with Asia, Europe, North America etc.