L-band Radar for Forest Temporal Dynamics

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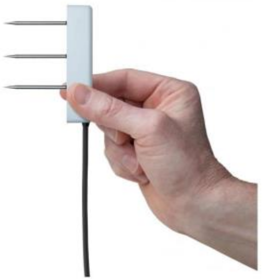
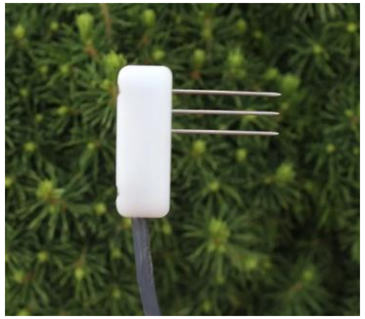
07/18/2023

In-situ measurement: Soil Moisture, Tree Dielectric, Tree Sap Flow



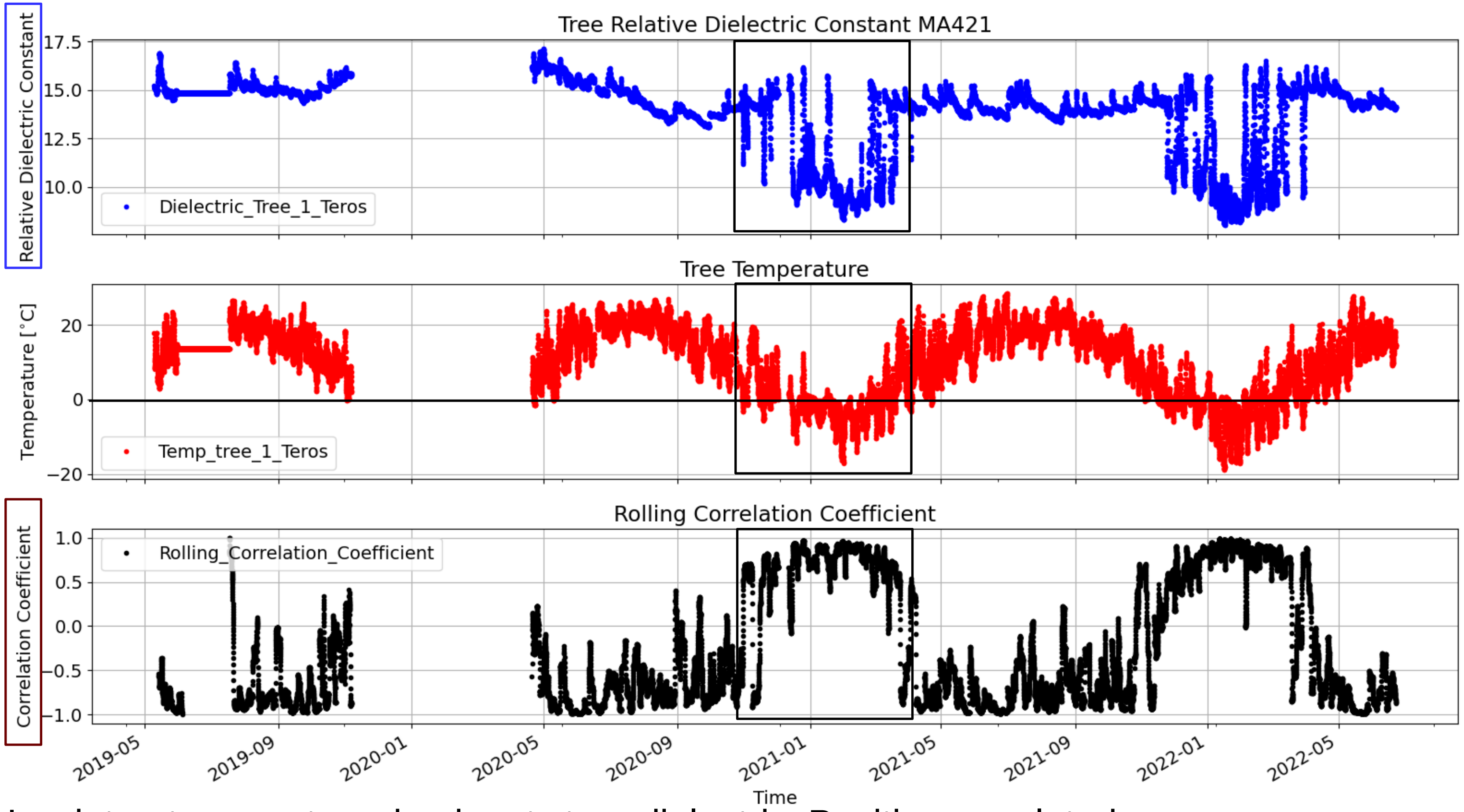
- Meter Teros 12 (5cm needle, 70MHz)
- Dielectric, temperature, electrical conductivity

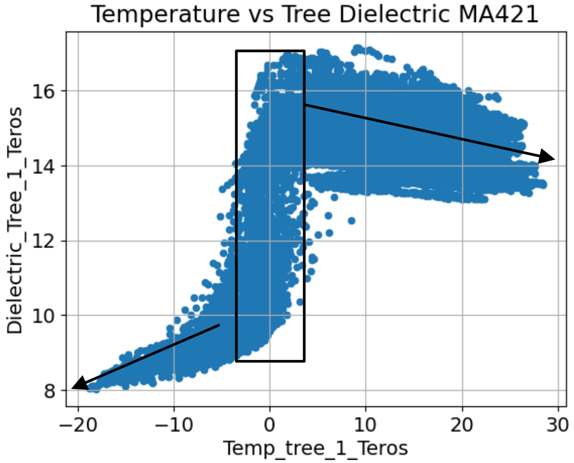


- East30 sap flow sensor (Heat Pulse Velocity)

- Stevens HydraProbe Soil Moisture Sensor

In Situ Time Series and Relationship: Tree Dielectric vs. Temperature

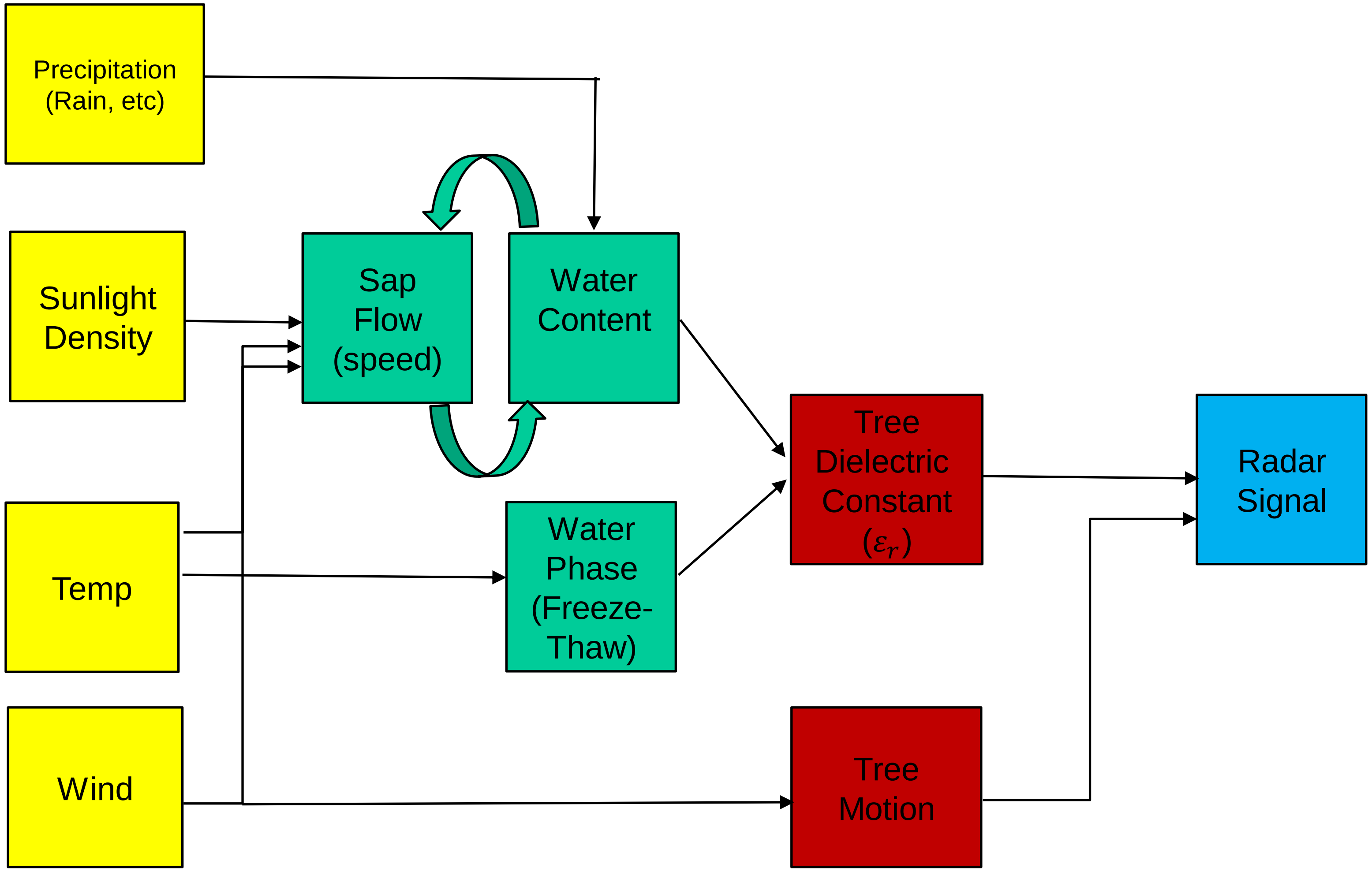




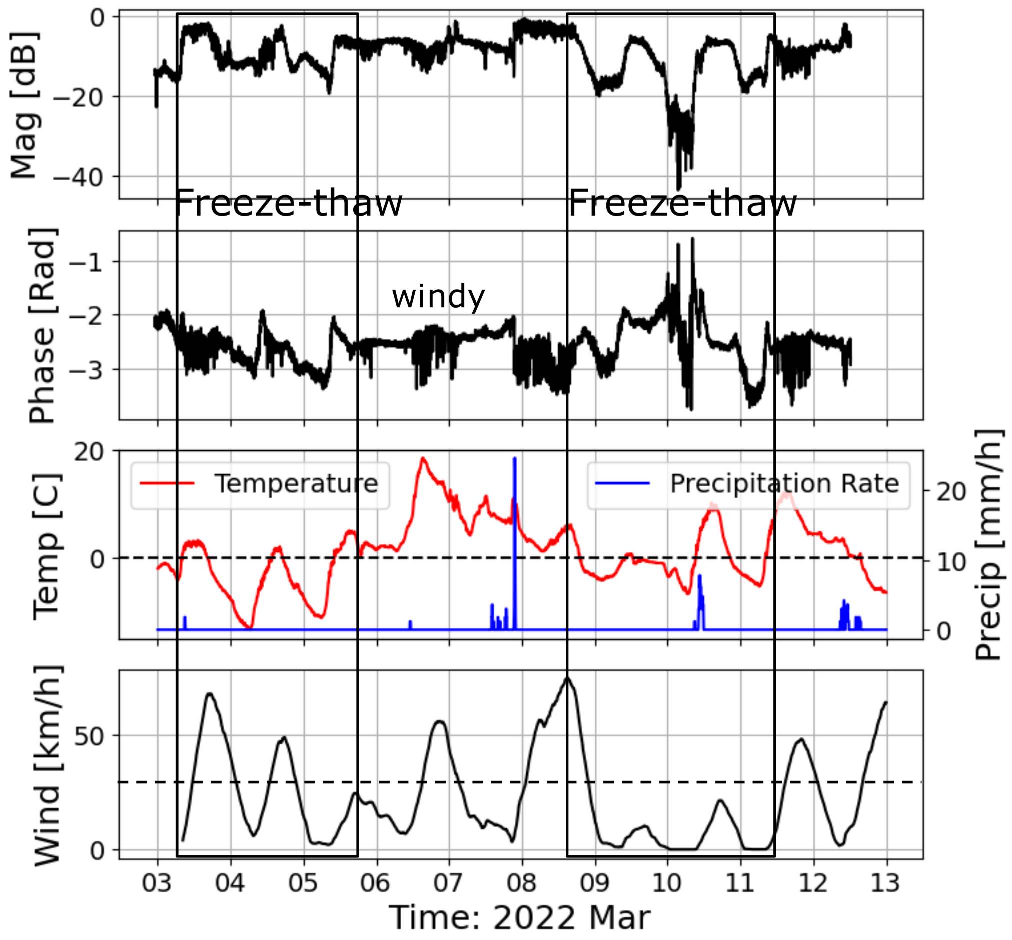
- Summer, higher temperature, faster transpiration and evaporation, lower dielectric/water content.
- Winter, water in tree freezes. Dielectric reaches minimum.
- When temperature is close 0 C, the range of tree dielectric is wide[9, 17] in this site
- Spring and Fall, dielectric increases and reaches maximum.

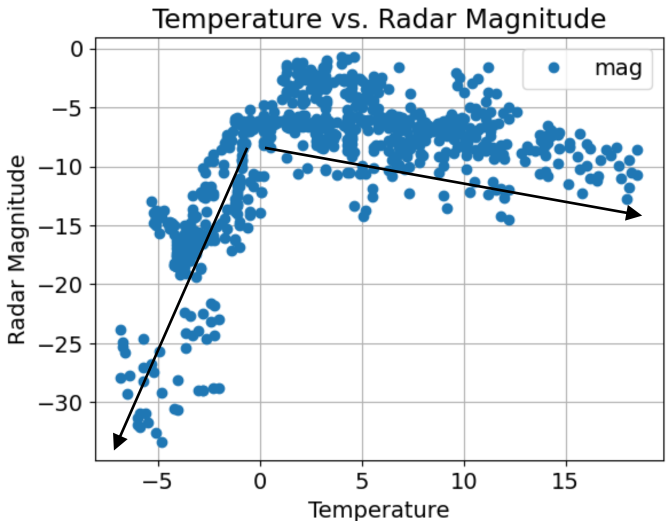
In winter, temperature dominants tree dielectric. Positive correlated
In summer, rain and transpiration dominants. Negative correlated. Correlation spikes due to rain, etc.

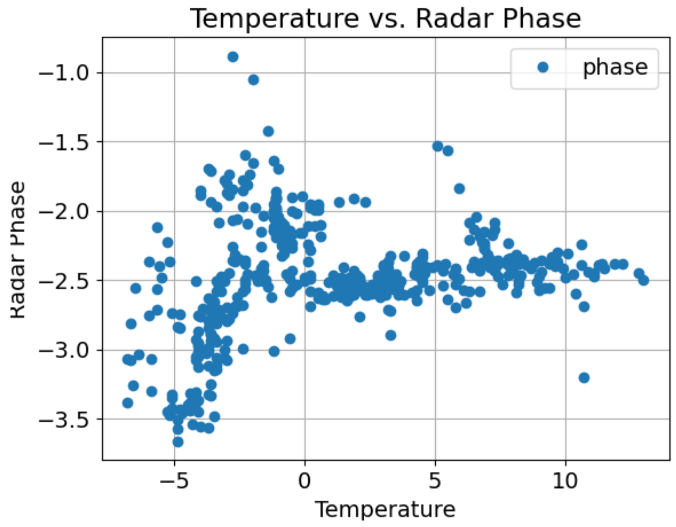
What causes the variations in radar signal?



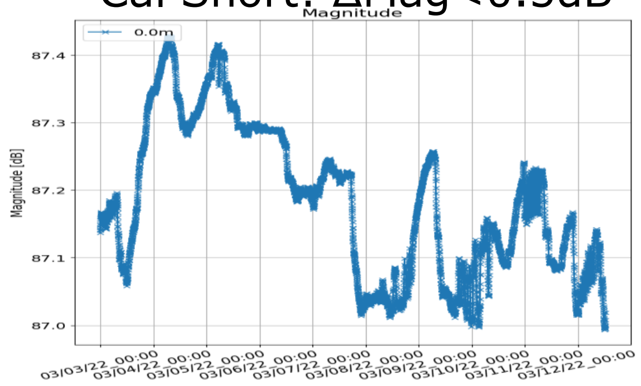
L-band Radar Time Series Measurement
Amherst Massachusetts, Early Spring 3/3/22-3/13/22



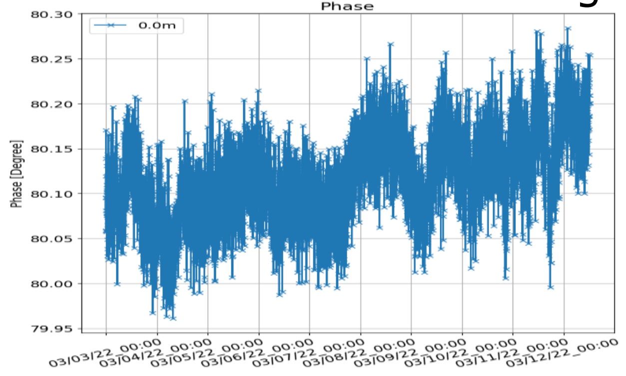




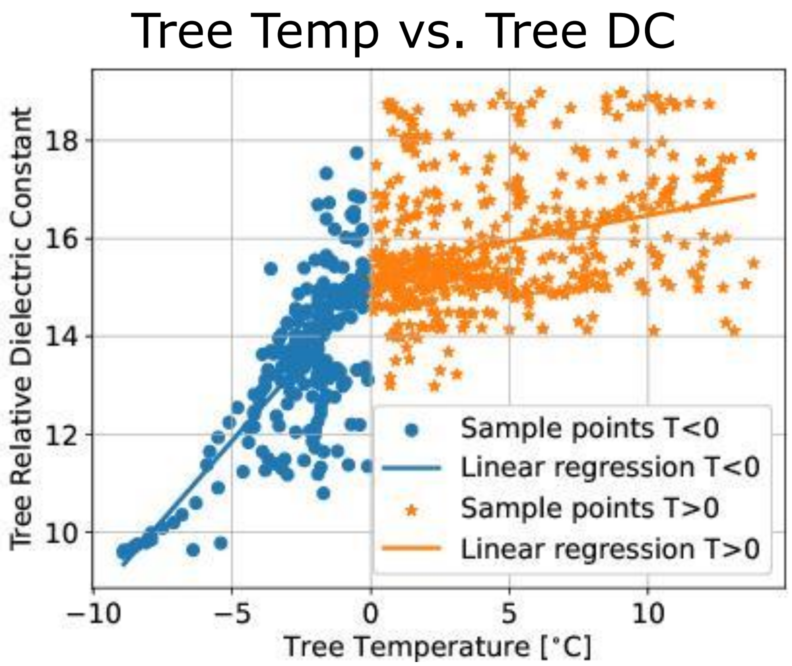
- Cal Short: ΔMag<0.5dB

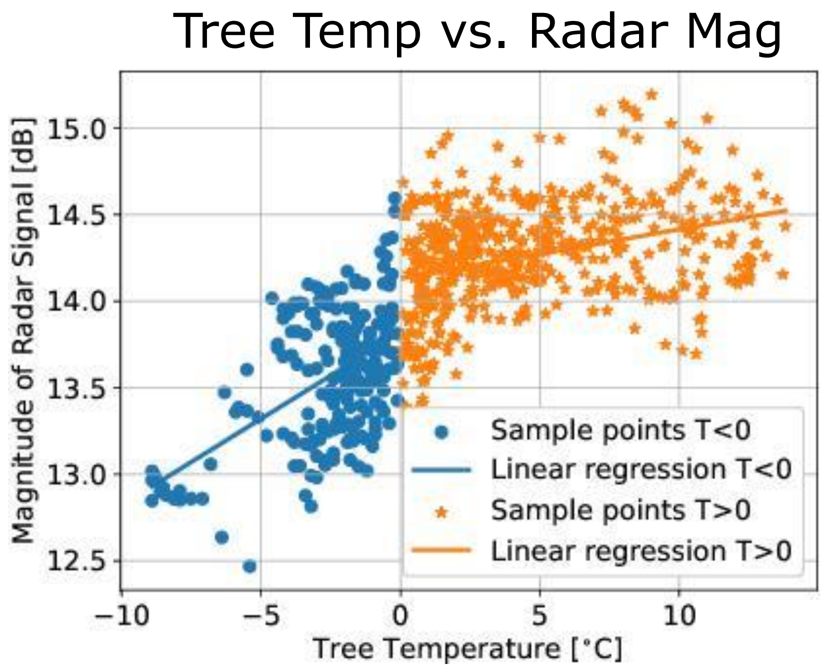


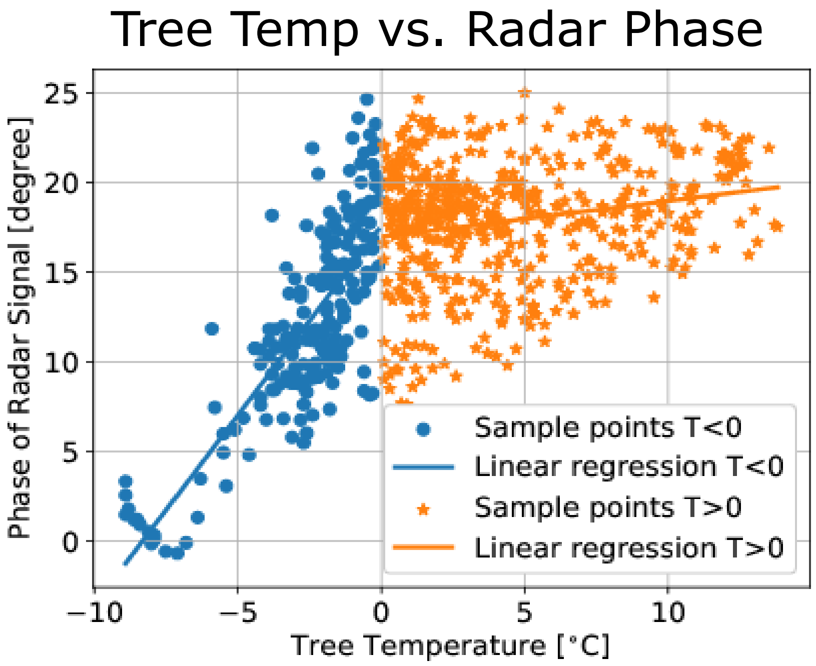
- Cal Short: ΔPhase<0.4 degree



L-band Radar Data:
Amherst Massachusetts, Winter 11/26/2022-12/26/2022



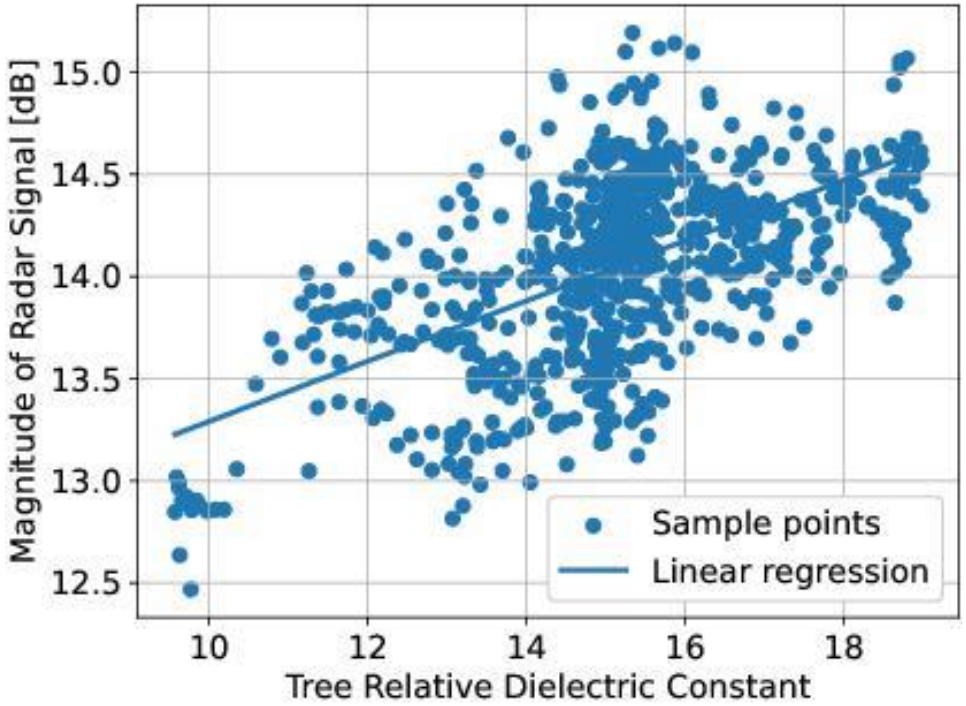




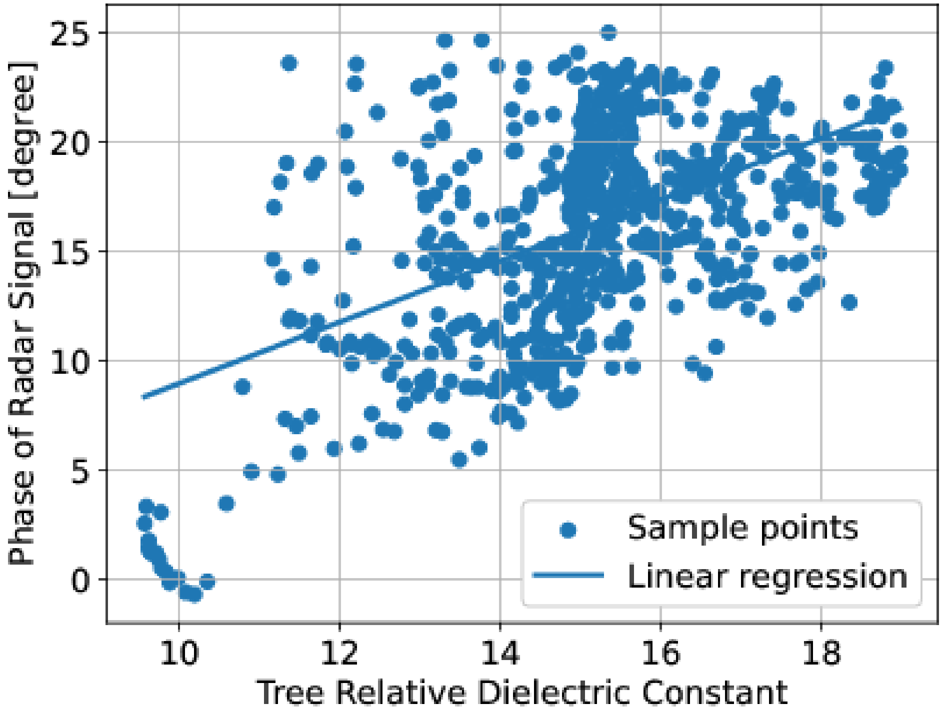
- Data comparison: in situ sensors are in radar’s field of view
- When the temperature decreases below 0°C, the magnitude and phase have a down-trend.
- Confirmed by the tree dielectric sensor.

L-band Radar Data
Amherst Massachusetts, Winter 11/26/2022-12/26/2022

Tree Dielectric vs. Radar Magnitude

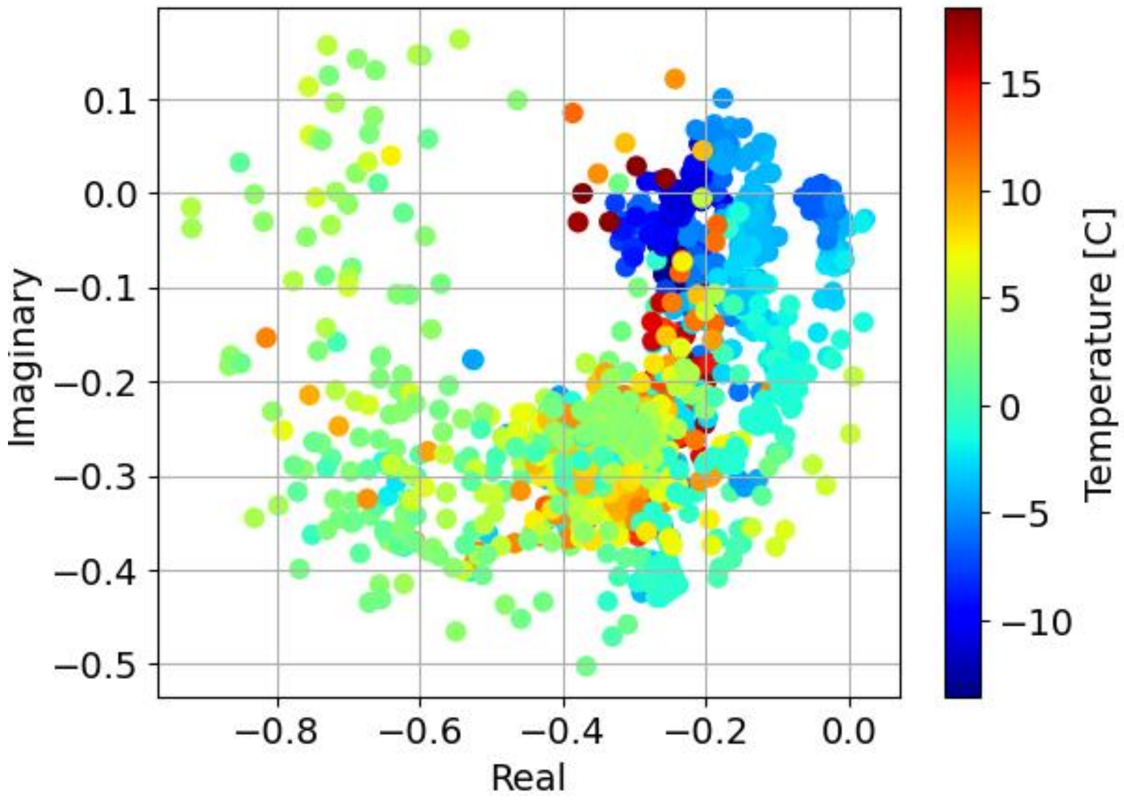


Tree Dielectric vs. Radar Phase



- Magnitude vs. Dielectric has a linear relationship.
- Phase vs. Dielectric need careful characterization with more data.

Real and Imaginary Part of the Radar Signal
Amherst Massachusetts, Early Spring 3/3/2022-3/13/2022

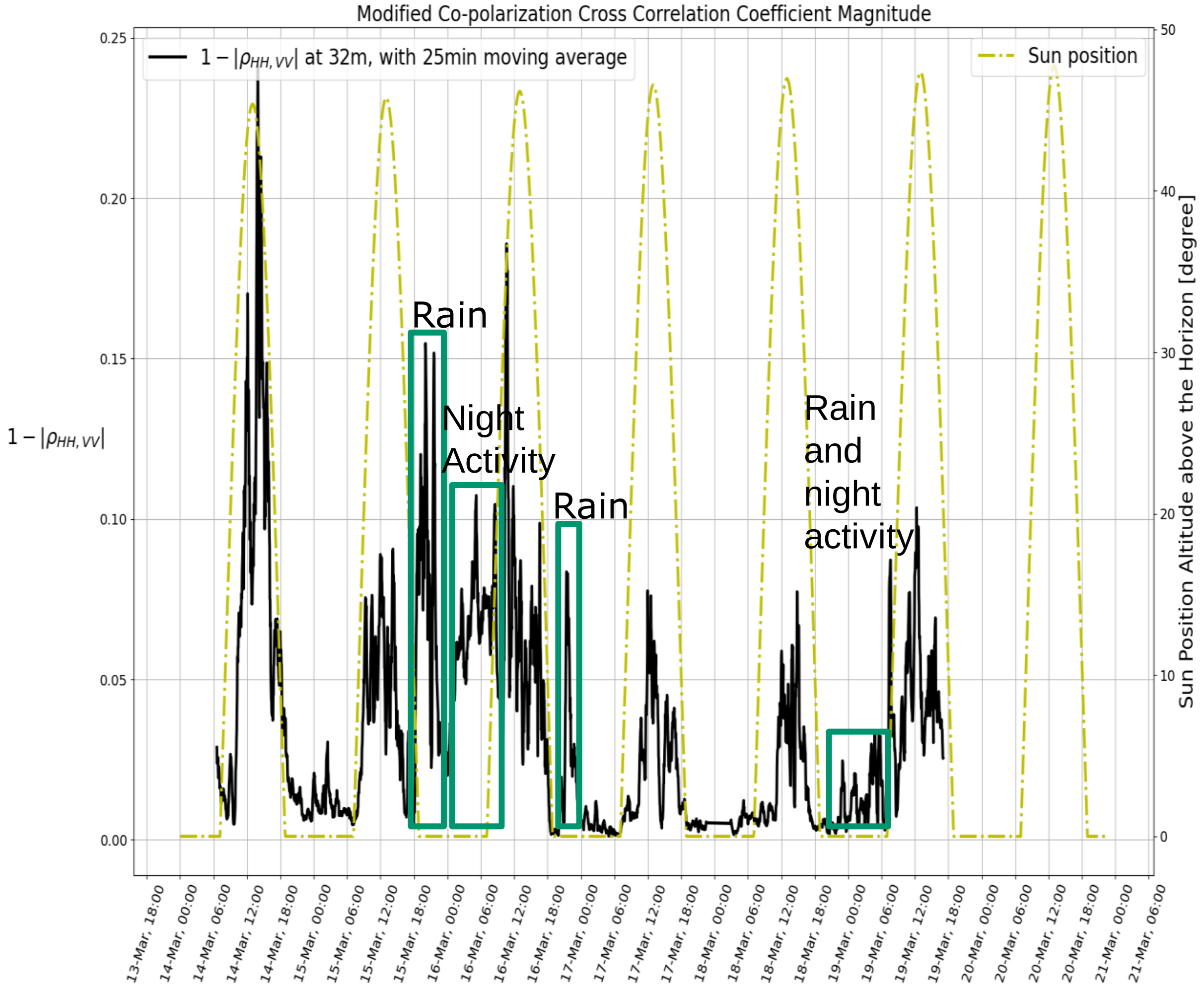


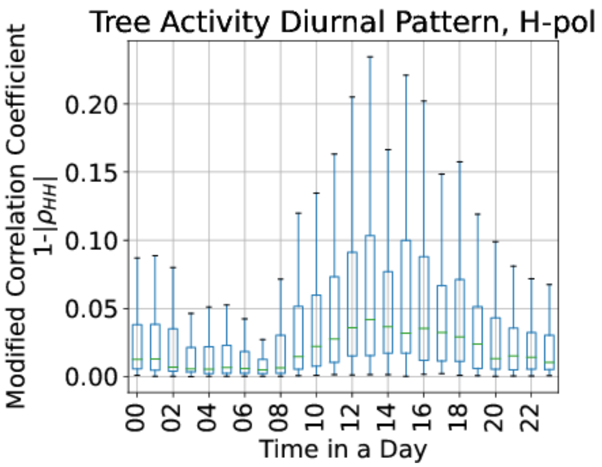
- Real and imaginary part of the radar signal where red maples are located at 18.25 meters in radar's FOV. The wave impedance of the tree changes with temperature.
- The dielectric change in the wave transmission path and load makes a change in phase and spiral-circle impedance.
- The dielectric change can be caused by the maple trees' extracellular freezing and supper cooling, making denser cell liquid get a lower freezing point and generating sugar sap.

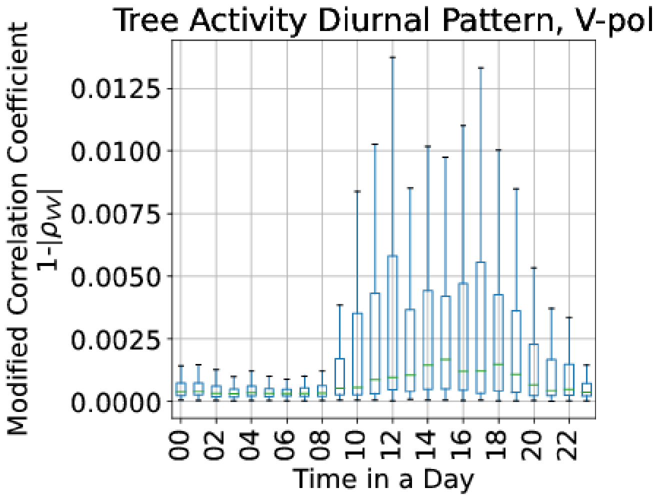
Modified Correlation Coefficients(MCC)

Two polarization Measurement

$$\rho_{HH,VV} = \frac{cov(H,V)}{\sigma_H \sigma_v}$$





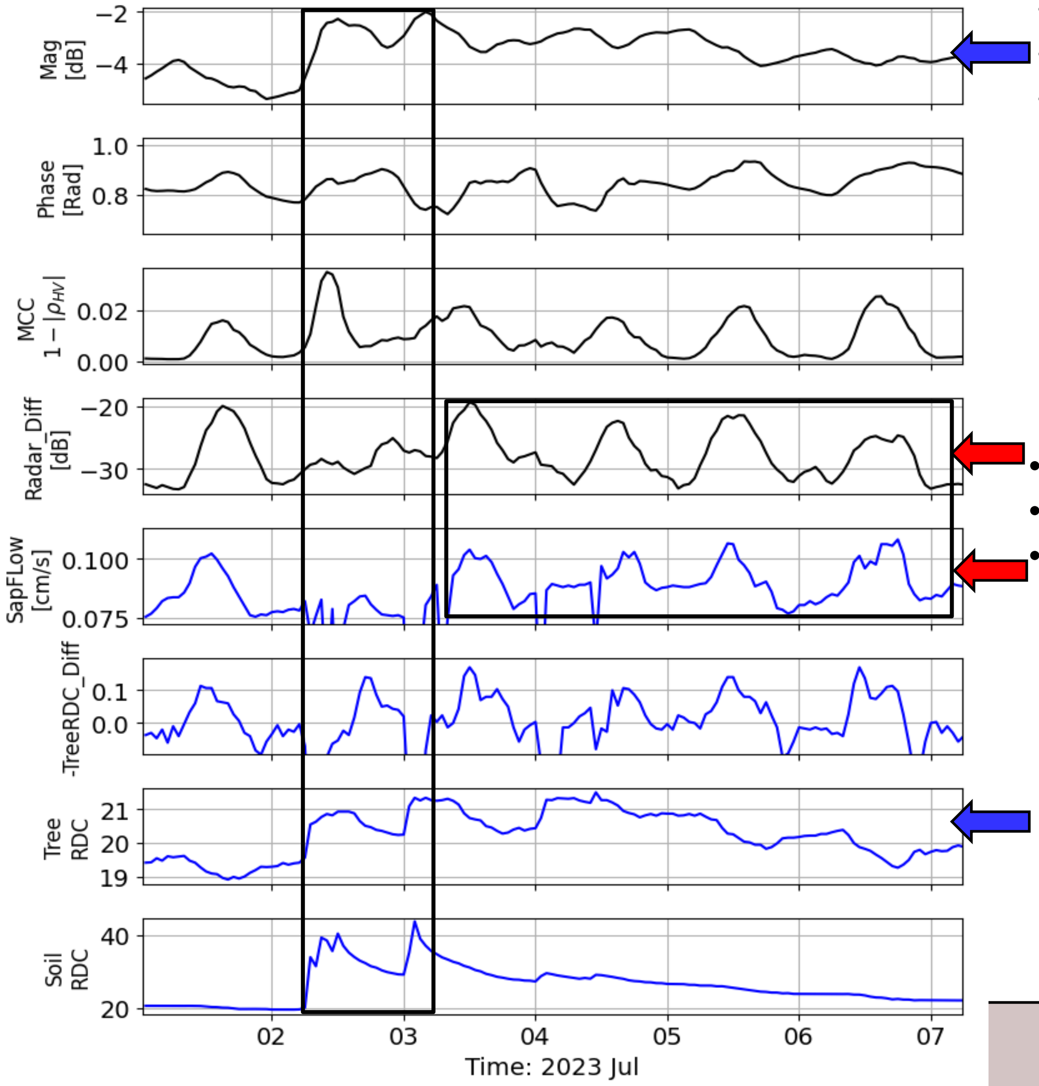


$$1 - |\rho_{HH}| = 1 - |\frac{cov(H,H)}{\sigma_H \sigma_H}|$$

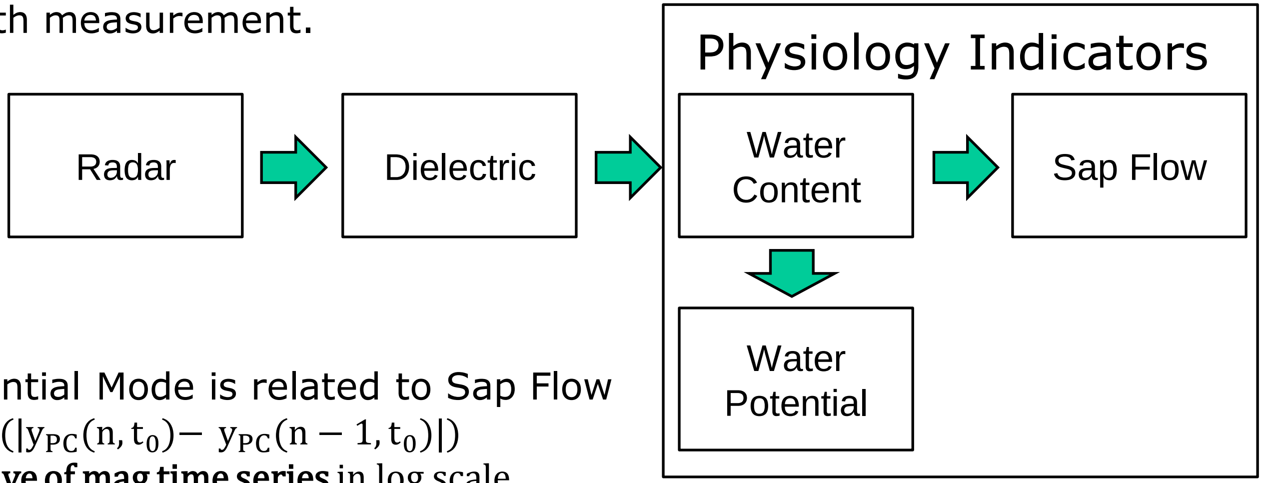
$$1 - |\rho_{VV}| = 1 - |\frac{cov(V,V)}{\sigma_V \sigma_V}|$$

- An indicator for tree activity.
- Sensitive to the water content change.
- The H-pol MCC is more sensitive than V-pol.

Time Series: H-pol Radar vs. In Situ Sensors
07/01/2023-07/07/2023 Amherst



- Mag is related to Water Content: $20log_{10}(|y_{PC}(n, t_0)|)$
- t_0 is time of wave propagation, related to a fixed distance.
- n is n th measurement.

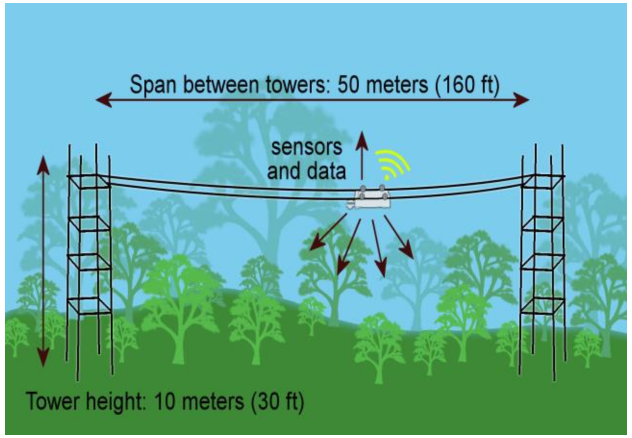


- Differential Mode is related to Sap Flow
- $20\log_{10}(|y_{PC}(n, t_0) - y_{PC}(n-1, t_0)|)$
- **Derivative of mag time series** in log scale

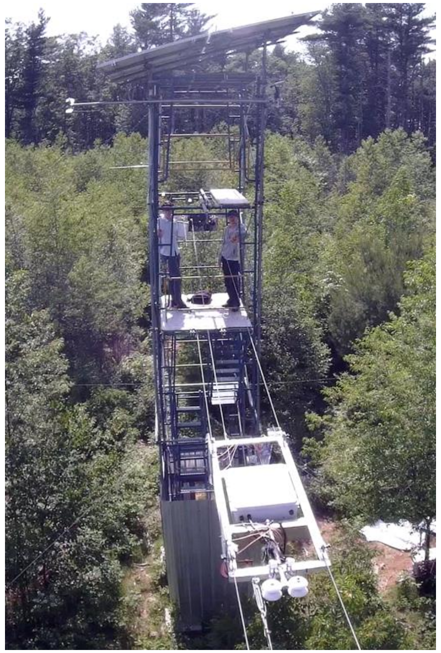
Indicators for Tree Hydraulics	How to Measure and Calculate
Water Content	Measured by radar magnitude
Sap Flow	Calculated as the change rate in water content
Water Potential	Linearly related to water content

A Ground SAR and Tram System for Forest Application

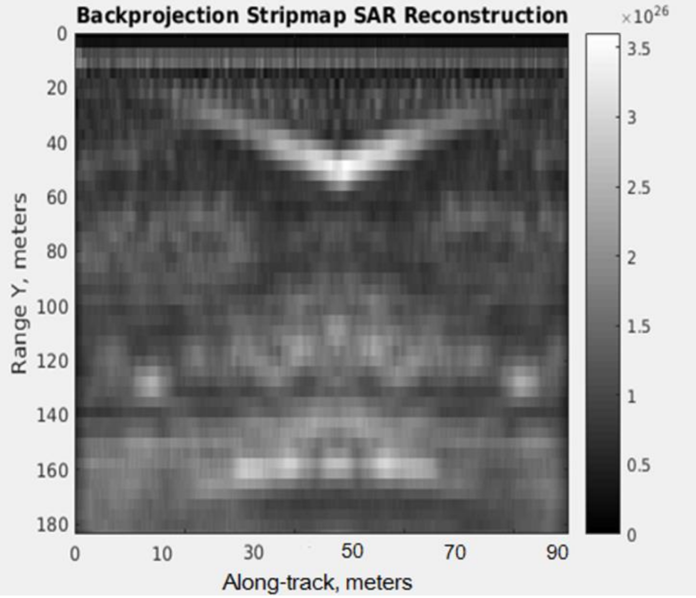
Ground SAR



Tram System



Ground SAR round trip measurement in Harvard Forest



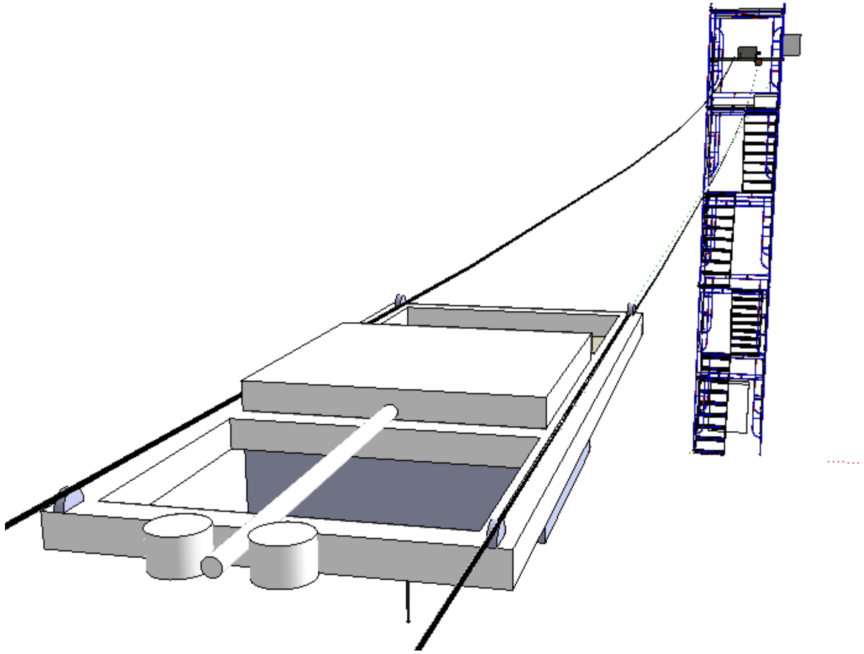
Tram Radar Figure of Merit

Center Frequency	1.4135GHz
Wavelength	21.2cm
Bandwidth	20MHz
Range Resolution	7.5m
Sampling Rate	56MSamples/Sec
Chirp Duration	0.6ms
Antenna Beamwidth	66degree
Tx Rx Antenna Isolation	50dB
Receiver Noise Figure	8dB
Transmit Power	100mW
Total Power Consumption	18W
Tram Speed	0.5m/Sec

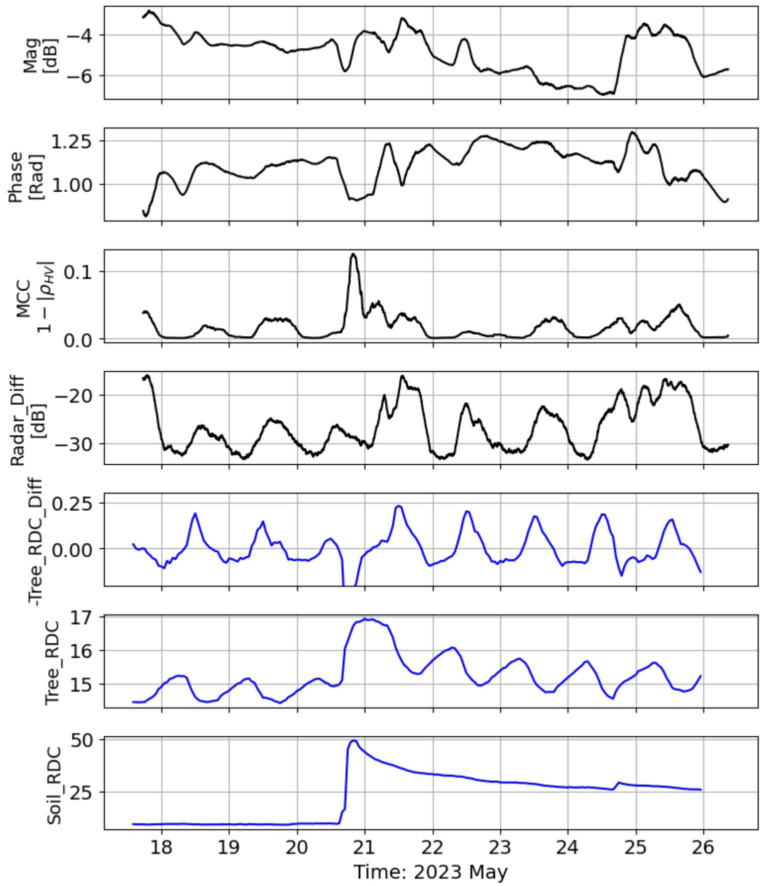
- Harvard Forest Application: clear-cutting area is about 0.4 km^2 filled by young trees such as Birch, Cherry, Maple.
- Drought and wildfire prediction, tree mortality, agriculture water usage, forest transpiration rate, etc.
- Ground calibration for spaceborne temporal decorrelation

Questions and Discussion

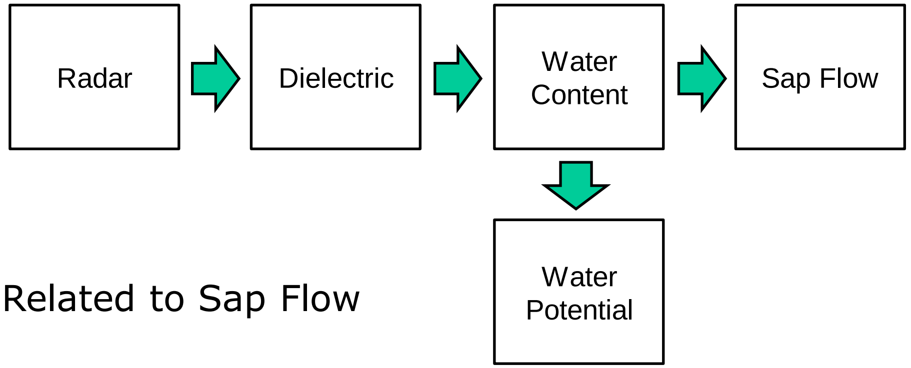
Thank you



20230517-20230526 Amherst H-pol Radar vs. In Situ Sensors



Related to Water Content



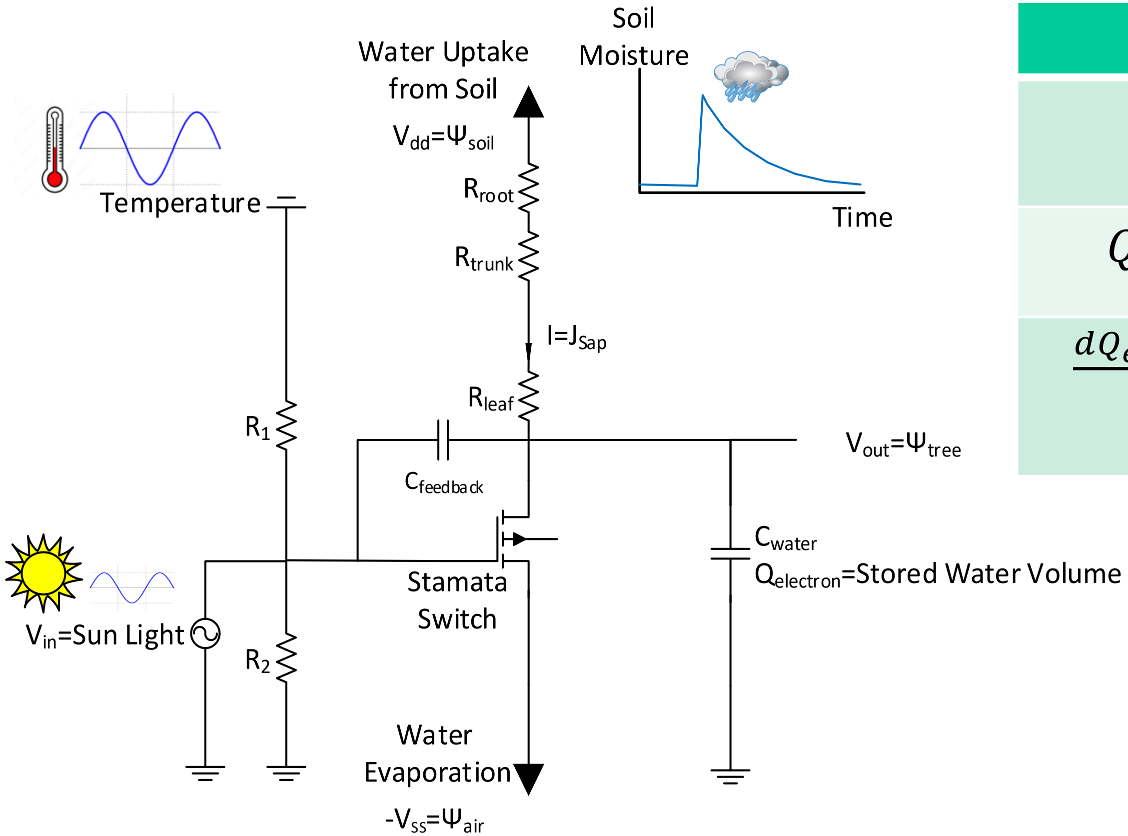
Related to Sap Flow

Indicators for Tree Hydraulics	How to Measure and Calculate
Water Content	Measured using radar magnitude
Sap Flow	Measured as the rate of change in water content
Water Potential	Linearly related to water content

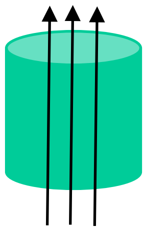
Explanation of Differential Mode

- The differential mode measures the changes in radar back scatter.
  1. $\Delta s_{RX}(n,t) = s_{RX}(n,t) - s_{RX}(n-1,t)$, where $s_{RX}(n,t)$ is radar received signal in time domain. $\Delta s_{RX}(n,t)$ is a difference between two measurements which are next to each other(2-3 minutes apart). n is nth measurement and t is the time in milliseconds for the received radar pulse.
  2. Radar pulse compression by matched filter: $\Delta y_{PC}(n,t) = \Delta s_{RX}(n,t) * s_{TX}^{H}(t)$
  3. Differential mode time series: $x(n) = 20log_{10}(|\Delta y_{PC}(n,t_0)|)$, where n is nth measurement and t_0 is the time delay corresponding for a distance where trees are located.
- The differential mode measures sap flow:
  - Since convolution is linear: $\Delta \mathrm{y}_{\mathrm{PC}}(\mathrm{n},\mathrm{t}_0) = \mathrm{y}_{\mathrm{PC}}(\mathrm{n},\mathrm{t}_0)$- $\mathrm{y}_{\mathrm{PC}}(\mathrm{n}-1,\mathrm{t}_0)$
  - Because the differential mode is equivalent to derivative of magnitude($\mathrm{y}_{\mathrm{PC}}(\mathrm{n},\mathrm{t}_0)$) time series $\Delta \mathrm{y}_{\mathrm{PC}}(\mathrm{n},\mathrm{t}_0) = \frac{\mathrm{y}_{\mathrm{PC}}(\mathrm{n},\mathrm{t}_0) - \mathrm{y}_{\mathrm{PC}}(\mathrm{n}-1,\mathrm{t}_0)}{n-(n-1)} = \frac{\Delta \mathrm{y}_{\mathrm{PC}}(\mathrm{n},\mathrm{t}_0)}{\Delta \mathrm{n}}$
- Assuming the radar RFFE is stable during each consecutive measurements, the differential mode cancels the common mode nonlinearity from RF frond end such as PA and LNA given that radar is time deterministic and coherent.

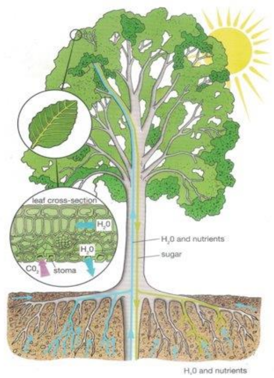
Tree Hydraulic Circuit



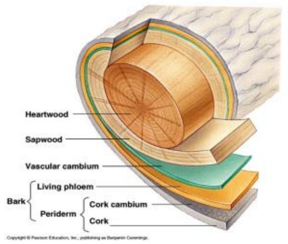
Electronics	Tree Hydraulics	Relationship
$I = \frac{V}{R}$	$J = K(\Psi_2 - \Psi_1)$	Sap flow vs. Water potential (Tree Ohm's Law)
$Q_{eletron} = CV$	$RWC = C\Psi$	Water Content vs. Water Potential
$\frac{dQ_{eletron}}{dt} = I\ [\frac{Coul}{s}]$	$\frac{dV_{water}}{dt} = J_{in} - J_{out}\ [cm^3/s]$	Water Content vs. Sap Flow (Conservation of mass)



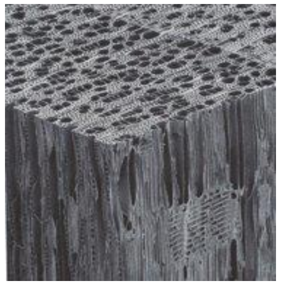
Transpiration



Layers of Tree Trunk



Sapwood, Xylem

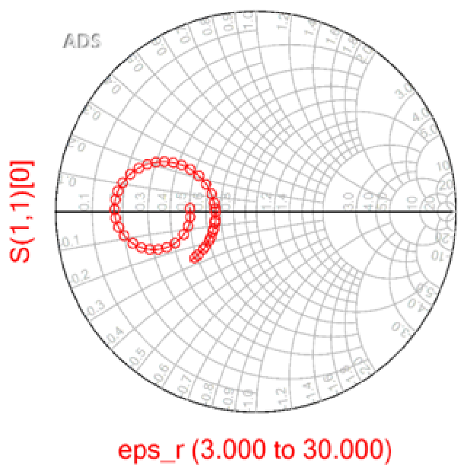


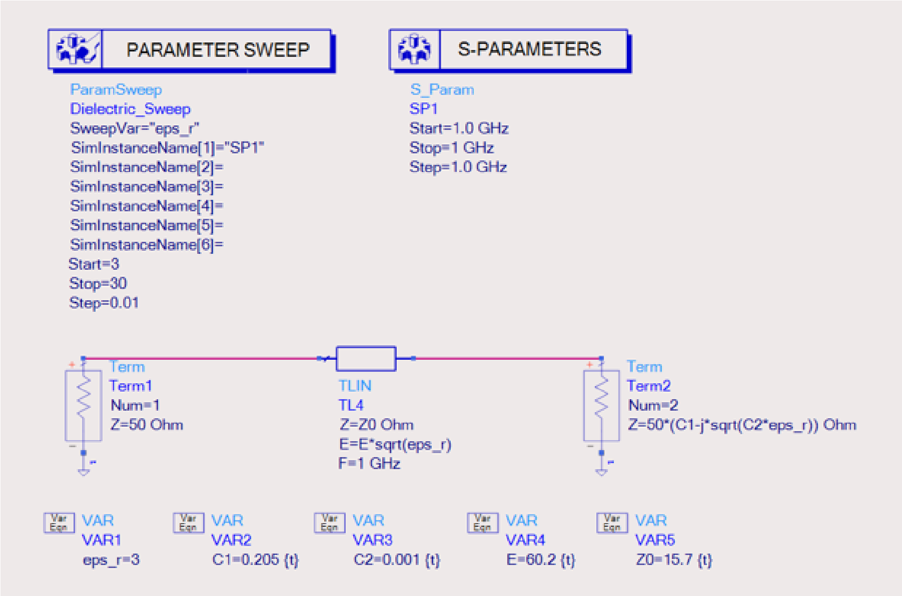
- The flow of water through trees can be compared to a current through a network of resistors and capacitors.

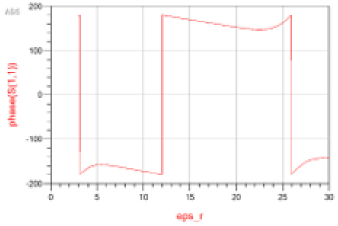
Units for Electronics and Tree Hydraulics

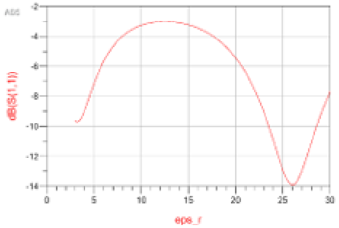
Electronics/ circuit	Symbol	Unit	Fluid mechanics	Symbol	Unit	Tree Hydraulics	Symbol	Unit
Current	I	Ampere(coul/s)	Fluid Flow	Q	m^3/s	Sap Flow	J	cm^3/s
Voltage	V	Volt	Potential	Psi	Pa	Water Potential	Psi	Pascal, kPa
Quantity of electric charge	C	Coulomb	Volume of Fluid	V	m^3	Volume of Water	V	cm^3

Explanation: Real and Imaginary Part of the Radar Signal
Amherst Massachusetts, Early Spring 3/3/2022-3/13/2022





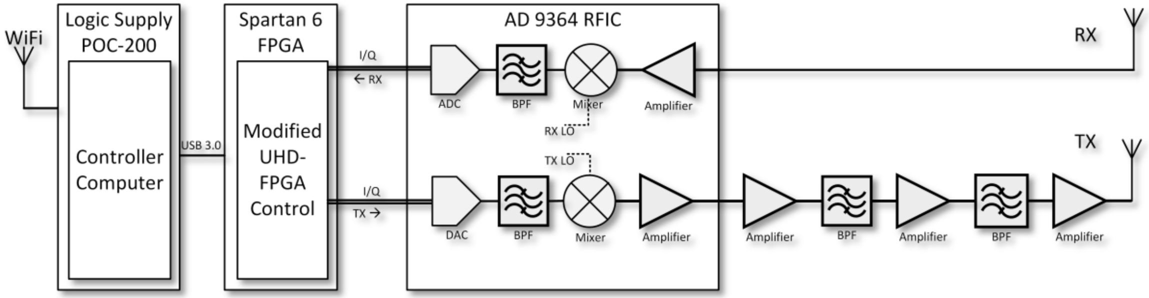




- E = 60 degrees, that is 5cm length at 1GHz. The wave hits the tree and penetrates 5cms. The load impedance is determined by tree dielectric, etc. The phase circles due the change of the tree dielectric and hence change the electrical length of the penetration distance. Assuming Z0 is fixed.
- C1 determines the real axis location of the starting point for er sweeping.
- If adding dielectric var in C1 C2, then the circle spirals. So dielectric change in load impedance disperses the radius of the circle.

§ The dielectric change in the transmission line and load makes a change in phase and spiral-circle impedance. Simulated it in Keysight ADS.

L-band FMCW Radar System



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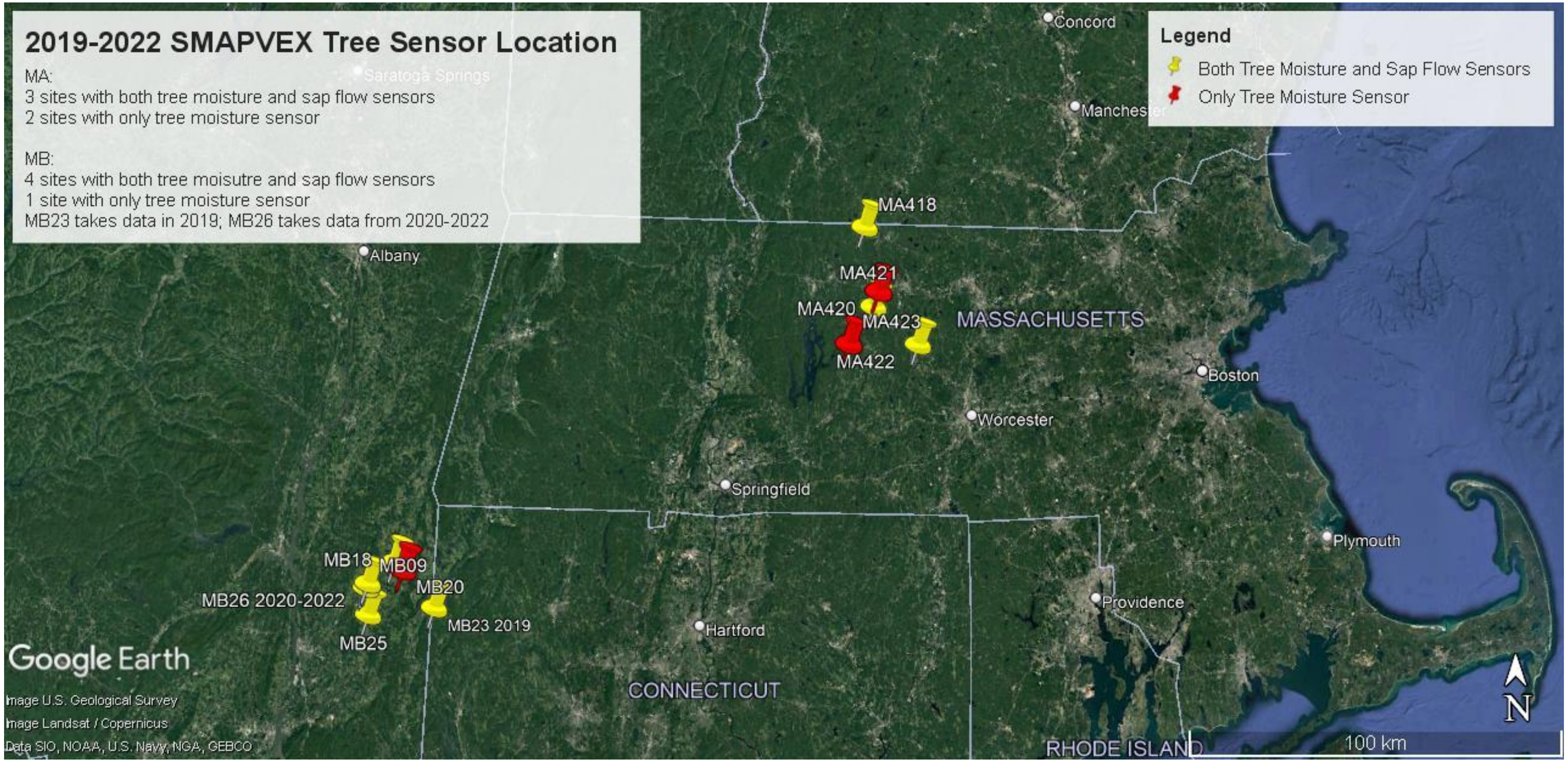
Range Resolution	7.5m
Sampling Rate	56MSamples/Sec
Chirp Duration	0.6ms
Antenna Beamwidth	66degree
Tx Rx Antenna Isolation	50dB
Receiver Noise Figure	8dB
Transmit Power	100mW
Total Power Consumption	18W
Tram Speed	0.5m/Sec

- Ettus B200mini Software Defined Radio + Bandpass Filter + Power Amplifier + Antenna
- Easy to configure in software: TX waveform, center frequency, etc.

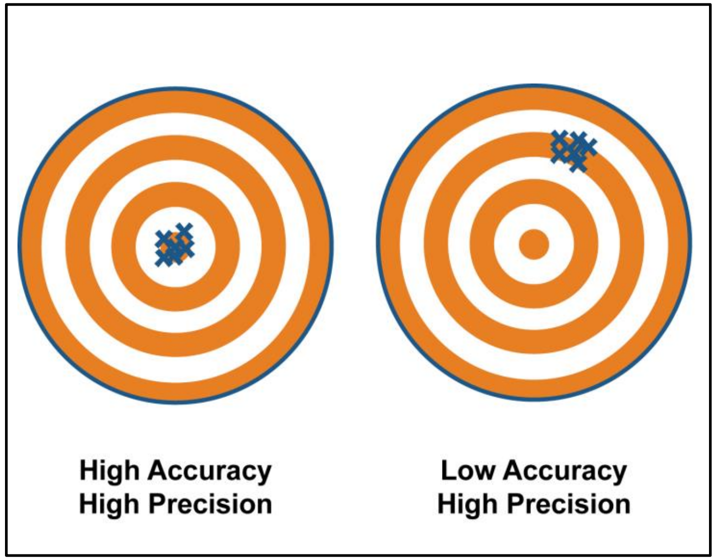
SMAPVEX Tree Sensor Location: MA 5 sites, MB 5 sites

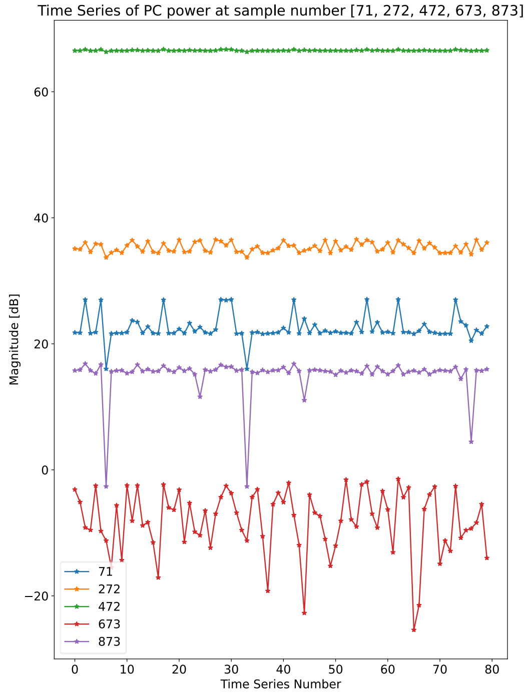


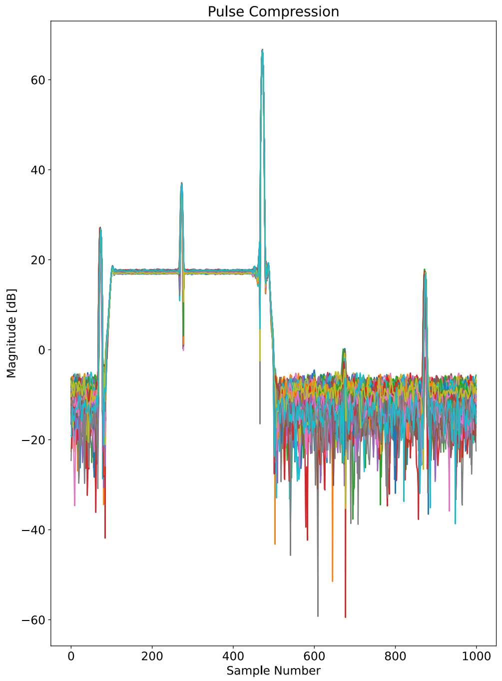
Can radar detect forest variation? Yes.

1. Sensitivity:
   - signal > thermal noise + intermodulation noise
2. Repeatability:
   - A stable radar

- Forest signal: slow, small

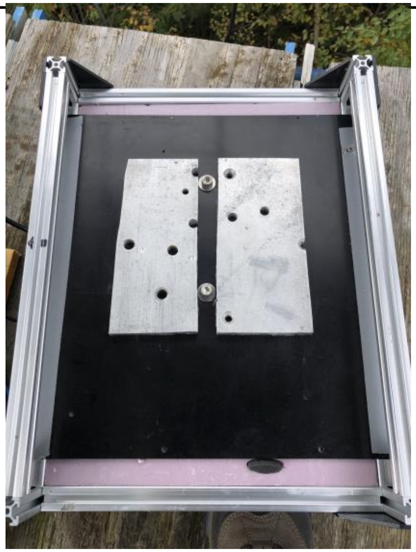


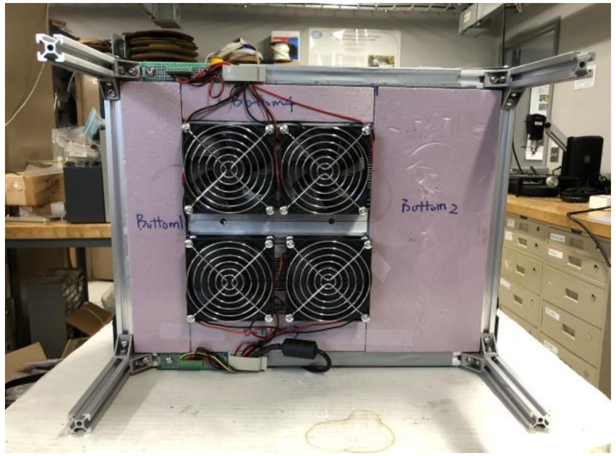


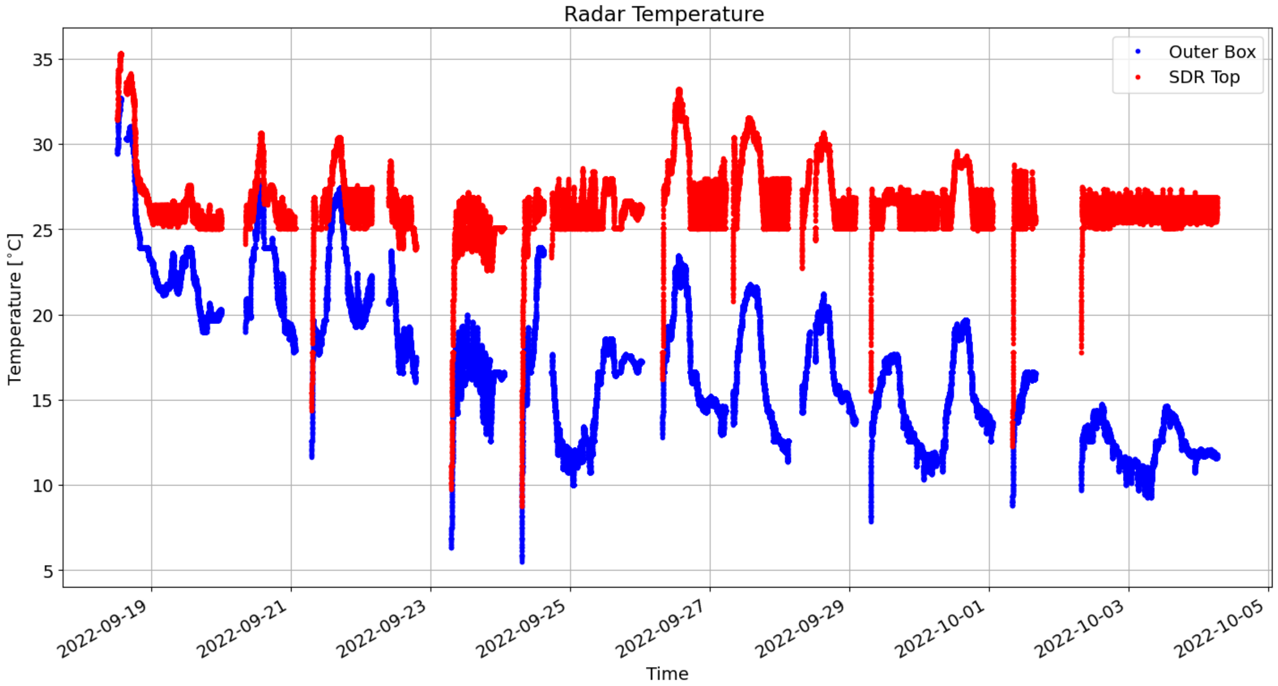


- Radar stability test by delay module loopback

Radar Temperature in HF



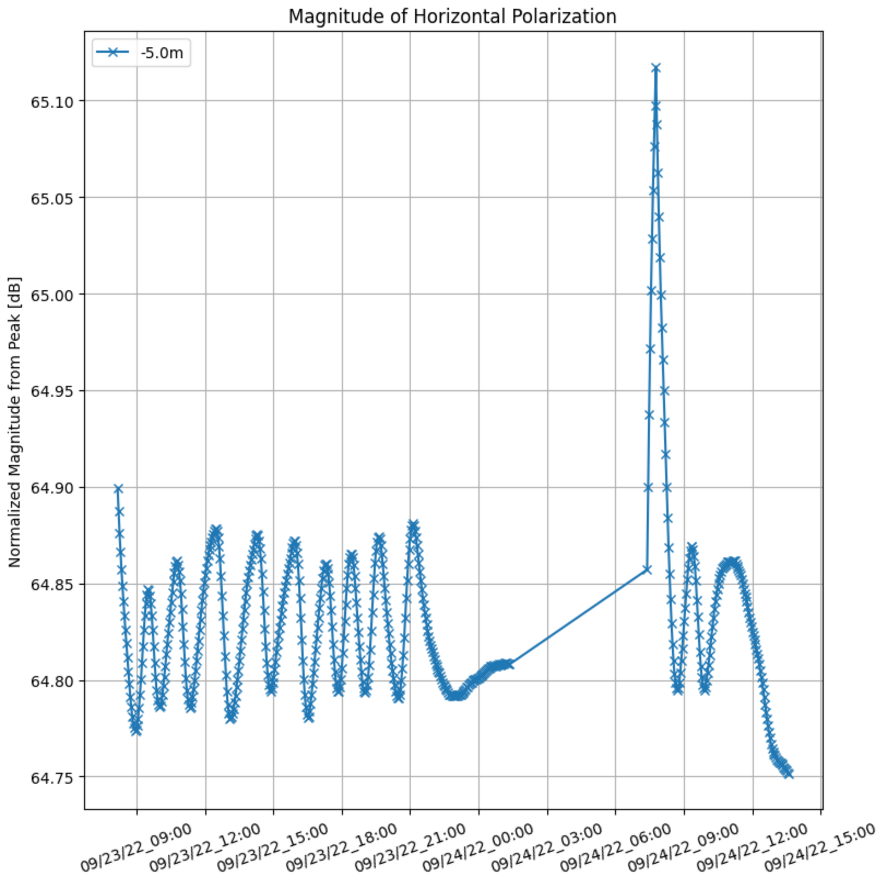


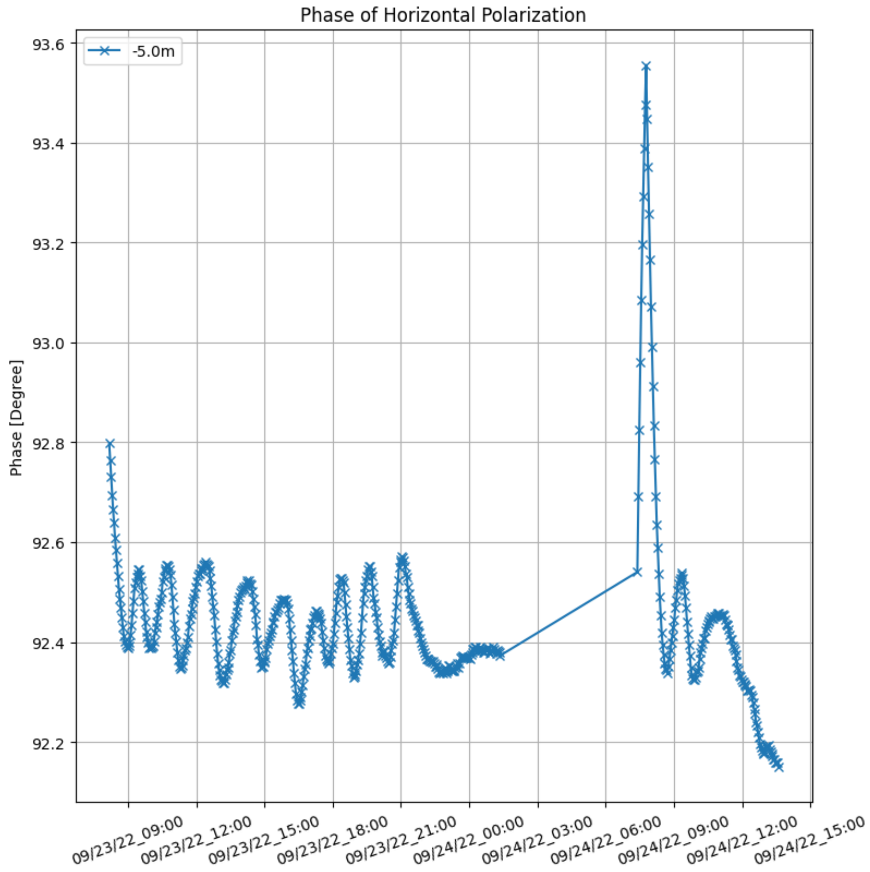


- Peltier Plate
- Fans
- Heat Sink
- Thermal Isolation Box
- Aluminum tape

Verify power stability
Short Port (HF 20220923-24)

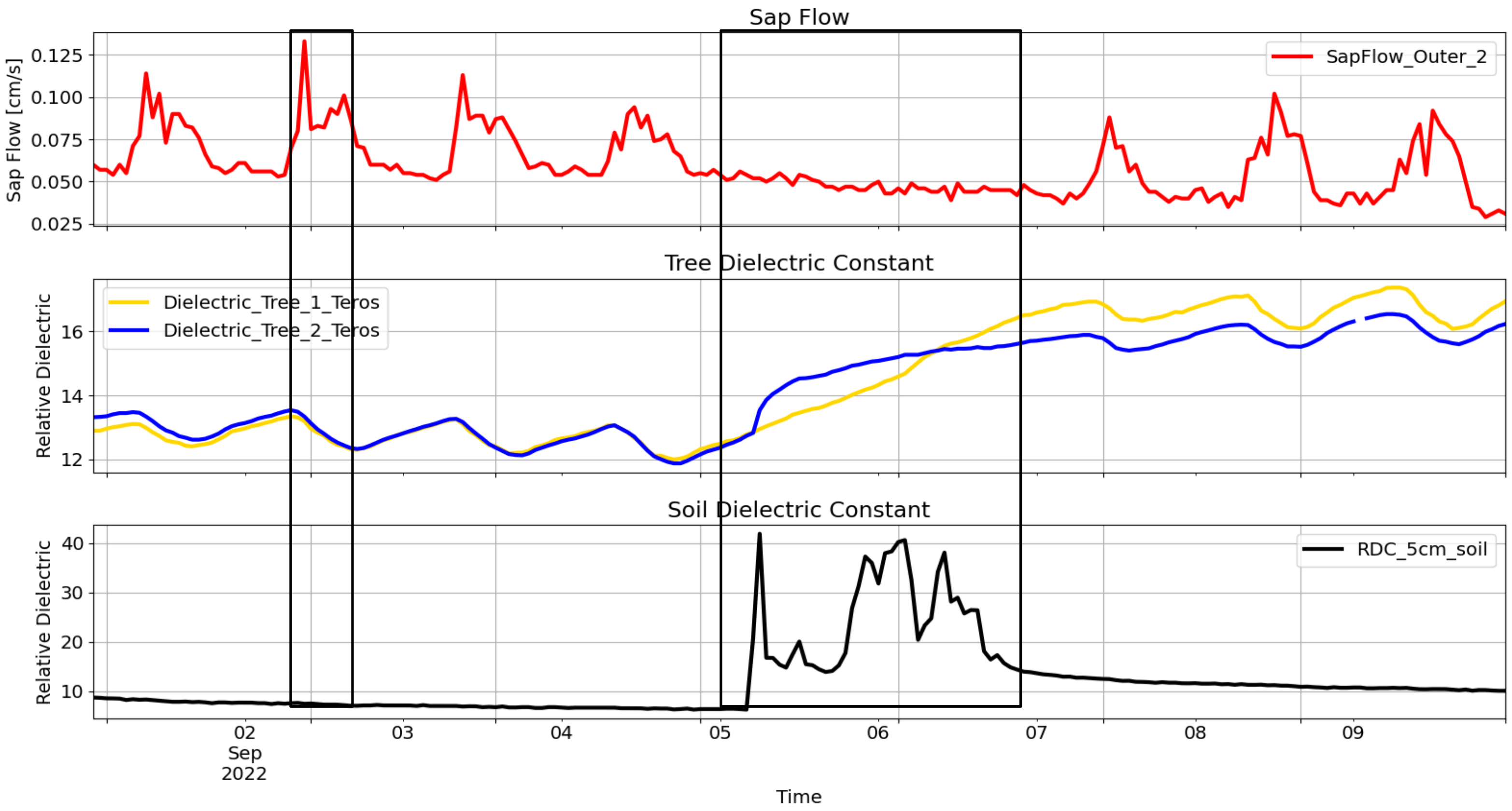
- Δ Magnitude<0.5dB
- Δ Phase<1.5 degree





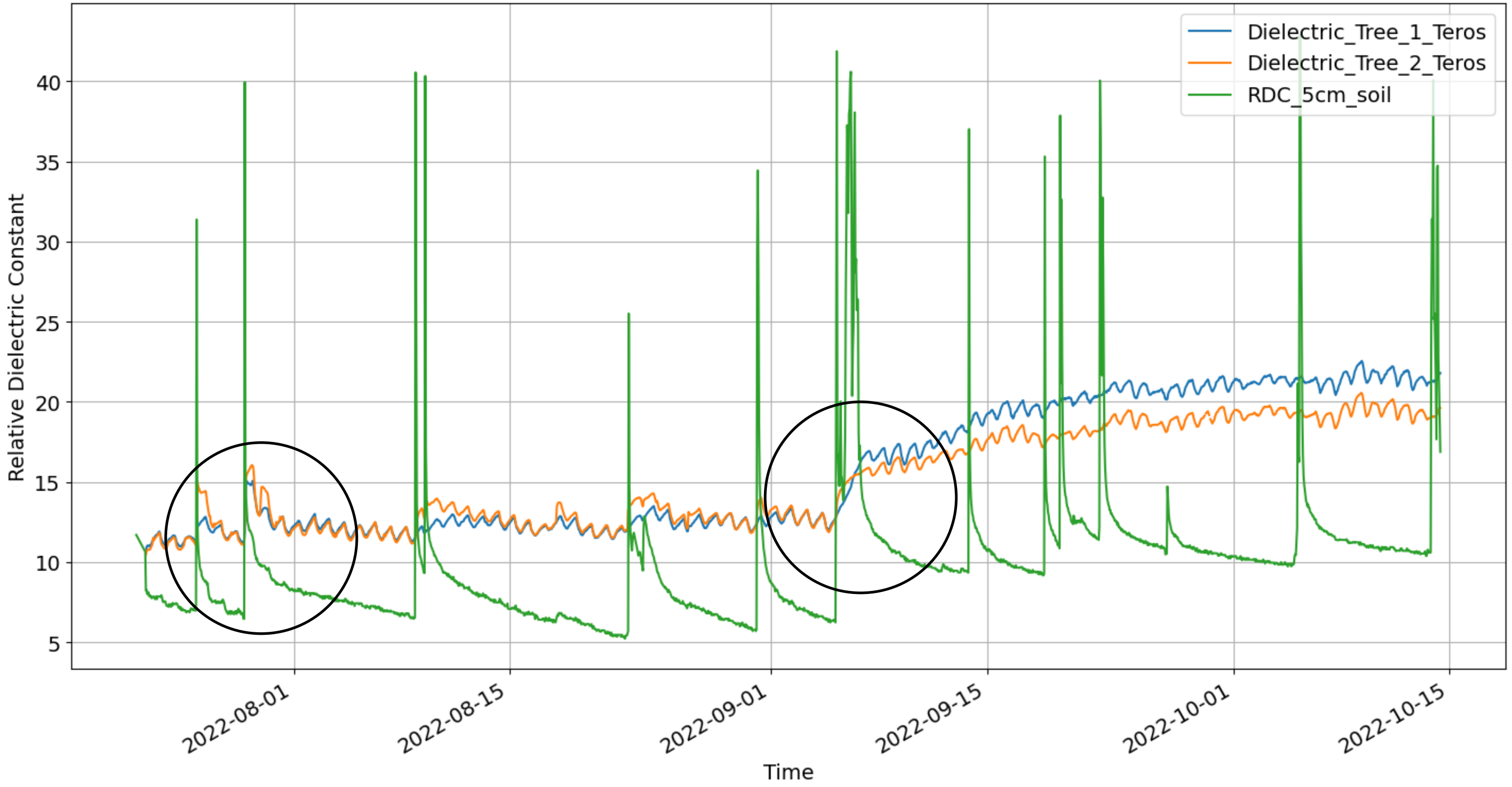
SAR

Relationship: Soil Dielectric, Tree Dielectric, Tree Sap Flow



- The decrease in tree water content corresponds to high sap flow
- How to find the relationship between tree dielectric and sap flow?

Soil Moisture, Tree Dielectric and Rain



- Dielectric daily pattern:
  - Small variation.
  - High at night, low in the middle of the day.
- Seasonal pattern:
  - Large variation.

L-BAND RADAR FOR FOREST TEMPORAL DYNAMICS

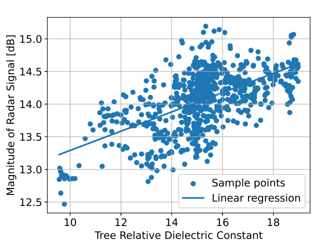
Xingjian Chen[1], Paul Siqueira[1], Kyle McDonald[2], Michael Cosh[3], Andreas Colliander[4], and Mark Vanscoy[5]

[1]University of Massachusetts Amherst
[2]City College of New York
[3]United States Department of Agriculture
[4]Jet Propulsion Laboratory, California Institute of Technology
[5]Harvard Forest

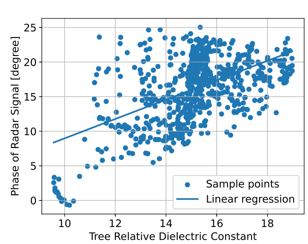
ABSTRACT

L-band FMCW radar is implemented for monitoring forest dynamics. It took short-term and long-term measurements with an internal calibration system that guarantees stability and precision. The radar data is compared to in-situ measurement, which infers causal relationships between radar backscatter signal and forest physiology index such as tree dielectric. This paper explains the relationship between radar signals and environmental components such as precipitation based on the measurement. The radar demonstrates some interesting observations, for example, trees' diurnal activity and freeze-thaw process.

***Index Terms*—** Radar System, Forest Dynamics, Tree Physiology, Dielectric, Water Content, Sap Flow



(a) Dielectric vs. Magnitude



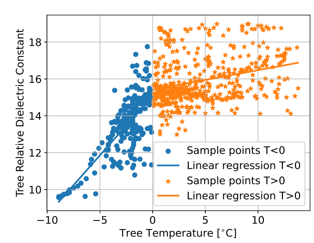
(b) Dielectric vs. Phase

Fig. 1. The relationship between the tree's dielectric constant and radar signal. The plots above compare a tree's relative dielectric constant with the corresponding radar signal magnitude (a) and phase (b). Note that the magnitude and phase are from radar measurements. A moisture sensor Teros12 inserted in a red maple tree's trunk, positioned 1.7 meters above the ground, measures the tree's dielectric and temperature. The red maple is located 18 meters away from the radar.

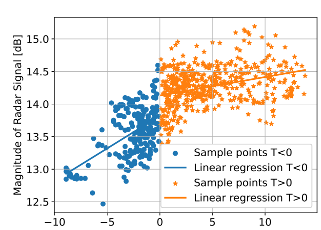
A partial contribution to this work was made at JPL under a contract with NASA.

1. INTRODUCTION

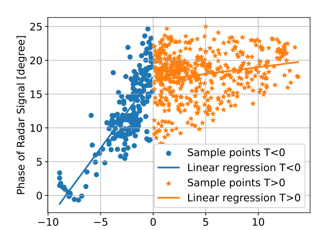
The characterization of forests through forest structure is of great value to terrestrial, habitat biodiversity, and global carbon storage assessments. For this reason, monitoring and quantifying the state of, and change in, above-ground biomass along with other forest biophysical characteristics of interest is desirable. Further, knowledge of the global forest biomass



(a) Tree Temperature vs Tree Relative Dielectric Constant



(b)Temperature vs Magnitude



(c) Temperature vs Phase

Fig. 2. The tree's relative dielectric constant is positively correlated to temperature when it is lower than $0°C$ because the state of the liquid in trees changes. The radar signal reflects the same trend in magnitude and phase. This indicates that the water in trees is partially frozen. The data is taken between 2022/11/26 and 2022/12/29. Note that the relative dielectric constant of water is about 80, while ice is 3.

distribution is essential for monitoring the carbon and water cycles and addressing the impacts of these cycles on climate change. Forest physiology is significantly influenced by environmental conditions, and includes parameters such as tree dielectric constant, sap flow, and soil moisture which all represent components of forest physiology. For example, water uptake and storage after a rain event affects the dielectric constant (permittivity) of a tree's hydroactive tissues; during periods of pronounced evapotranspirative demand, the associated response in sap flow may indicate a tree's response to regulating water loss. Microwave remote sensing, such as provided by radars, is sensitive to the dielectric constant and its variation[1, 2]. Thus, by measuring the forest's effective dielectric constant, given some basic environmental information such as temperature, wind speed, sunlight density, and precipitation, it may be possible to infer parameters that interest Botany, Agronomy, and Climatology using microwave remote sensing techniques.

On a larger scale, spaceborne systems such as NASA's upcoming NISAR mission, utilize imaging radar to measure the reflected electromagnetic waves from forested regions and use the radar backscatter to efficiently estimate the spatial distribution of above-ground biomass and forest height over vast areas. However, studies have shown that the signal can be a function of the moisture content, which varies with time due to tree transpiration, changes in weather conditions, and seasonal effects[3, 4, 5, 6, 7]. Ignoring such variations affects the accuracy of structural parameter estimates[8]. Hence, to improve spaceborne measurements of forested regions using microwave sensors, it is desired to account for the effect of dynamic forest physiology for radar scattering. This work utilizes a ground-based radar system to provide a spatially and temporally-explicit characterization for a temperate forest[9]. Moreover, it explains reasons for the variation of radar backscatter and explores its correlation with soil moisture, tree water content, and sap flow.

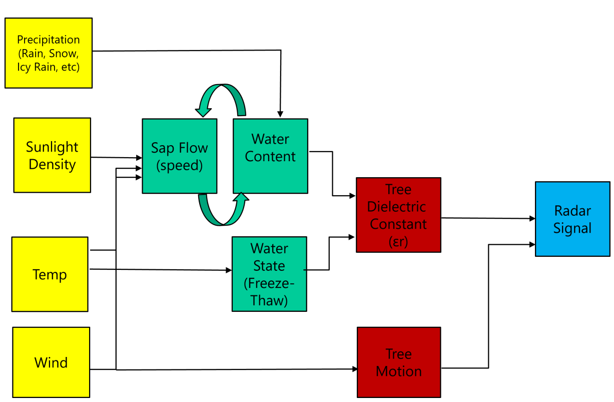


Fig. 3. Causal relationship among forest environment components, tree physiological indicators, and radar signal.

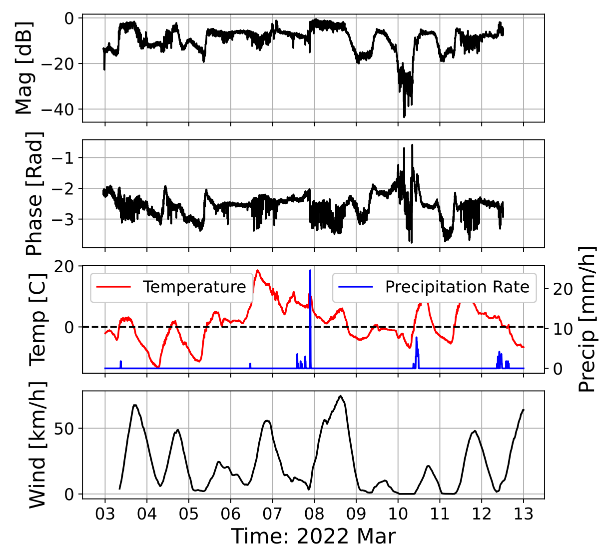


Fig. 4. During the time series measurement from 2022/03/03 to 2022/03/13, the freeze-thaw process causes changes in the state of water in trees, hence changing tree dielectric. This leads to the variation of radar signal in magnitude and phase. There are no leaves on the trees during the measurement. Sap flow is very slow or nonexistent. Water is well conserved in trees during the thaw period. So mag and phase are stable when $T > 0°C$, except rain increases the radar magnitude. Wind makes noisy time series due to the motion of trees.

2. RADAR IMPLEMENTATION

An L-band FMCW (Frequency-Modulated Continuous-Wave) radar is implemented for monitoring forest dynamics. The radar consists of software-defined radio and external RF components. Short-term and long-term radar observations were acquired with an internal calibration system and temperature control that guaranteed stability and precision. Sensitivity and repeatability are critical for long-term measurements. The self-interference of the radar and active leakage cancellations are studied to obtain a good sensitivity. The forest backscatter needs to be stronger than the intermodulation noise floor caused by the leakage signal and non-linearity of the radar RF front end. The internal calibration and temperature control are designed for repeatability. A calibration pod takes short, open, and load measurements to overcome the temperature drifts and ensure radar stability in the RF front end. A weather-proof enclosure with temperature monitoring and controlling components holds the radar system. It isolates radar from the circumambient environment, keeps radar in a temperature-stable environment, and minimizes temperature drift.

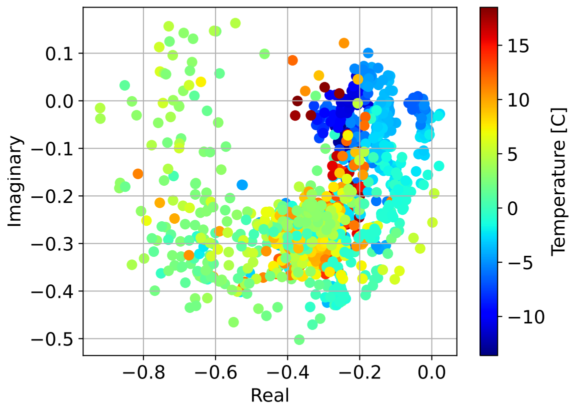


Fig. 5. Real and imaginary part of the radar signal where red maples are located at 18.25 meters in radar's FOV. The wave impedance of the tree changes with temperature 2022/03/03-2022/03/13. The changes can be caused by the trees' extracellular freezing and supper cooling, making denser cell liquid get a lower freezing point and generating sugar sap.

3. MEASUREMENT RESULT

The radar signal is examined by several indicators such as magnitude, phase, modified correlation coefficient, differential signal, real and imaginary part; *in situ* measurements of soil moisture, tree water content, and sap flow were acquired over the same period. This comprehensive data set elucidates relationships between radar signals and key forest parameters such as tree dielectric constant. It also explains the causal relationship between radar signals and environmental components, such as precipitation, temperature, wind, and sunlight in Figure 3. The experiments found some interesting facts captured by the instrument, for example, the freeze-thaw process in Figure 2, 4 and 5 and daily tree activity in Figure 6.

During the winter and early spring, the radar observes the freeze-thaw process. The magnitude and phase of radar are positively correlated to tree temperature, especially when the temperature is below $0°C$. See Figure 1 and 4. The radar signal variation is mainly due to the water state change by temperature. The work of Roy et al. reports a similar observation[11]. Since some trees have no leaves attached, the tree sap flow is deficient, and precipitation has less impact than in the summertime.

In the summertime, shown in Figure 6, precipitation affects the magnitude of the radar signal, and a 2-10 dB variation is observed. Due to the daily tree transpiration and water content cycle in typical weather, a 0-2 dB magnitude variation is observed. Other results include: a). Soil moisture has a different pattern than tree water content. Soil moisture has a spike-and-slowly-down pattern due to quick wetting by precipitation and dry-down that takes multiple days. In contrast,

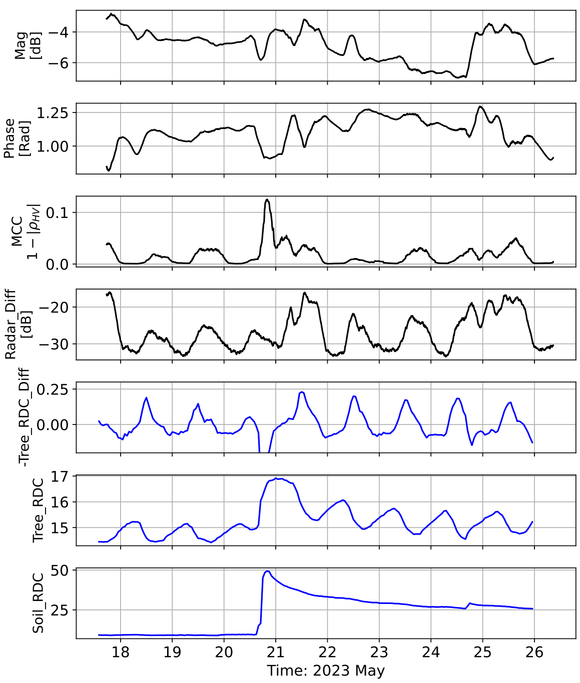
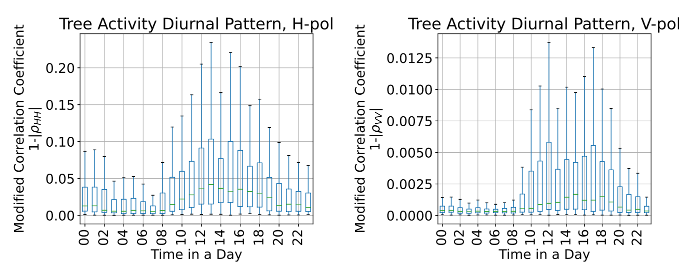


Fig. 6. Summer time series 2023/05/17-2023/05/26. Radar's magnitude (Mag) and phase (Phase). The modified correlation coefficient (MCC) measures the changes in the radar signal. The differential mode is the subtraction between two successive measurements. The differential mode of the radar time series (Radar_Diff) is similar to the differential of the tree dielectric time series (-Tree_RDC_Diff). Trees' dielectric (Tree_RDC) has a diurnal pattern and responds to precipitation directly. The soil dielectric (Soil_RDC) indicates precipitation events on 05/20 and 05/24.



(a) Diurnal tree activity H-pol (b) Diurnal tree activity V-pol

Fig. 7. The H-pol is more sensitive to the tree's water content change. The reason is that the interaction mechanism of H-pol and V-pol EM waves with trees differs. The H-pol's forest transmissivity is higher[10].The measurement spanned from 2022/03/14 to 2022/04/15, with a 3-minute interval.

trees' water content has a diurnal pattern related to transpiration and water usage. For example, the trees' water content decreases during the day and increases at night. Rain increases the trees' water content promptly. b). The modified correlation coefficient (MCC) indicates the forest's activity level due to changing water content. It shows that the high activity level happens during the daytime, and trees are calm at midnight. It also reflects rain events. c). Figure 7 compares MCC in two polarizations. The activity level measured by the modified correlation coefficient shows that tree water content change horizontally is larger than vertically. Both polarizations show trees correcting their activity levels for water management around noon 12-3 pm. This infers the tree's reaction to manage water loss during significant evapotranspiration demand. d). Even though radar cannot measure sap flow directly, it is known that the time derivative of the tree's water content is related to its sap flux[12]. The Radar's differential mode is the subtraction between two successive measurements. It is equivalent to the time derivative and can be related to sap flux. Finally, *in situ* data shows that the sap flow stops or is low during rain events and after defoliation.

4. CONCLUSION

The radar system has demonstrated high sensitivity and repeatability. The observations made by the radar have revealed new insights into the diurnal activity of trees and the freeze-thaw process, providing valuable information about the relationships among radar signals, tree physiology, and environmental components. Further research and development of this technology could lead to advancements in forest management and improvements in monitoring forests globally.

5. REFERENCES

[1] K. McDonald, R. Zimmermann, J. Way, and W. Chun, "Automated instrumentation for continuous monitoring of the dielectric properties of woody vegetation: system design, implementation, and selected in situ measurements," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 37, no. 4, pp. 1880–1894, 1999.

[2] K. McDonald, R. Zimmermann, and J. Kimball, "Diurnal and spatial variation of xylem dielectric constant in norway spruce (picea abies [l.] karst.) as related to microclimate, xylem sap flow, and xylem chemistry," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 40, no. 9, pp. 2063–2082, 2002.

[3] M. Dobson, K. McDonald, and L. Pierce, "Diurnal variation in radar backscatter from a loblolly pine forest in late summer," in *[Proceedings] IGARSS'91 Remote Sensing: Global Monitoring for Earth Management*, vol. 3, 1991, pp. 1115–1116.

[4] A. R. Monteith and L. M. H. Ulander, "A tower-based radar study of temporal coherence of a boreal forest at p-, l-, and c-bands and linear cross polarization," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 60, pp. 1–15, 2022.

[5] J. Jorge Ruiz, R. Vehmas, J. Lemmetyinen, J. Uusitalo, J. Lahtinen, K. Lehtinen, A. Kontu, K. Rautiainen, R. Tarvainen, J. Pulliainen, and J. Praks, "Sodsar: A tower-based 1–10 ghz sar system for snow, soil and vegetation studies," *Sensors*, vol. 20, no. 22, 2020.

[6] M. Watanabe, T. Motohka, T. Shiraishi, R. B. Thapa, C. Yonezawa, K. Nakamura, and M. Shimada, "Multitemporal fluctuations in l-band backscatter from a japanese forest," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 53, no. 11, pp. 5799–5813, 2015.

[7] C. Albinet, P. Borderies, T. Koleck, F. Rocca, S. Tebaldini, L. Villard, T. Le Toan, A. Hamadi, and D. Ho Tong Minh, "Tropiscat: A ground based polarimetric scatterometer experiment in tropical forests," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 5, no. 3, pp. 1060–1066, 2012.

[8] S. Hensley, S. Oveisgharan, S. Saatchi, M. Simard, R. Ahmed, and Z. Haddad, "An error model for biomass estimates derived from polarimetric radar backscatter," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 52, no. 7, pp. 4065–4082, 2014.

[9] X. Chen and P. Siqueira, "A ground-based l-band synthetic aperture radar system for forest temporal dynamics monitoring," in *2017 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, 2017, pp. 3429–3432.

[10] W. Gu, J. Jeong, R. Gao, L. Tsang, A. Colliander, and S. Yueh, "Multiple scattering effects of trees on l-band microwave using a hybrid method," in *2022 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (AP-S/URSI)*, 2022, pp. 1–2.

[11] A. Roy, P. Toose, A. Mavrovic, C. Pappas, A. Royer, C. Derksen, A. Berg, T. Rowlandson, M. El-Amine, A. Barr, A. Black, A. Langlois, and O. Sonnentag, "L-band response to freeze/thaw in a boreal forest stand from ground- and tower-based radiometer observations," *Remote Sensing of Environment*, vol. 237, p. 111542, 2020.

[12] Y. Liu, N. M. Holtzman, and A. G. Konings, "Global ecosystem-scale plant hydraulic traits retrieved using model–data fusion," *Hydrology and Earth System Sciences*, vol. 25, no. 5, pp. 2399–2417, 2021.