STUDY OF SPECTRA WITH LOW-QUALITY RESONANCE PEAKS

Application for plant investigation platforms

03.06.2019 I VIKTOR A. SYDORUK

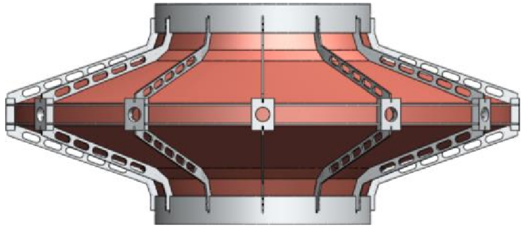
MOTIVATION

for development of Microwave/Radio Frequency resonator based measurement setups

- Noninvasive method: monitoring of plant growth during an extensive period of time.
- Speed: scanning of up to 300 plants per day.
- Sensitivity: possibility to detect changes of <1% of total plant weight.
- Fully-automatic operation.

RESONATOR BASED MEASUREMENT SETUPS

phenoCave GreenHouse:

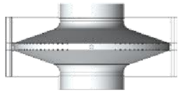


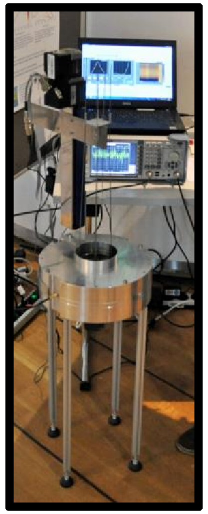
36 cm

width of objects that can be measured

11 cm

phenoCave lab:





V. A. Sydoruk, et al., “*Design and Characterization of Microwave Cavity Resonators for Noninvasive Monitoring of Plant Water Distribution*,” IEEE TMTT (2016) doi: 10.1109/TMTT.2016.2594218.

RESONANCE

In terms of

- **sound**…:

  the reinforcement or prolongation of sound by reflection from a surface or by the synchronous vibration of a neighbouring object

- **electricity…**:

  the condition in which an electric circuit or device produces the largest possible response to an applied oscillating signal

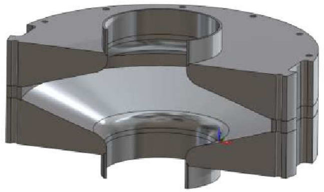
- **mechanics**…:

  the condition in which an object or system is subjected to an oscillating force having a frequency close to its own natural frequency

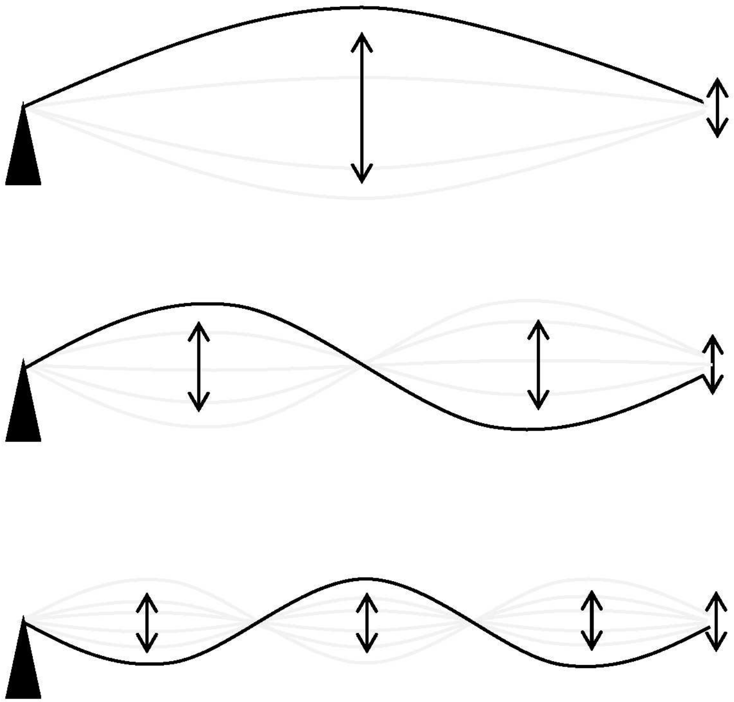
Oxford Dictionary

RESONANCE MODES

elastic band



microwave resonator

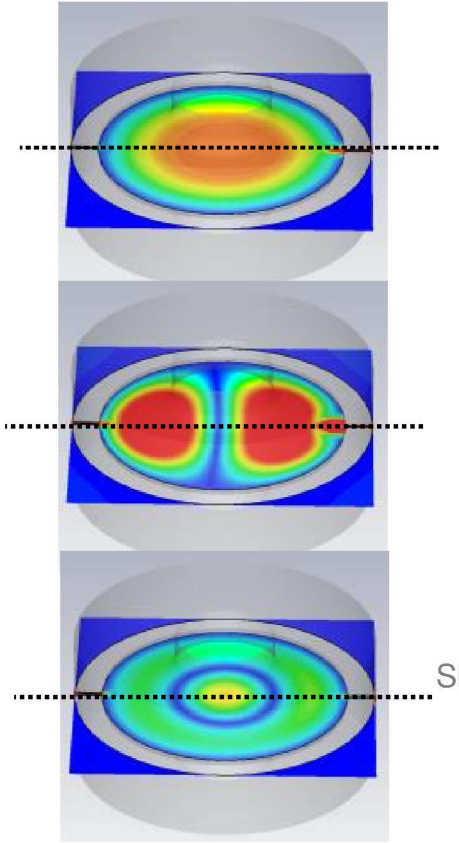


1st Mode

2nd Mode

3rd Mode

frequency of periodic disturbances

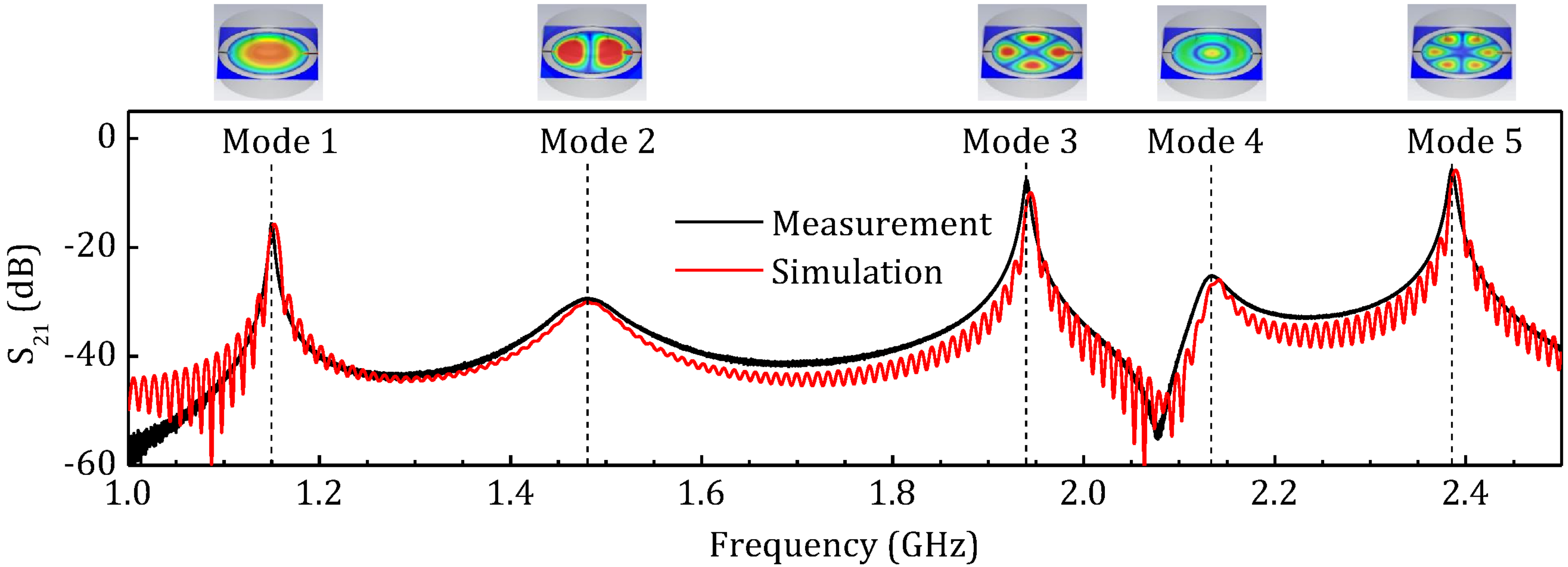


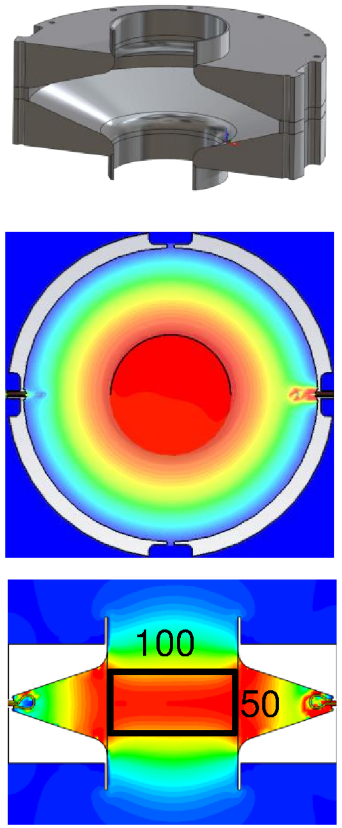
Color reflects electric field distribution

Simulation: CST Microwave Studio

RESONANCE MODES

Measured and simulated spectra of unloaded resonator

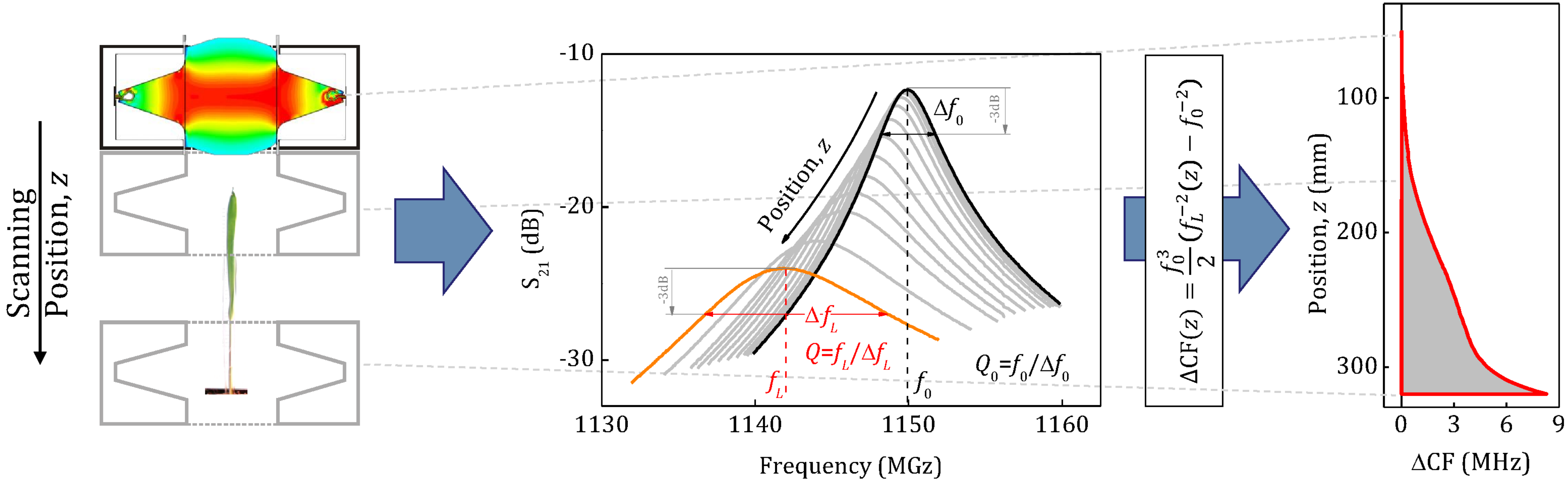




Simulation: CST Microwave Studio

doi: 10.1109/TMTT.2016.2594218

MEASUREMENT PRINCIPLE



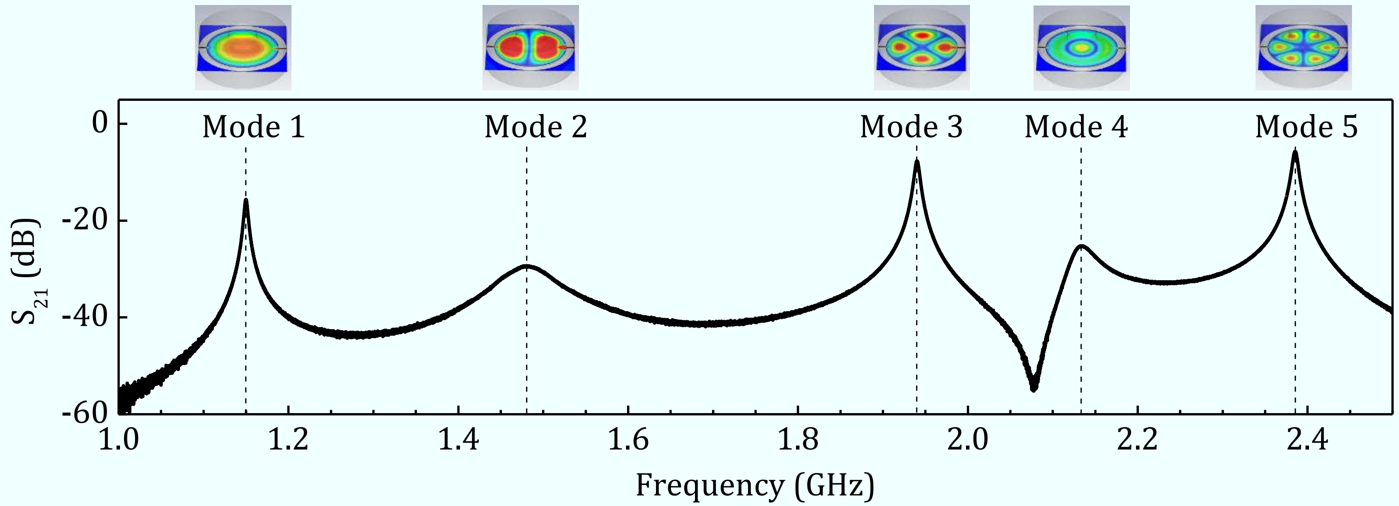
Estimation of

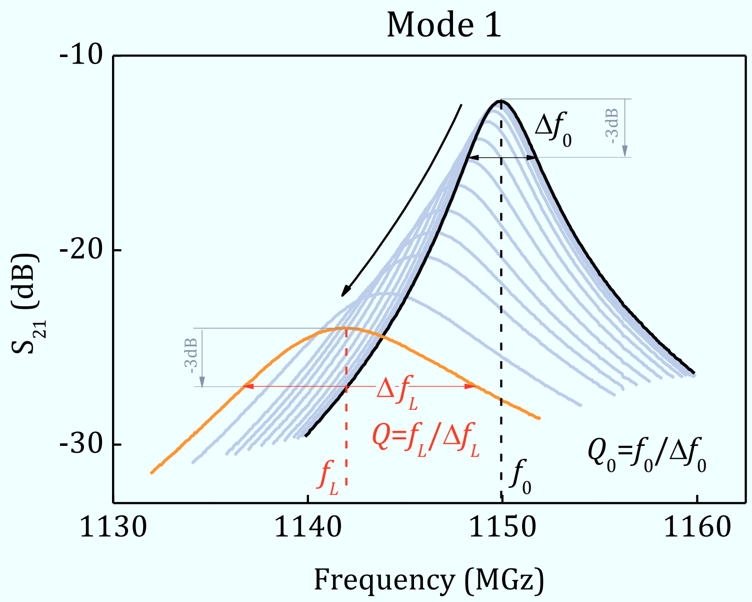
- Water Amount (WA): $\frac{f_0^3(z)}{2}\left(f_L^{-2}(z) - f_0^{-2}(z)\right) \sim WA(z)$ $\int_{-\infty}^{\infty} \frac{f_0^3(z)}{2}\left(f_L^{-2}(z) - f_0^{-2}(z)\right) dz \sim WA_{total}$
- Dry Weight (DW): $\frac{f_0^2(z)}{2 f_L(z) Q_0(z)}\left(\frac{f_0(z) Q_0(z)}{f_L(z) Q_L(z)} - 1\right) \sim DW(z)$ $\int_{-\infty}^{\infty} \frac{f_0^2(z)}{2 f_L(z) Q_0(z)}\left(\frac{f_0(z) Q_0(z)}{f_L(z) Q_L(z)} - 1\right) dz \sim DW_{total}$

doi: 10.1109/TMTT.2016.2594218

FITTING OF SPECTRA

Issues

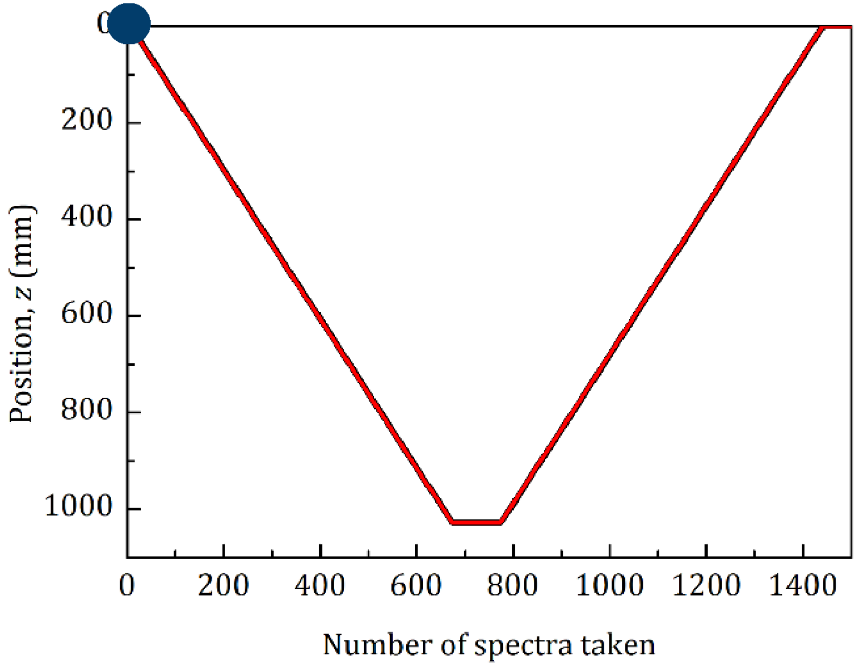


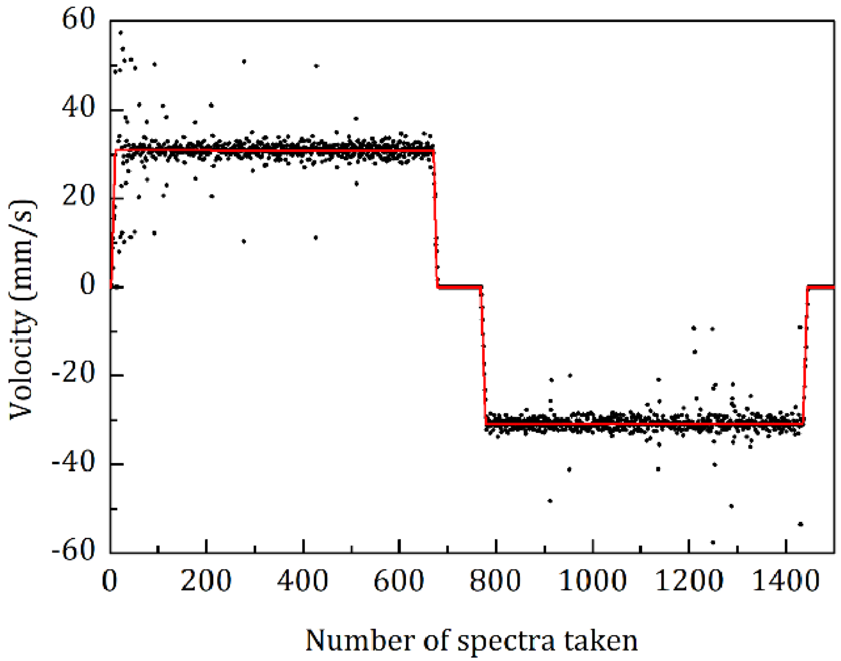


1. **Time delays** between position of a resonator and spectra points readings when the resonator moves continuously without intermediate stops.
2. Influence of **higher modes**.
3. **Impossibility** to ideally **calibrate** a vector network analyzer (especially for the Greenhouse setup).
4. Influence of **cables** and **surroundings**.

SPECTRA PREPARATION

1. When a resonator is continuously moving while receiving the spectra





SPECTRA PREPARATION

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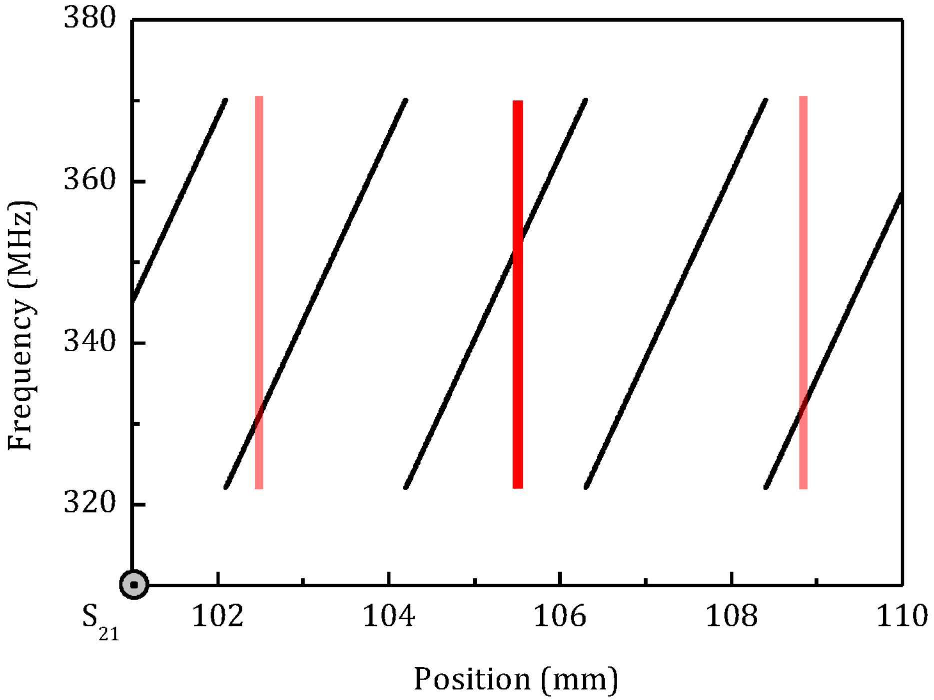


Each spectrum is recalculated using neighboring measured spectra (polynomial fit at the same frequency)

Additional pros:

- automatically smoothed spectrum
- possibility to detect outliers in combination with the Grubbs' test.

FITTING OF SPECTRA

2. Approaches

Note:

$$S_{21}(f) = 20 \cdot \log_{10}(|\Gamma(f)|/\Gamma_0)$$

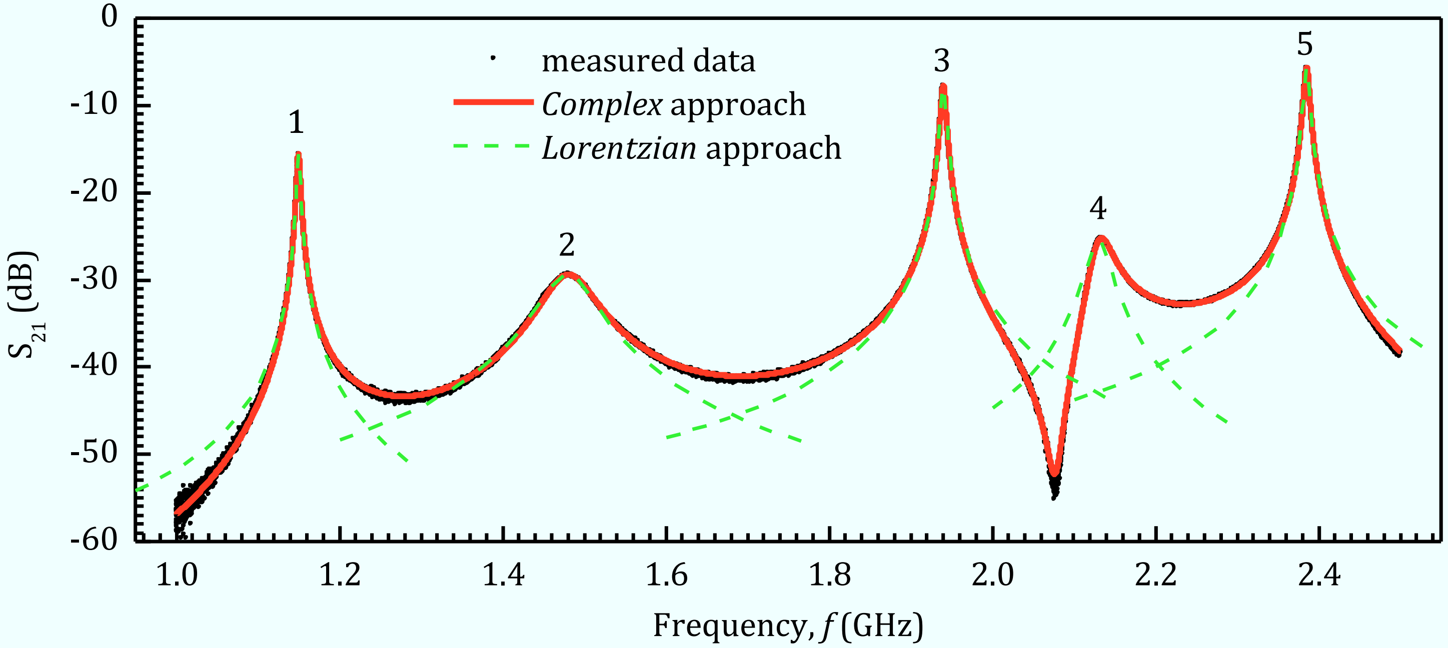
$$\tau_i(f) = (f - f_{0i})/f_{0i}$$

Lorentzian approach

$$\Gamma_i(f) = \frac{A_i}{\sqrt{1 + 4Q_i^2 \tau_i^2(f)}}$$

Complex approach

$$\Gamma(f) = \Gamma_S + \sum_i^n \frac{A_i \exp(j\varphi_i)}{1 + 2jQ_i\tau_i(f)}$$



FITTING OF SPECTRA

2. Comparison of different approaches; influence of higher modes

Note:

$$S_{21}(f) = 20 \cdot \log_{10}(|\Gamma(f)|/\Gamma_0)$$

$$\tau_i(f) = (f - f_{0i})/f_{0i}$$

Lorentzian approach

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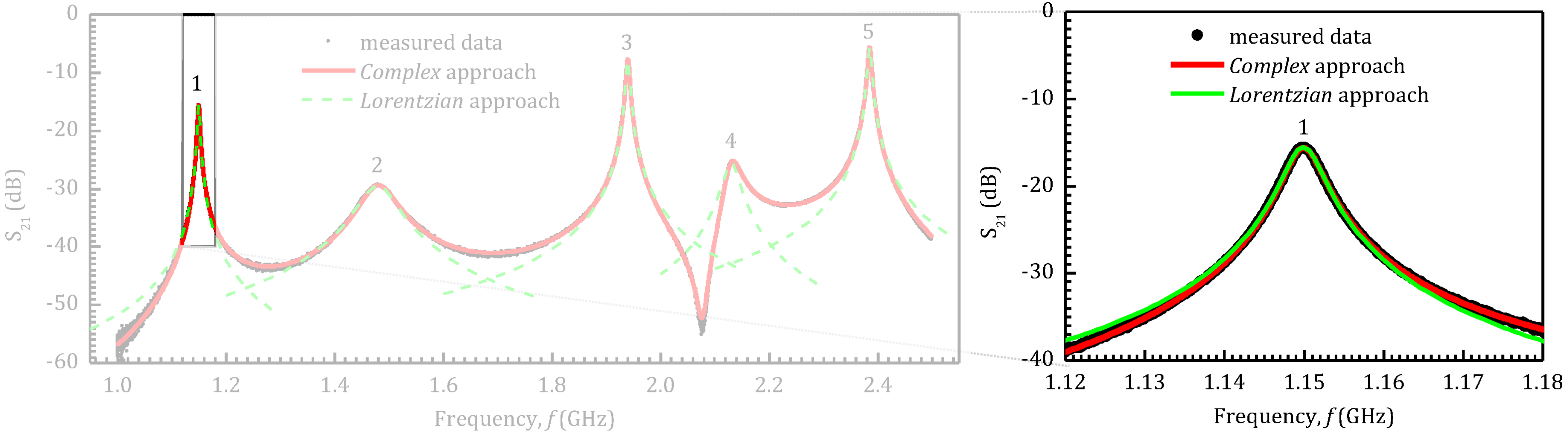
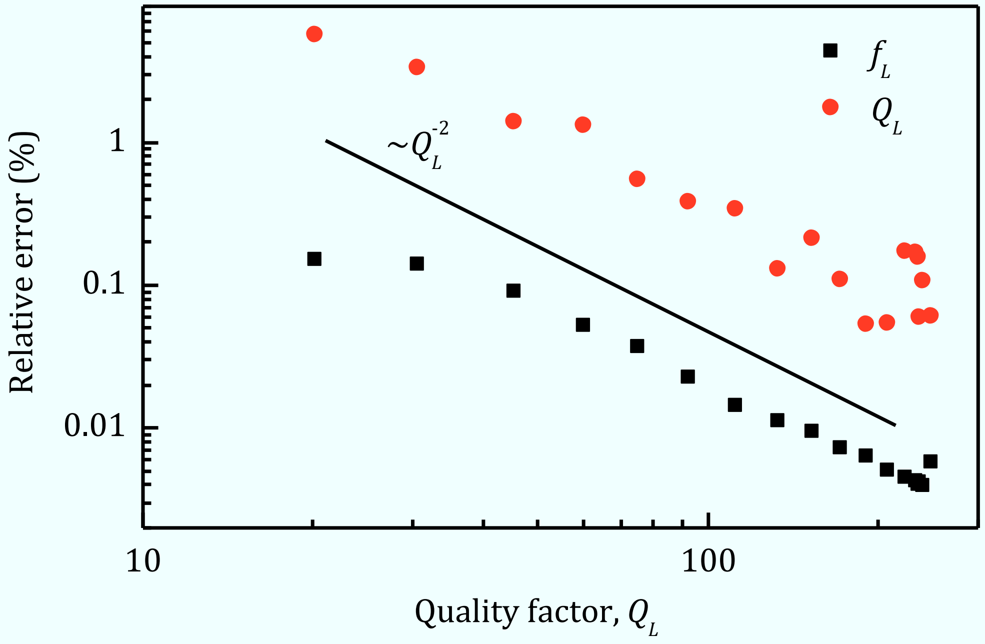


FITTING OF SPECTRA

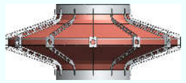
2. Influence of higher modes

$$Relative\ error = \left|p_{complex} - p_{Lorentzian}\right| / p_{complex} \times 100\%$$

where p is either resonant frequency f_L or quality factor Q_L of a loaded resonator.



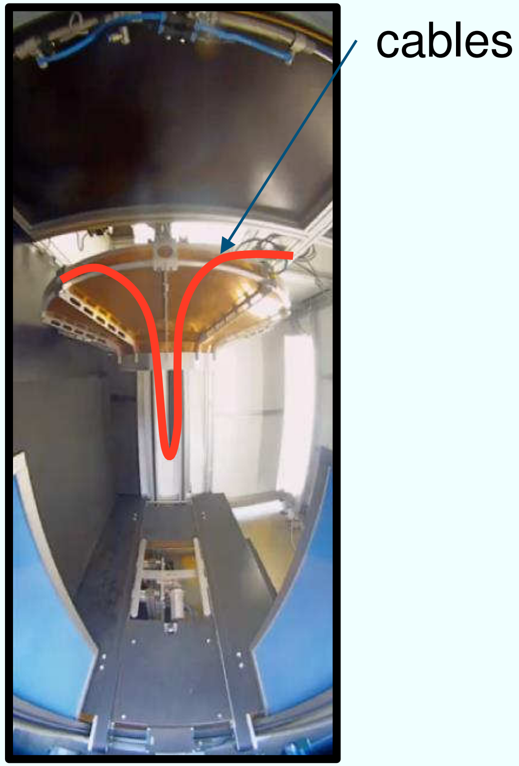
In terms of the plant Water Amount (WA):



- 0.2% of f_L is 2.3 MHz for phenoCave GreenHouse resonator, or ~1.5 µL/mm, which is for a young maize plant of 2 g fresh weight and about 200 mm height gives 0.3 mL of WA => 16% of error for the plant WA estimation.

RESIDUALS

3. Impossibility to ideally calibrate a vector network analyzer (especially for the Greenhouse setup)



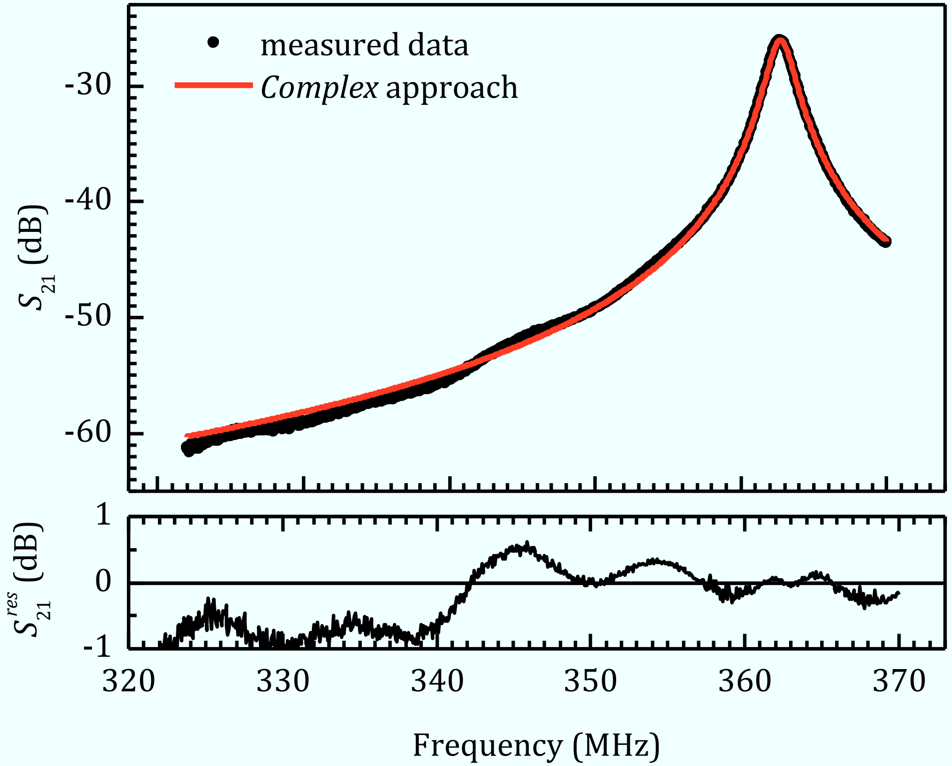
Reasons:

- Long cables.
- Resonator movements.

Residuals have periodic behavior, which should be taken into account.

$$S_{21}^{res}(f)=\sum_{i}^{k} a_{i\sin}\sin(2\pi f/f_{i\sin}+\varphi_{i\sin})$$

*Initial values obtained using FFT

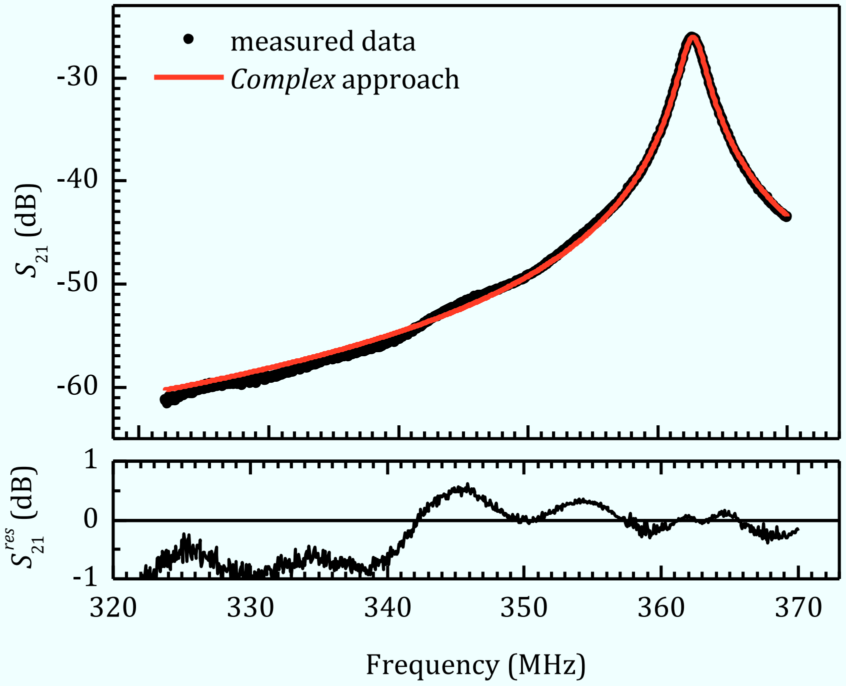


RESIDUALS

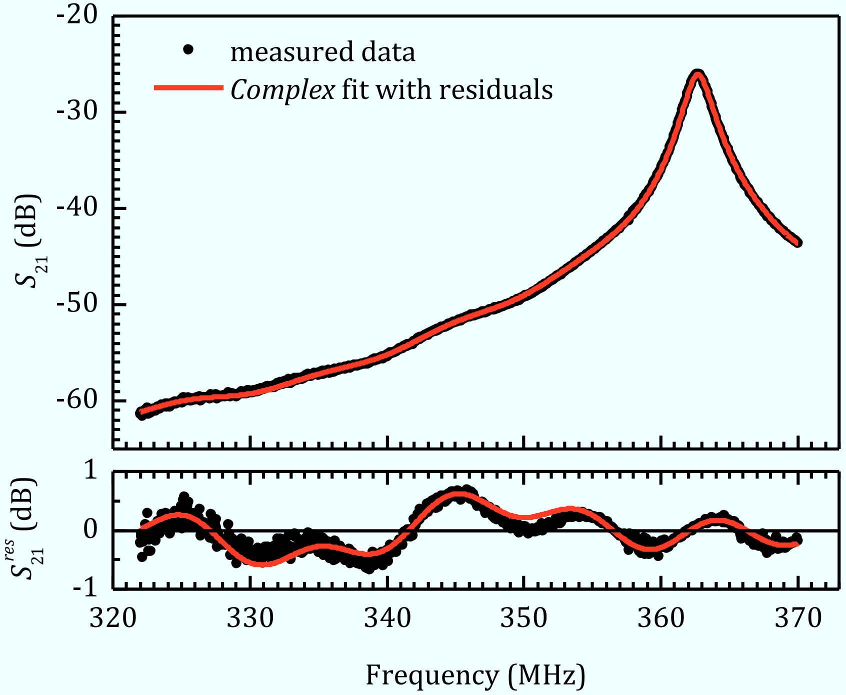
3. Fitting of residuals

Obtained parameters:

$f_0 = 362.700 \pm 0.002$ MHz $Q_0 = 191.0 \pm 0.4$



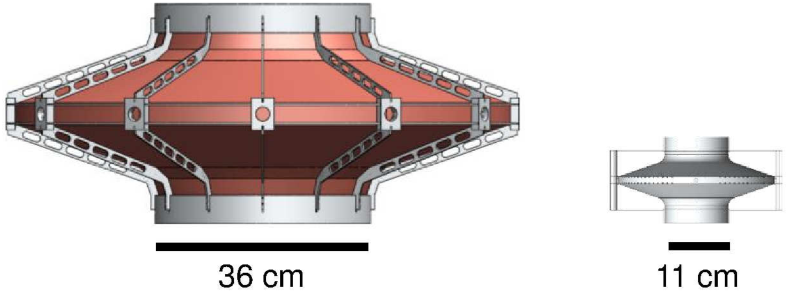
$f_0 = 362.675 \pm 0.002$ MHz $Q_0 = 187.1 \pm 0.3$

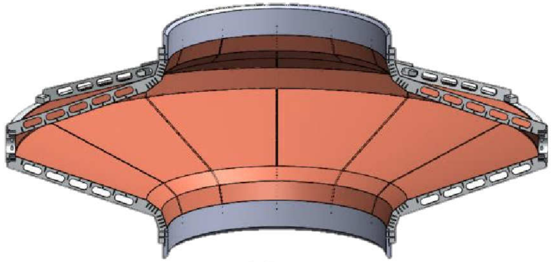


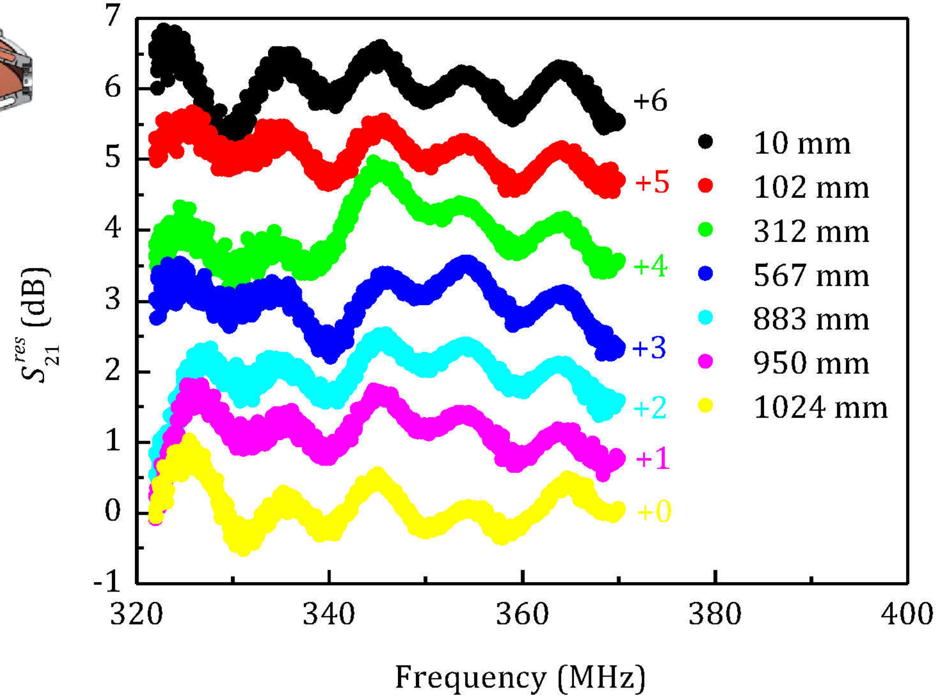
RESIDUALS

4. Influence of cables and surroundings

- Residuals depend on the position of a resonator due to large openings.

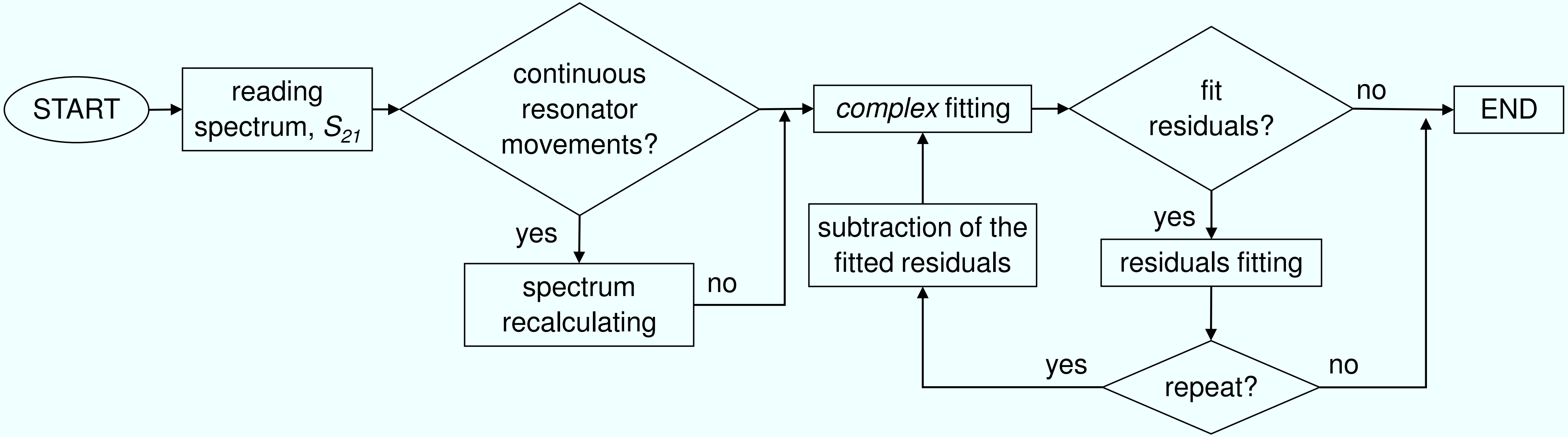






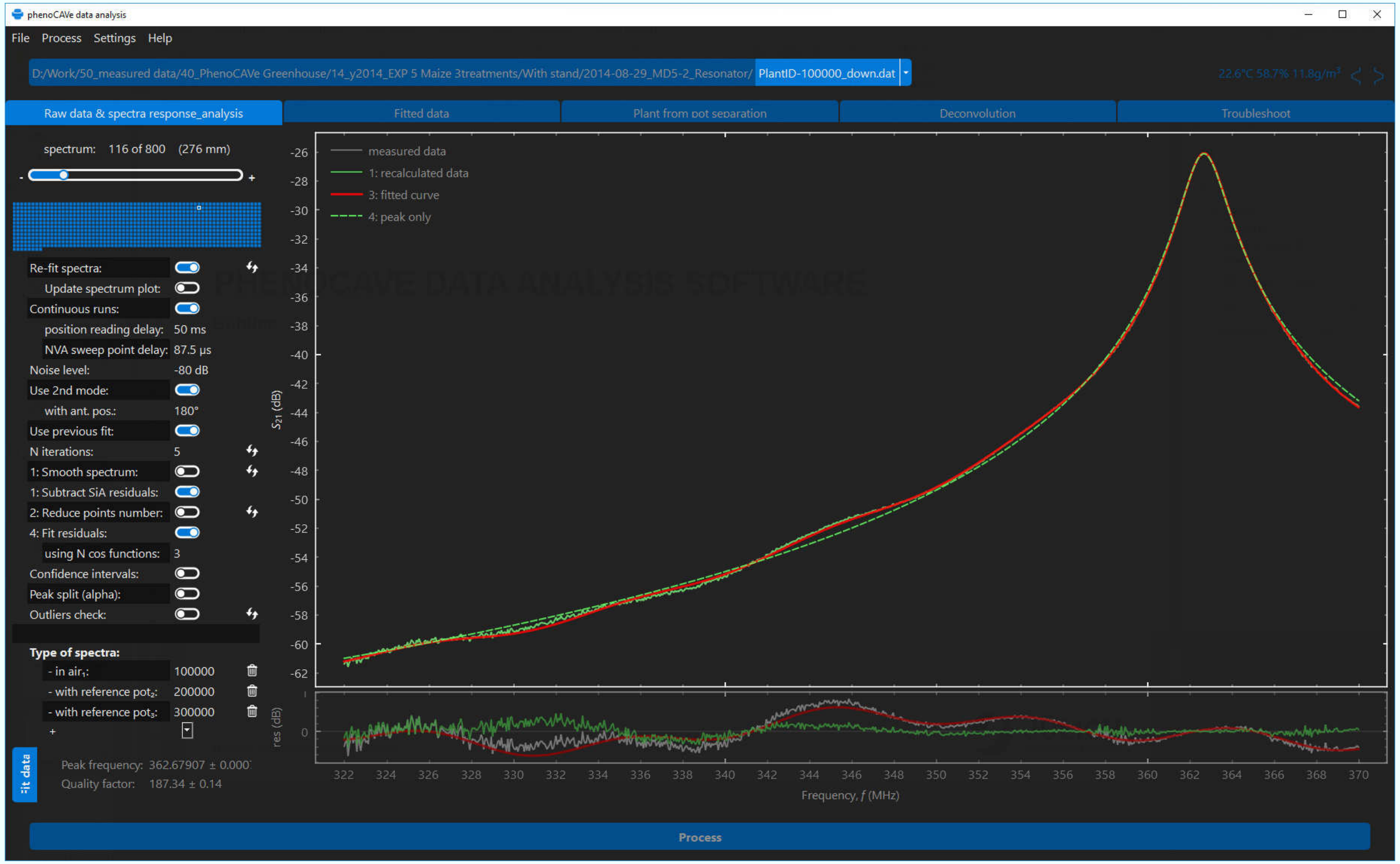
- Residuals from empty runs are used to fit spectra of loaded resonator (when a plant is measured)

SPECTRUM FITTING ROUTINE



PHENOCAVE DATA ANALYSIS SOFTWARE

Spectra analysis



spectrum: 116 of 800 (276 mm)

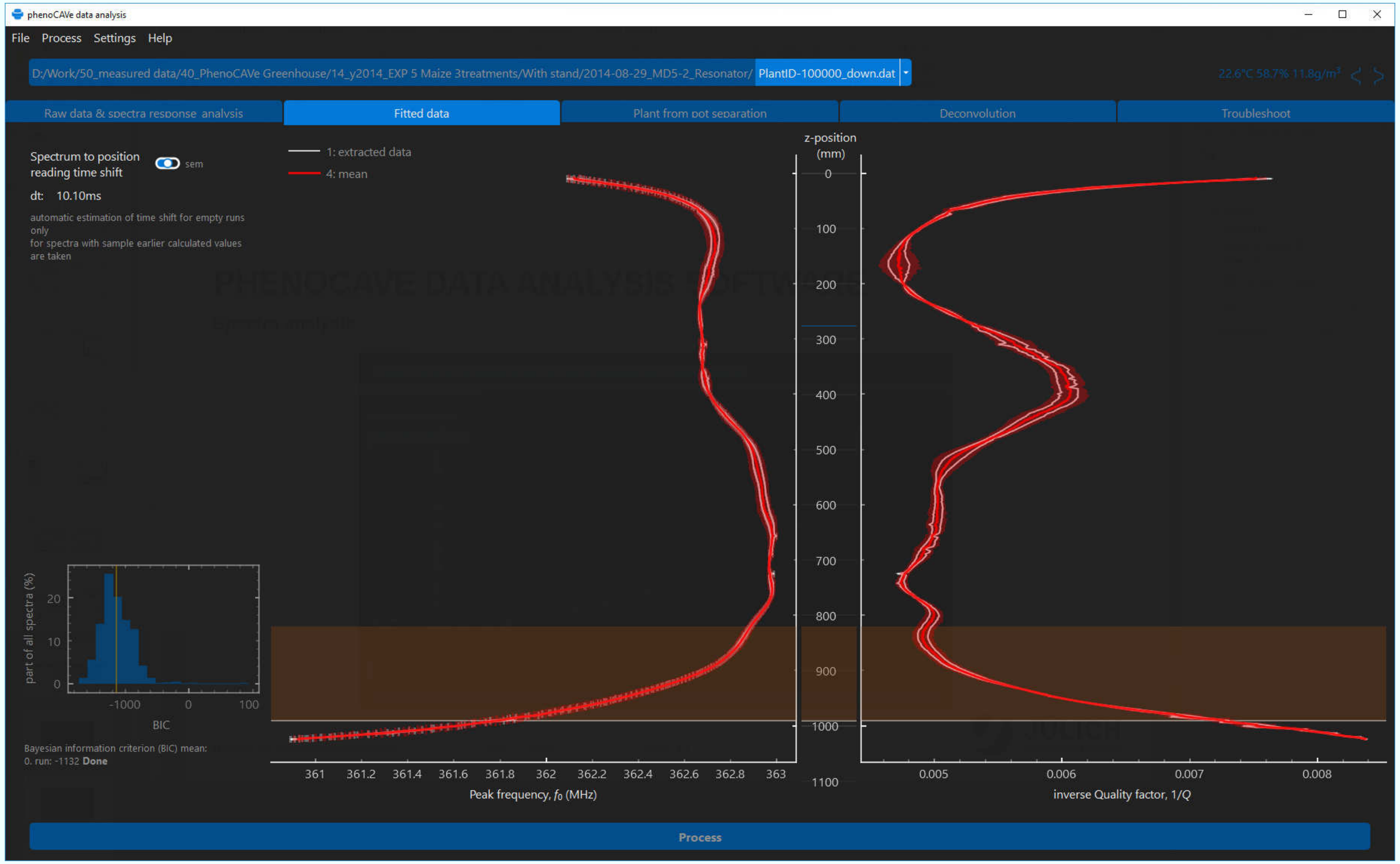
Re-fit spectra: ●
Update spectrum plot: ○
Continuous runs: ●
position reading delay: 50 ms
NVA sweep point delay: 87.5 µs
Noise level: -80 dB
Use 2nd mode: ●
with ant. pos.: 180°
Use previous fit: ●
N iterations: 5
1: Smooth spectrum: ○
1: Subtract SiA residuals: ●
2: Reduce points number: ○
4: Fit residuals: ●
using N cos functions: 3
Confidence intervals: ○
Peak split (alpha): ○
Outliers check: ○

Type of spectra:
- in air$_1$: 100000
- with reference pot$_2$: 200000
- with reference pot$_3$: 300000

Peak frequency: 362.67907 ± 0.000
Quality factor: 187.34 ± 0.14

PHENOCAVE DATA ANALYSIS SOFTWARE

Fitted data versus position



phenoCAVe data analysis

D:/Work/50_measured data/40_PhenoCAVe Greenhouse/14_y2014_EXP 5 Maize 3treatments/With stand/2014-08-29_MD5-2_Resonator/PlantID-100000_down.dat

Spectrum to position reading time shift — sem

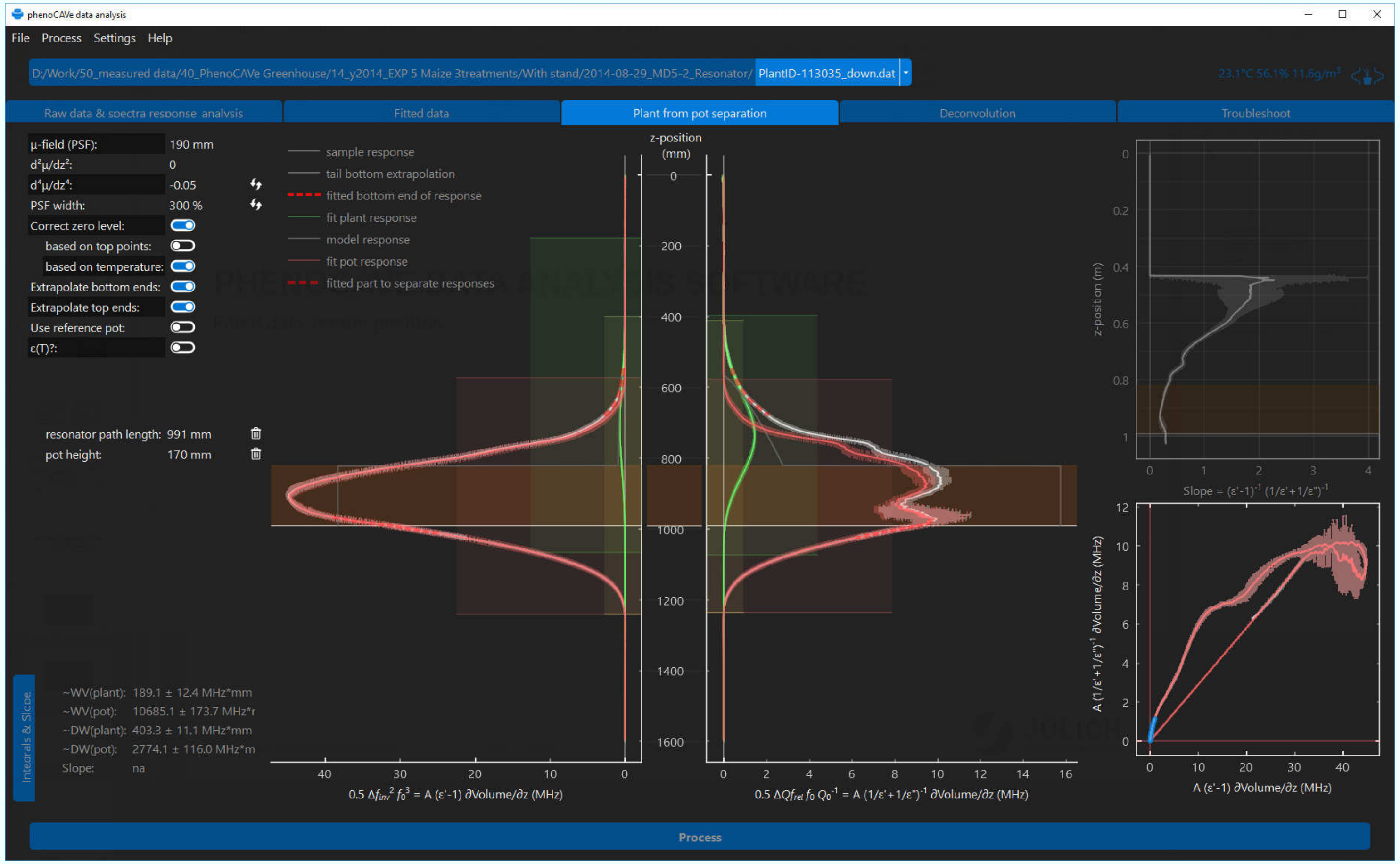
dt: 10.10ms

automatic estimation of time shift for empty runs only
for spectra with sample earlier calculated values are taken

Bayesian information criterion (BIC) mean:
0. run: -1132 **Done**

PHENOCAVE DATA ANALYSIS SOFTWARE

Extracting of WA and DW for a measured plant



D:/Work/50_measured data/40_PhenoCAVe Greenhouse/14_y2014_EXP 5 Maize 3treatments/With stand/2014-08-29_MD5-2_Resonator/PlantID-113035_down.dat

μ-field (PSF):	190 mm
$d^2\mu/dz^2$:	0
$d^4\mu/dz^4$:	-0.05
PSF width:	300 %
Correct zero level:	●
based on top points:	○
based on temperature:	●
Extrapolate bottom ends:	●
Extrapolate top ends:	●
Use reference pot:	○
ε(T)?:	○

resonator path length: 991 mm
pot height: 170 mm

~WV(plant):	189.1 ± 12.4 MHz*mm
~WV(pot):	10685.1 ± 173.7 MHz*r
~DW(plant):	403.3 ± 11.1 MHz*mm
~DW(pot):	2774.1 ± 116.0 MHz*m
Slope:	na

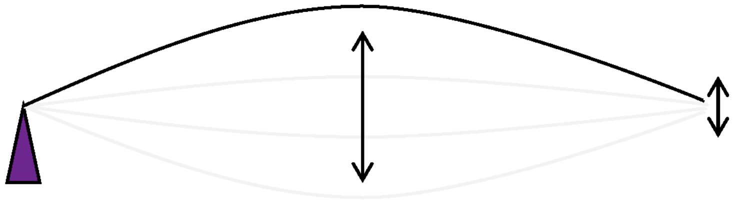
CONCLUSIONS

- The fitting approach is mainly developed to analyze low-quality resonance peaks on measured spectra.
- The simple *Lorentzian* fitting approach is compared with the *complex* one, to which a preference was given.
- Issues that may arise during the measurements using partially opened resonators are shown and discussed with their possible resolution.
- Among them are the influences of other modes, surroundings, cables, and continuous movements of either a resonator or an investigated object.
- The spectrum fitting routine was suggested and the software based on it was demonstrated.
- The suggested *complex* fitting approach is not newly developed but the proposed fully automated fitting routine has novel ideas which can be useful for the precise analysis of spectra with low-quality resonance peaks.

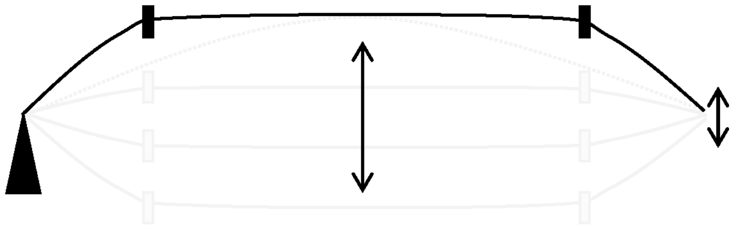
THANK YOU FOR YOUR ATTENTION!

RESONANCE MODES

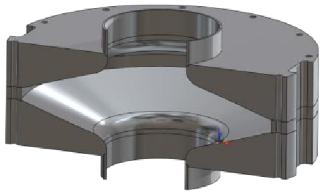
Usage of the 1^{st} mode; electromagnetic field distribution

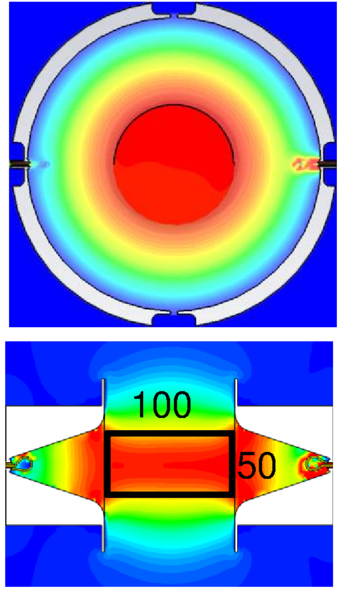


First prototype



Last prototype





Simulation: CST Microwave Studio

WATER AS A DIELECTRIC MATERIAL

Usage of the 1^{st} mode; electromagnetic field distribution

- Dielectric permittivity

$$\varepsilon' + j\varepsilon''$$

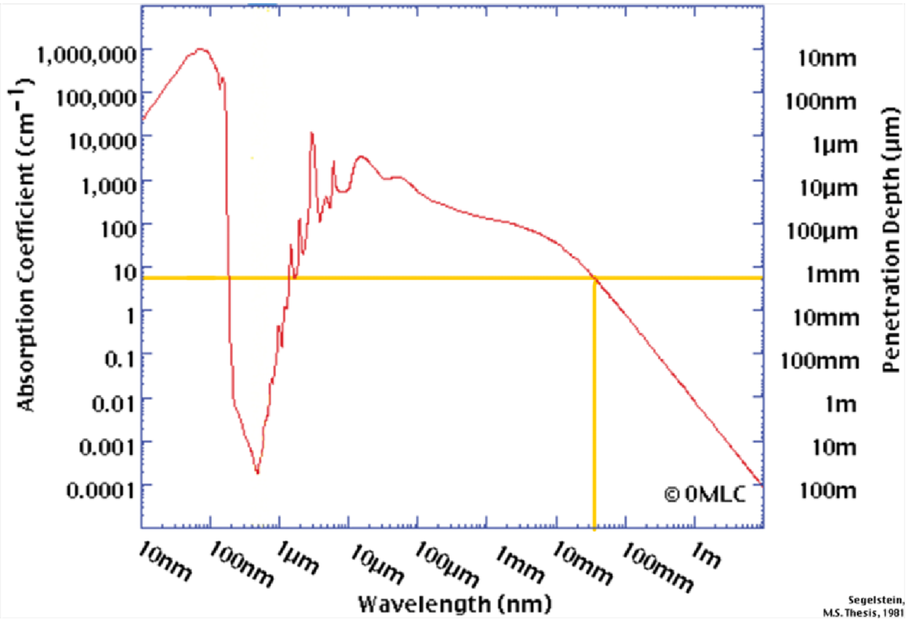
ε' - related to the stored energy;

ε'' - related to the dissipation (or loss) of energy.

- Water

ε' = 78.2 @ 1GHz

ε'' = 3.8 @ 1GHz

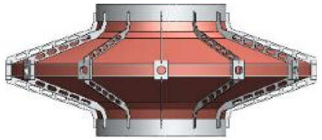


Segelstein, M.S. Thesis, 1981

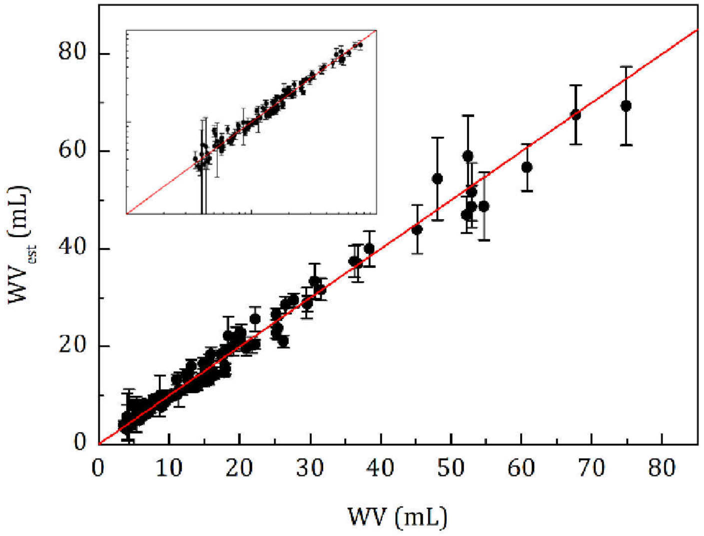
to obtain at least 2 mm penetration depth we should to work at < 7.5 GHz frequencies

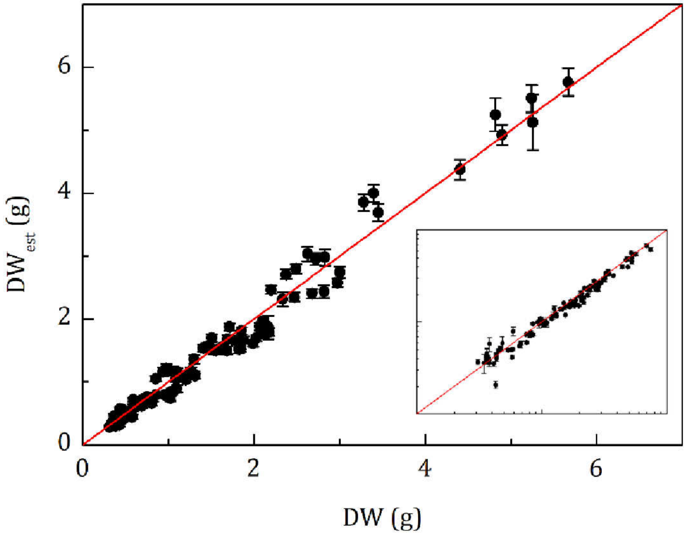
Simulation: CST Microwave Studio

RESULTS



- Estimated by the resonator vs destructively measured data



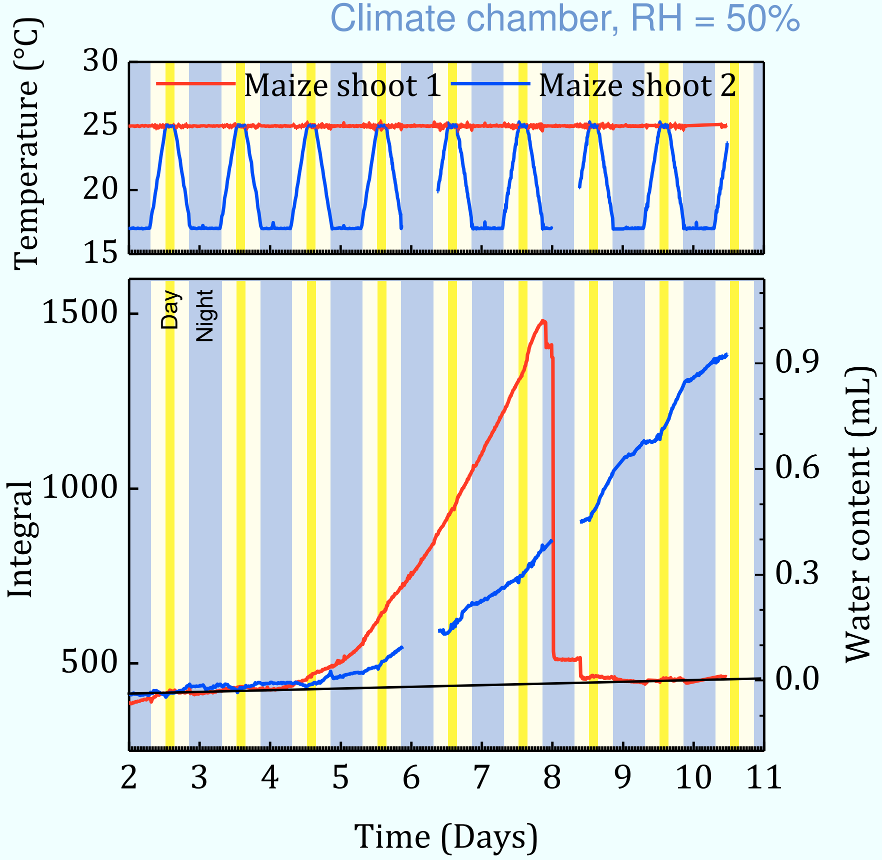


3 different stresses. Measurements of maize plants using phenoCave Greenhouse

*WV – Total Water Volume, DW – Total Dry Weight

MEASUREMENTS OF MAIZE SHOOTS

Climate chamber, RH = 50%



RESPONSES FROM DIFFERENT PARTS OF A PLANT