FDTD techniques applied to acoustic propagation in vegetable tissue:

THE ELASTODYNAMIC BEHAVIOR OF THE ORANGE FRUIT

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  - Aim of the work
  - Methodology
  - Morphology
- Experimental Setup
- Elastic Parameters Of The Orange Fruit
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INTRODUCTION

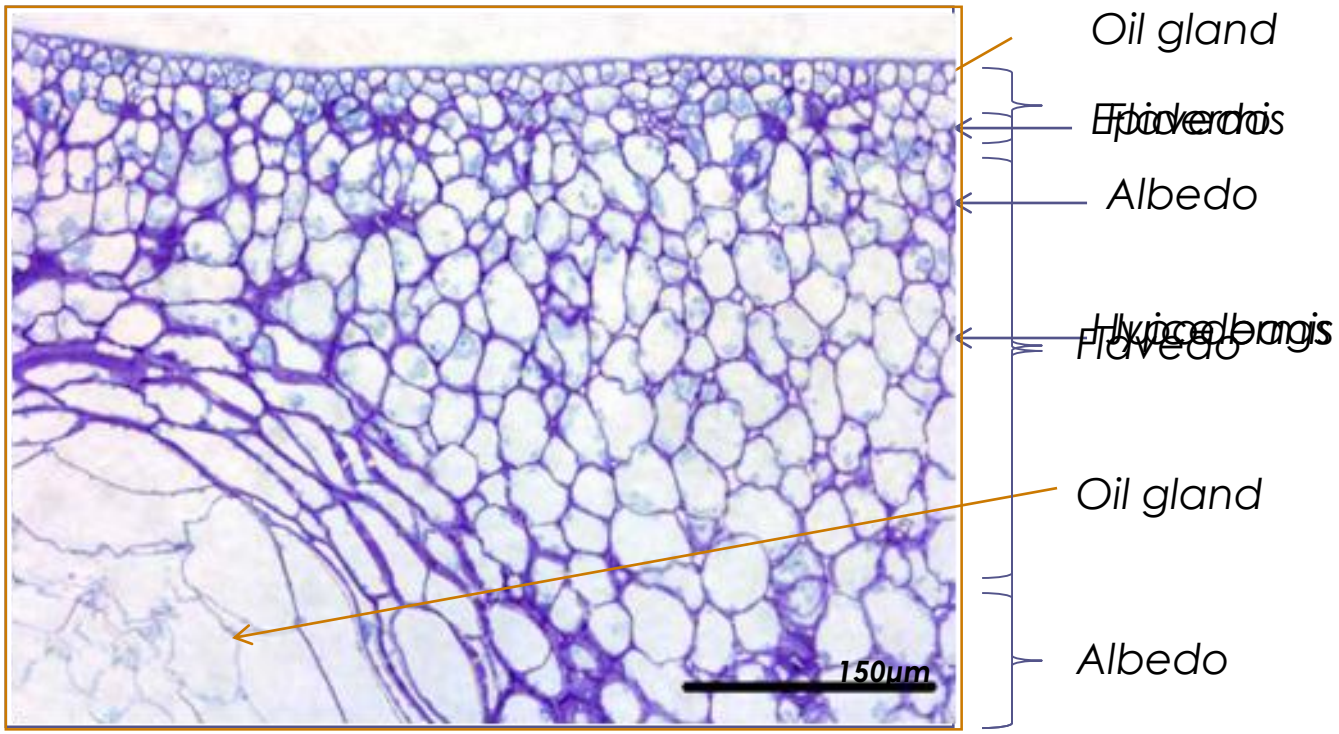
- INTRODUCTION
- EXPERIMENTAL SETUP
- ELASTIC PARAMETERS OF THE ORANGE FRUIT
- SURFACE WAVE FDTD SIMULATION
- RESULTS
- CONCLUSIONS

- Aim of the work:
  - Obtain a ultrasonic method to measure the ripening of fruits and vegetables for postharvest processes
  - Understanding the physical mechanisms exist in the ultrasonic propagation in biological media
- Methodology:
  - Experimental measurements
  - Numerical simulations

INTRODUCTION

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- Results
- Conclusions

- Citric: Morphology

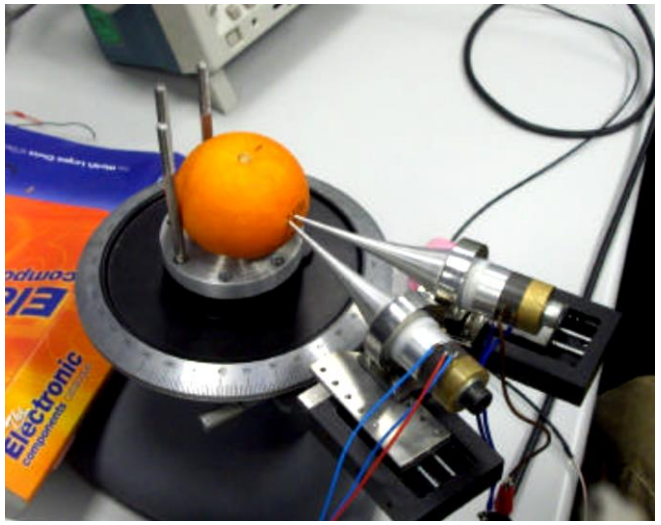


  - Solids structures, liquids, porous layers and gases

EXPERIMENTAL SETUP

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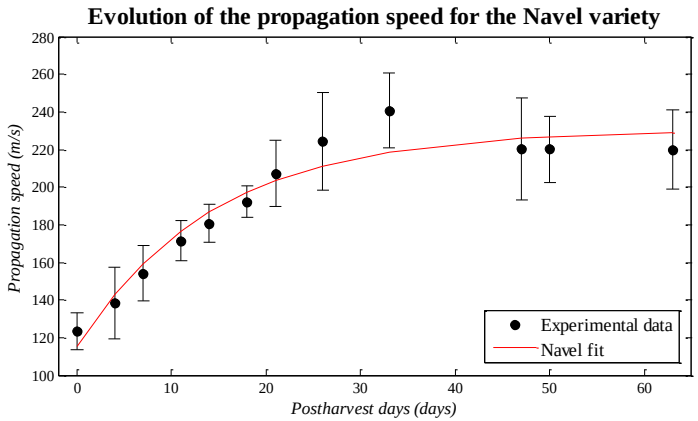
- Ultrasound device
  - Sandwich type transducers
  - Mechanical focuser
  - 2 transducers: Emission - Reception
- Measurement
  - Time of flight and amplitude at different distances
  - 2 orange varieties (Navel and Ortanique)
  - During 2 months
  - Dehydration processes
- Post process
  - Wave propagation speed
  - Total absorption

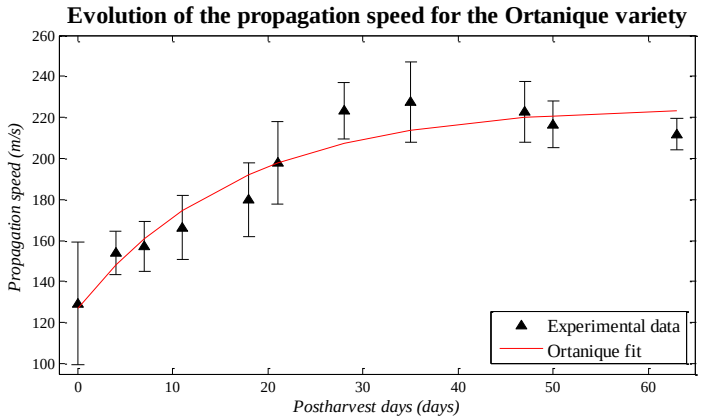


EXPERIMENTAL SETUP

- Introduction
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- Vegetable tissue acoustic characterization
  - Slow propagation speed
  - High absorption coefficients (1dB/mm to 3dB/mm)





$$c_{Navel} = 115,170^{0,69t} + 115,$$

$$c_{Ortanique} = 98,518^{0,67t} + 127,1$$

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- Vegetable tissue acoustic characterization
  - Slow propagation speed
  - High absorption coefficients

Media	Measured Propagation speed (m/s)	Measured Attenuation (dB/mm)
Orange	130-240	2,1-3,8 (40 kHz)
Avocado*	150-400	2,5-5,0 (50kHz)
Apple*	98-183	1,2-1,5 (1-5 MHz)
Melon*	61-90	2,6-7,1 (50 kHz)
Potato*	686,89	0,6791 (100 kHz)
Carrot*	341-500	1,02:1,23 (37-50 kHz)

** Ultrasonic measured acoustics parameters (Mizrach, 2008)*

ELASTIC PARAMETERS OF THE ORANGE FRUIT

- Introduction
- Experimental Setup
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- Vegetable tissue acoustic characterization:

$$c_P = \sqrt{\frac{\lambda + 2\mu}{\rho}} \qquad c_S = \sqrt{\frac{\mu}{\rho}}$$

Medio	Measured Propagation speed (m/s)	Density ρ (kg/m^3)	Static Young Modulus E (MPa)	Static Poisson coefficient v	Calculated Longitudinal propagation speed (m/s)	Calculated shear propagation speed (m/s)
Orange	130-240	903	1,57	0,34	82,7	54,6
Avocado*	150-400	963	0,48	0,33	32,1	18,2
Apple*	98-183	1003	3,33	0,17	65,1	36,5
Melon*	61-90	1209	5,54	0,30	76,4	49,6
Potato*	686,89	1087	7,14	0,25	60,8	34,1
Carrot*	341-500	1021	6,96	0,30	104,1	64,1

** Elastic parameters measured with stress-strain techniques (Singh, 2006), (Baryeh, 2000)(Grotte, 2002)(Jindal, 1985)(Bunyaphlann, 1973). Ultrasonic measured acoustics parameters (Mizrach, 2008)*

ELASTIC PARAMETERS OF THE ORANGE FRUIT

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- Hypothesis:
  1. Measured waves are Rayleigh surface waves:
     - The high damping of the porous Albedo layer inhibit the creation of Lamb type waves
  2. The orange skin is a waterlike media
     1. Poisson's coefficient is close to 0.5 → $c_R = 0{,}95\ c_S$
     2. Exist a longitudinal wave → $c_{L\ (orange)} = c_{L\ (water)}$

$$\mu = \rho\left(\frac{1}{0.95} c_{R,measured}\right)^2$$

$$\lambda + 2\mu = \rho c_{p,water}^2$$

Media	Measured density ρ (kg/m^3)	Young Modulus E (MPa)	Poisson coefficient v	Longitudinal propagation speed (m/s)	Measured Propagation speed (m/s)	Calculated Rayleigh surface wave
Orange	903	107,7	0,491	1540	130-240	200

SURFACE WAVE FDTD SIMULATION

- Introduction
- Experimental Setup
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- Physic model: **Linear elastic solid,** *(velocity stress formulation)*

$$\rho\frac{\partial \boldsymbol{v}}{\partial t}=\nabla\cdot\boldsymbol{\tau} \qquad \frac{\partial \boldsymbol{\tau}}{\partial t}=\lambda\bar{\mathbf{I}}(\nabla\cdot\boldsymbol{v})+\mu(\nabla\boldsymbol{v}+\boldsymbol{v}\nabla)$$

  - $\boldsymbol{\tau}$ stress tensor, $\boldsymbol{v}$ velocity vector, λ and μ Lame's parameters, ρ density

- 3D Cartesian coordinates with damping term: **9 equations set**

$$\rho\frac{\partial v_\xi}{\partial t}=\frac{\partial \tau_{\xi\xi}}{\partial \xi}+\frac{\partial \tau_{\psi\psi}}{\partial \psi}+\frac{\partial \tau_{\xi\zeta}}{\partial \zeta}$$

$$\frac{\partial \tau_{\xi\xi}}{\partial t}+\eta_P\tau_{\xi\xi}=(\lambda+2\mu)\frac{\partial v_\xi}{\partial \xi}+\lambda\frac{\partial v_\psi}{\partial \psi}+\lambda\frac{\partial v_\zeta}{\partial \zeta}$$

$$\frac{\partial \tau_{\xi\psi}}{\partial t}+\eta_S\tau_{\xi\psi}=\mu\left(\frac{\partial v_\xi}{\partial \psi}+\frac{\partial v_\psi}{\partial \xi}\right)$$

  - $\eta_{\xi\xi}$, $\eta_{\xi\psi}$ longitudinal and shear damping coefficients

SURFACE WAVE FDTD SIMULATION

- Spatial and temporal staggered discretization (9 unknowns)

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$$\tau_{xx,yy,zz}(i,j,k)$$

$$v_x\left(i+\frac{1}{2},j,k\right)$$

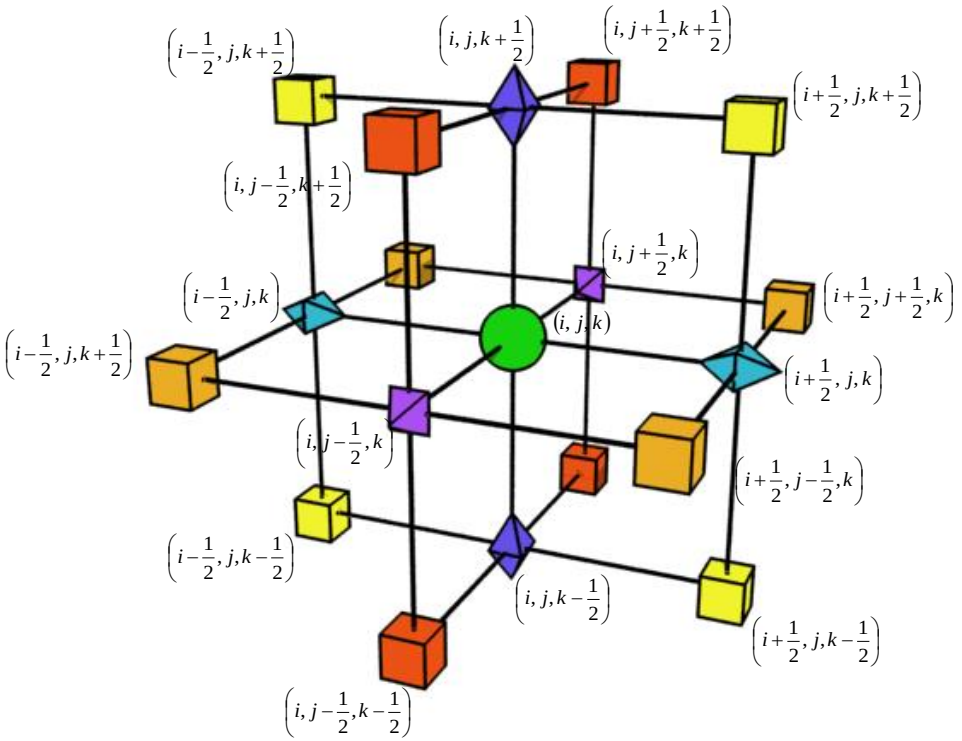
$$v_y\left(i,j+\frac{1}{2},k\right)$$

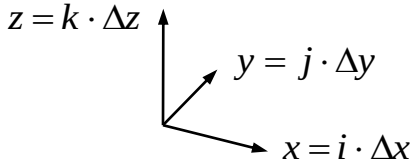
$$v_z\left(i,j,k+\frac{1}{2}\right)$$

$$\tau_{xy}\left(i+\frac{1}{2},j+\frac{1}{2},k\right)$$

$$\tau_{yz}\left(i,j+\frac{1}{2},k+\frac{1}{2}\right)$$

$$\tau_{xz}\left(i+\frac{1}{2},j,k+\frac{1}{2}\right)$$

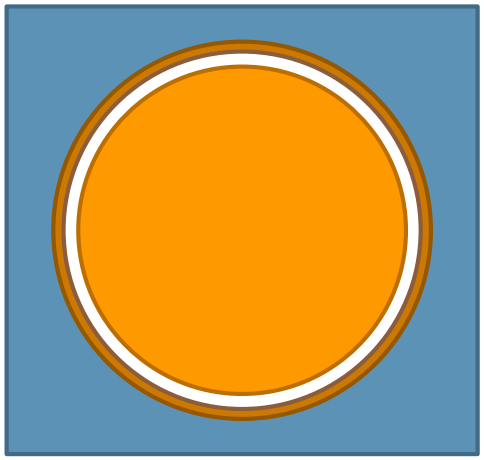




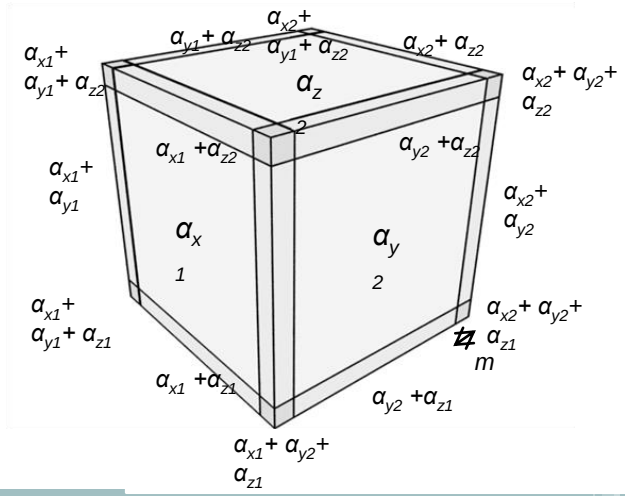
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- **Computational cost complete orange domain:**
  - 12 cubic grids
    - 6 Stress
    - 3 Velocity
    - 1 Density
    - 2 Lame's parameters
  - Memory:
    - **N_λ=10; 10cm → 31,5 GB**

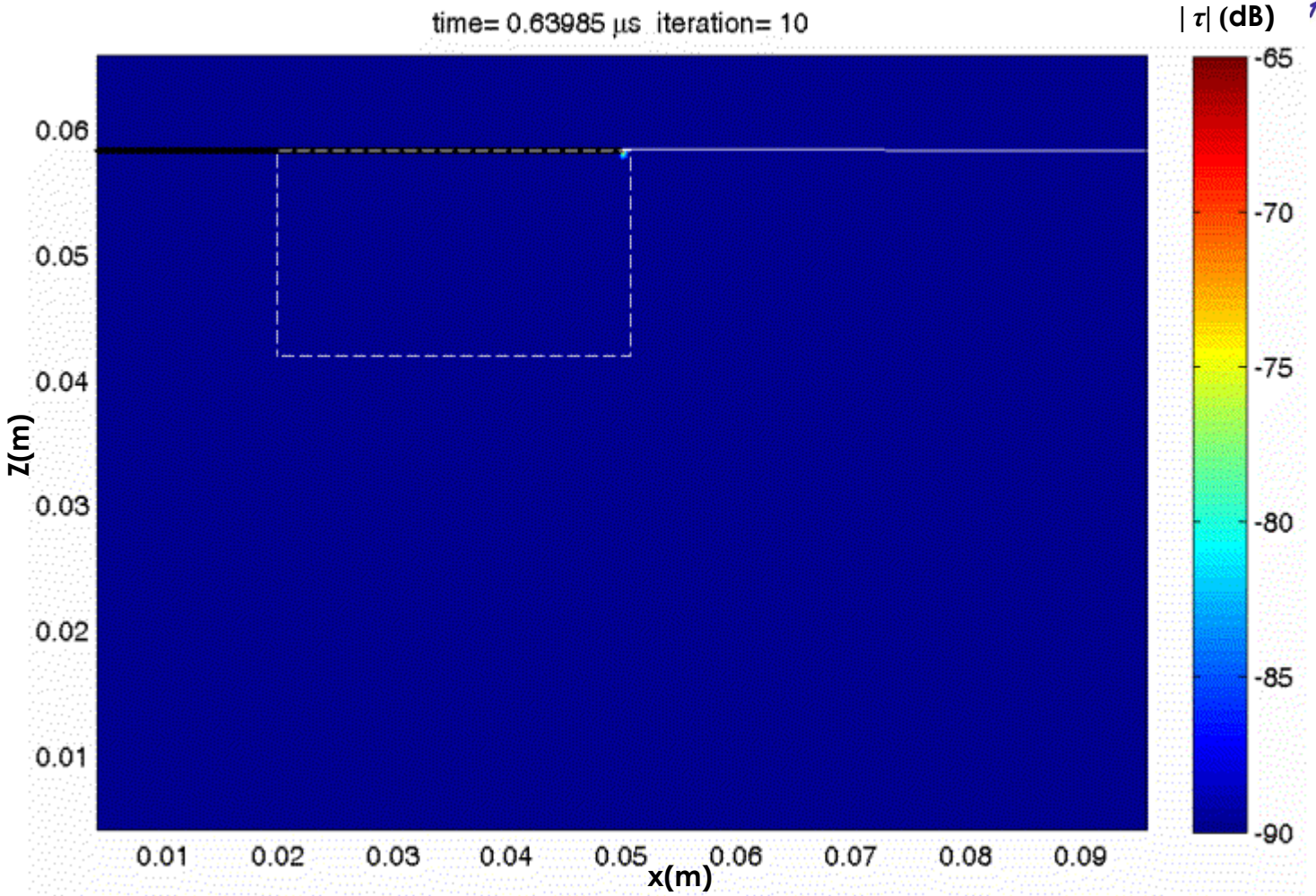


- **Computational cost with PML *complex coordinate stretching* type ABC's:**
  - 37+9 cubic grids
    - 15 Stress
    - 9 Velocity
    - 1 Density
    - 2 Lame's parameters
    - +9 additional for PML
  - Memory:
    - **N_λ=15; 4cm → 800 MB**



RESULTS

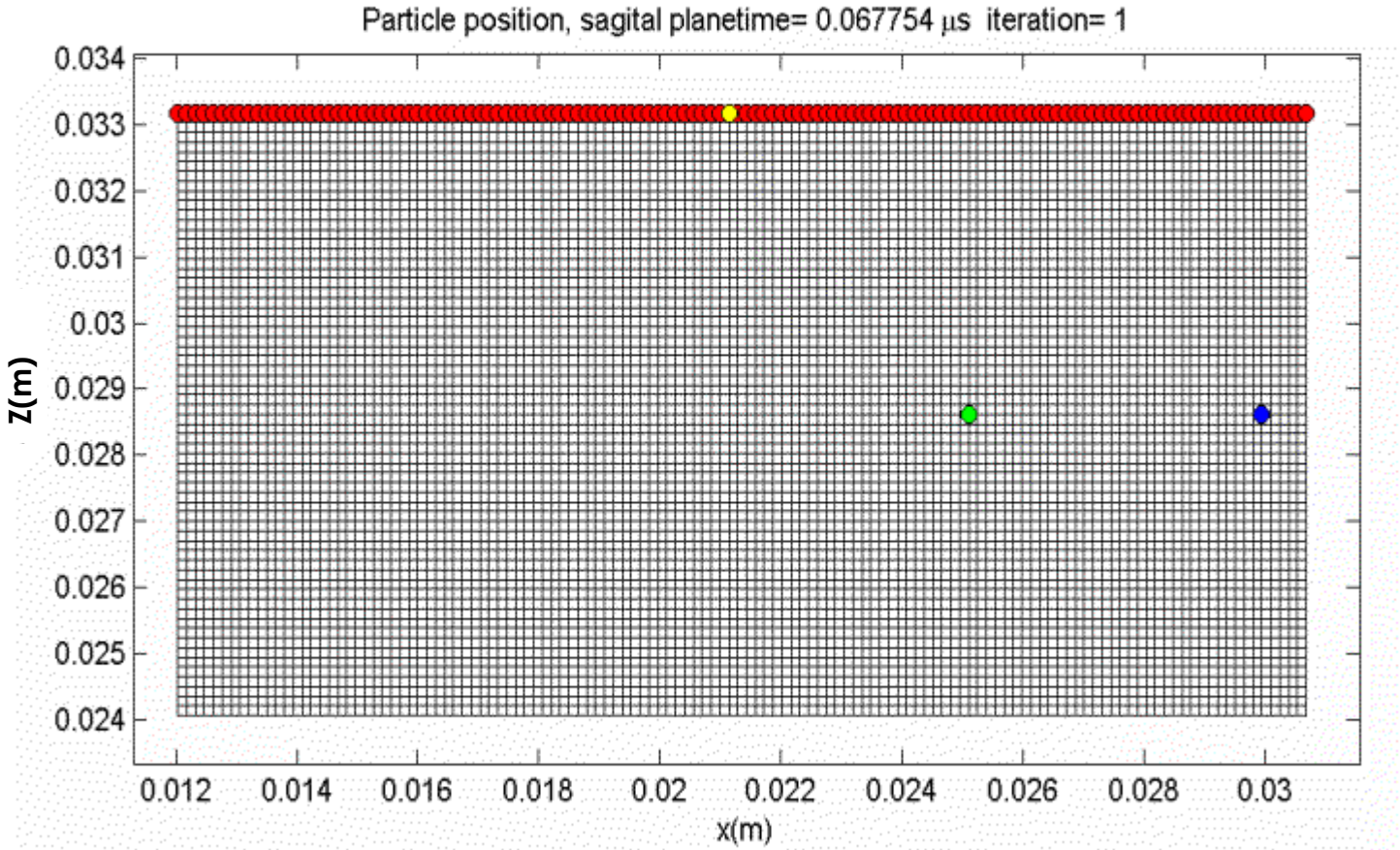
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- No layers, plane geometry

RESULTS

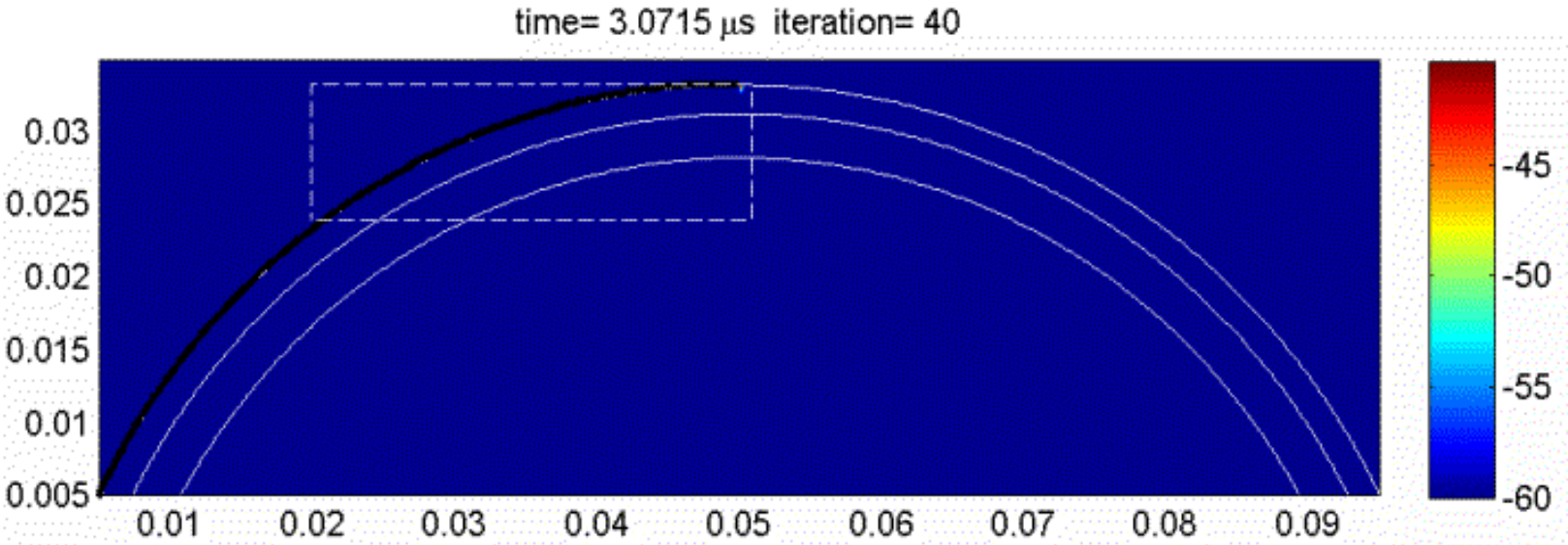
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- No layers, plane geometry, particle motion

RESULTS

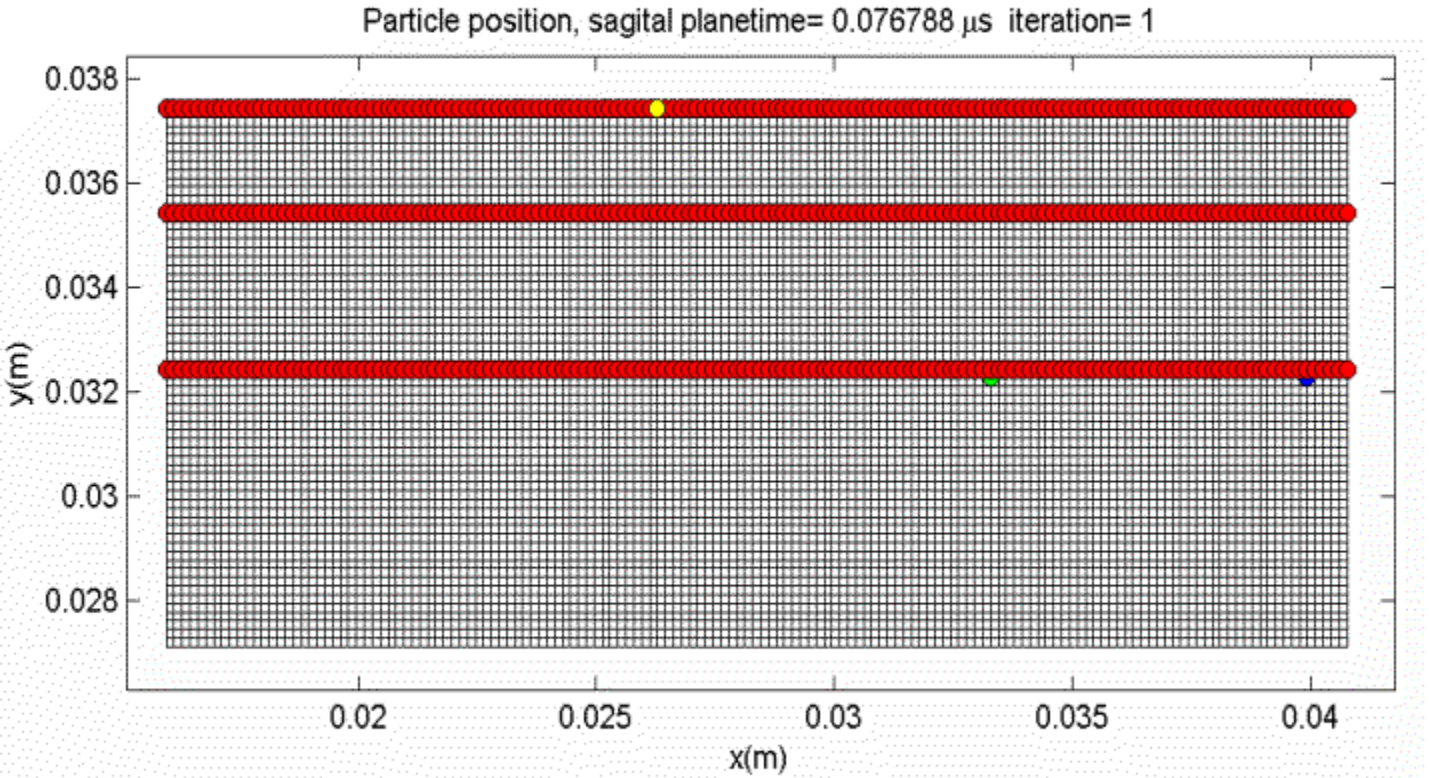
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- Orange multilayer model,
- Attenuation: 3 dB/mm

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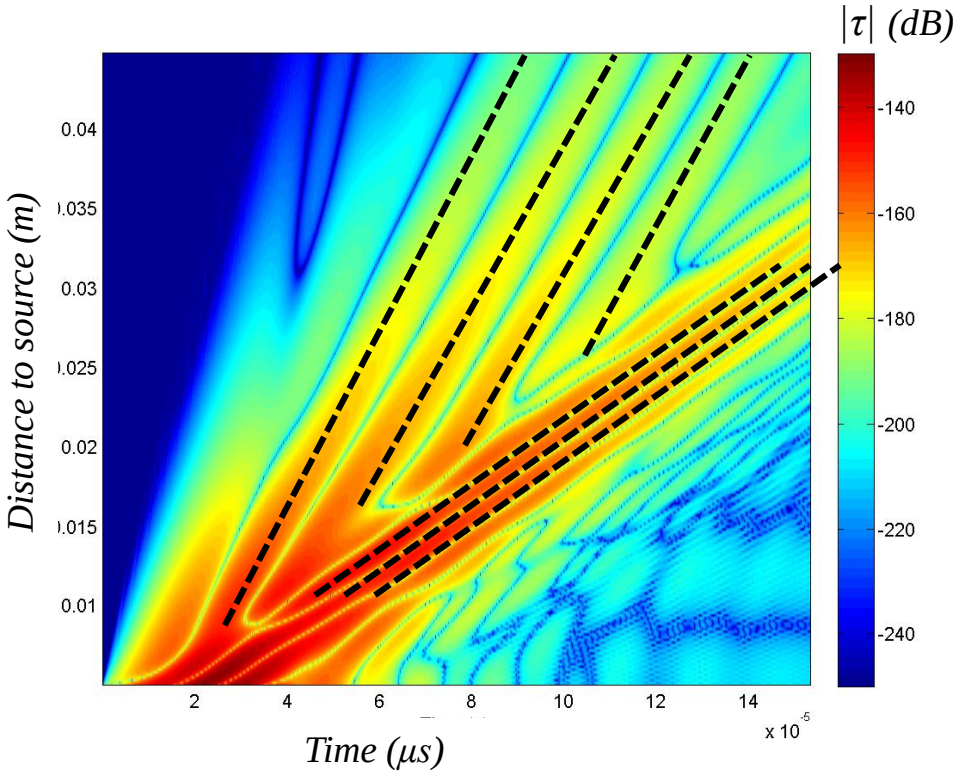


- Orange multilayer model,
- Attenuation: 3 dB/mm

RESULTS

- Recording over the orange's surface: **NO DAMPING**
  - Time vs. Distance to source plot

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$C_{R,numeric}$ = 191,02 m/s

$C_{R,\ theoretical}$ = 197.42 m/s

$C_{R,\ experimental}$ = (130,240) m/s

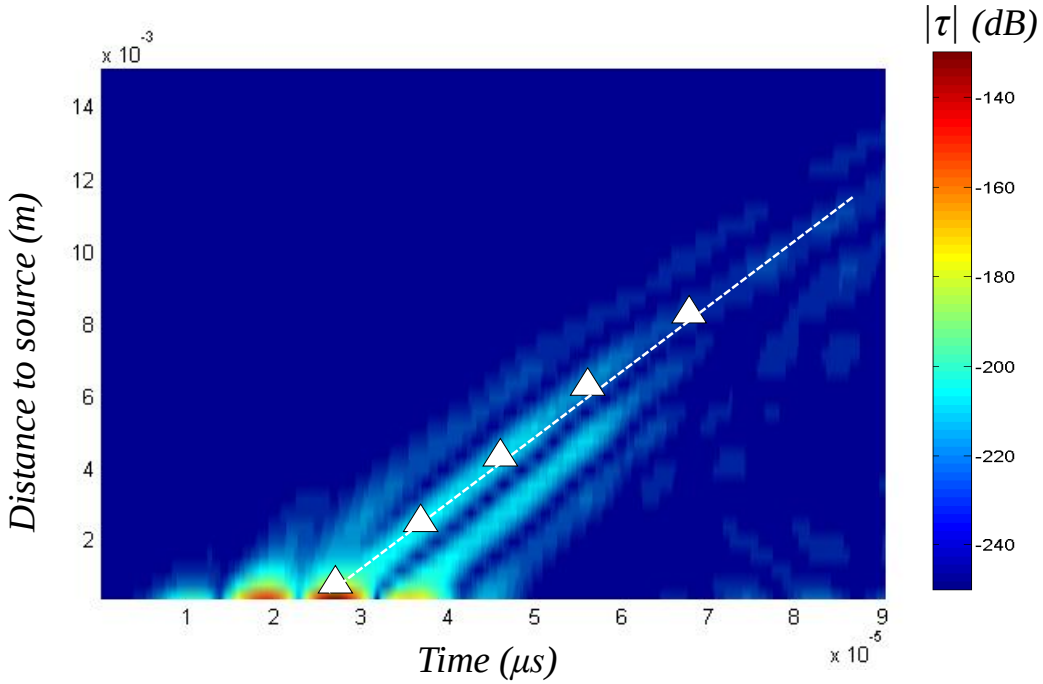
$C_{L,\ numeric}$ =1357.40 m/s

$C_{L,theoretical}$ =1540 m/s

RESULTS

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- Recording over the orange's surface: **3dB/mm DAMPING**
  - Time vs. Distance to source plot



$C_{R,numeric}$ = 183,97 m/s

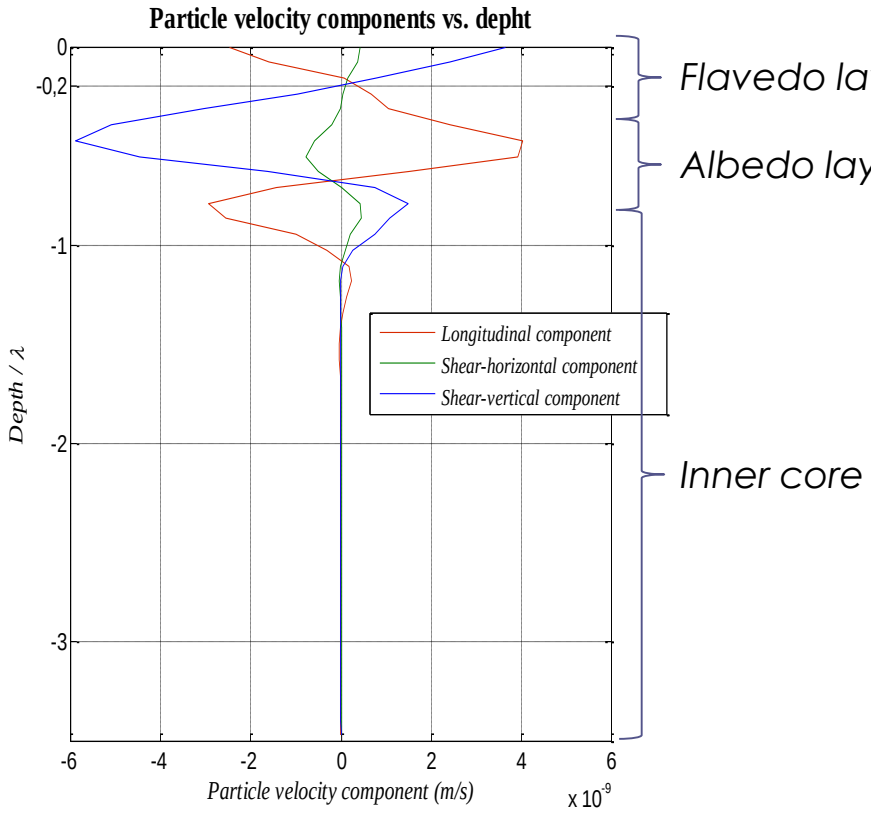
$C_{R,\ theoretical}$ = 197.42 m/s

$C_{R,\ experimental}$ = (130,240) m/s

RESULTS

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- Particle motion analysis:



1. Can't penetrate at depth>λ
2. Motion inversion below 0,2 λ
3. No motion at 0,2 λ

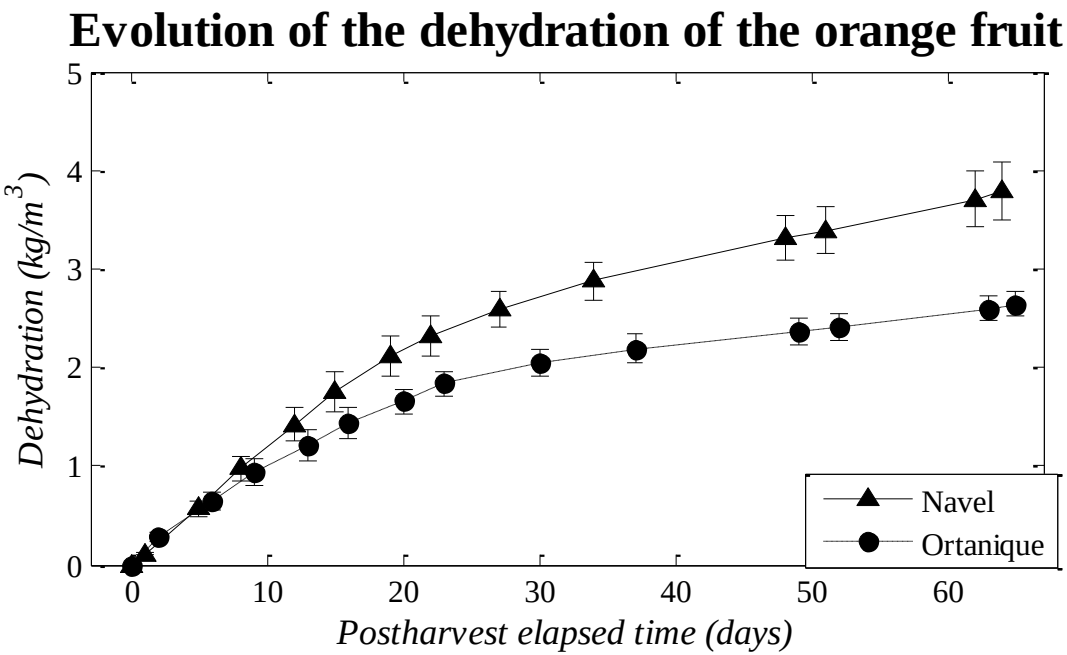
RAYLEIGH SURFACE WAVES

Hypothesis can be true

RESULTS

- How to find an absolute maturity index?
  - Measure a physiological process:
    - Dehydration of the entire fruit: *weighing over time*

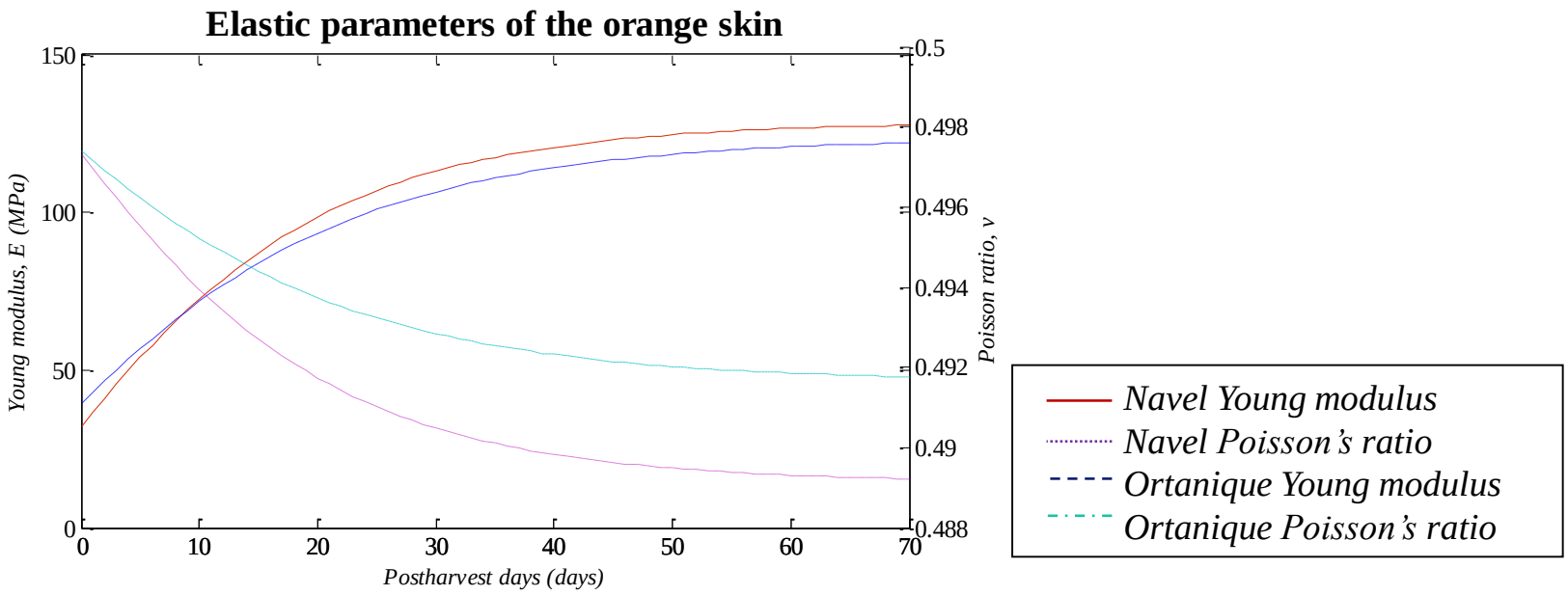
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RESULTS

- How to find an absolute maturity index?
  - Deduce the elastic parameters from the experimental Rayleigh wave speed:
    - Rayleigh wave speed: *ultrasonic device*
    - Elastic parameters: *Proposed model*

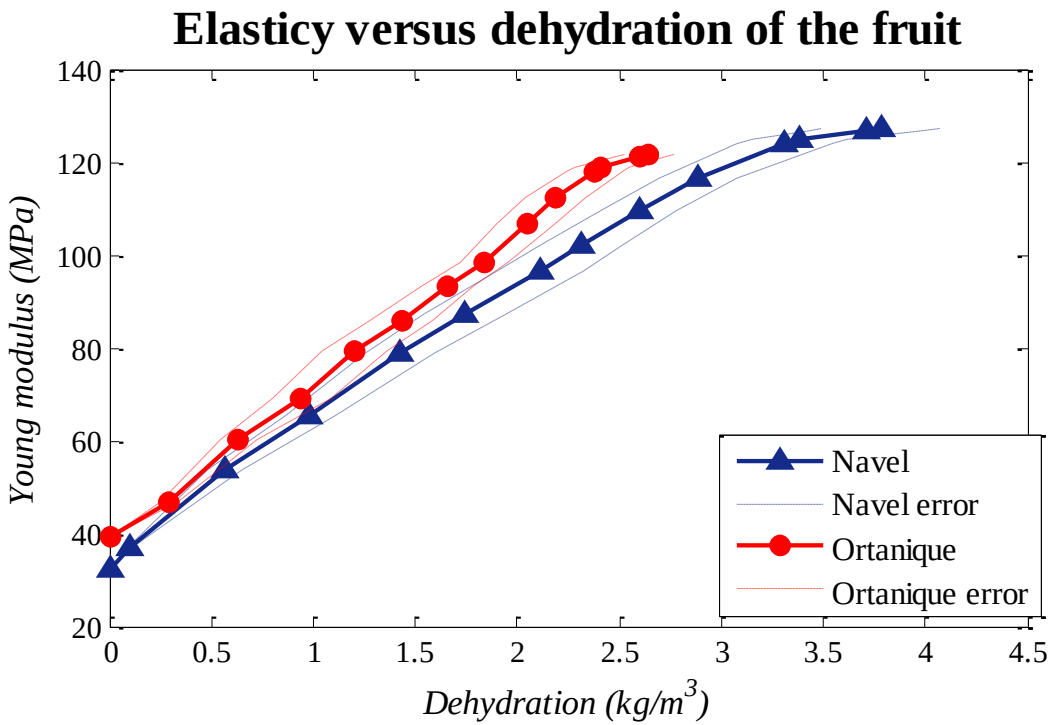
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RESULTS

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- How to find an absolute maturity index?
  - Nearly linear correlation of an acoustic parameter and a physiological process for the two varieties



CONCLUSIONS

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- A ultrasonic method for determine the physiological state of the orange was developed
- The FDTD simulations determine that Rayleigh surface motion determine the elastodynamic behavior of the orange skin
- The dehydration process is strongly correlated with the evolution of the elastic parameters of the fruit skin
- Thus, the proposed model is adequate to predict the ripeness of the Orange fruit in postharvest processes only measuring the ultrasonic surface wave speed

FUTURE LINES

- Introduction
- Experimental Setup
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- Results
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- Proposed model:
  - Characterization of dynamic elastic parameters:
    - frequency dependent Young's modulus and Poisson in plant tissues
- Development and implementation of more complex models:
  - Nonlinear effects, viscoelasticity, ...
- Other applications
  - Medical imaging:
    - Elastography
    - Monitoring HIFU treatments

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Questions?

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