

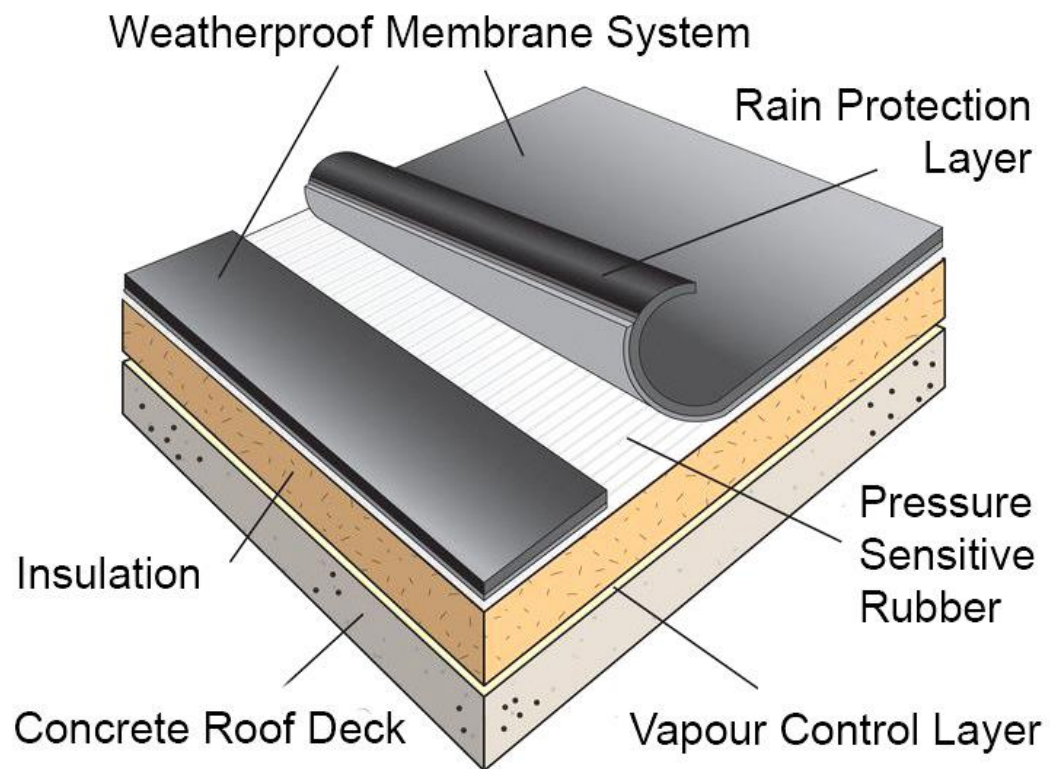


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**INNOVATIVE SCANNING METHOD  
IN NON-DESTRUCTIVE ROOF MOISTURE DIAGNOSTICS**

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## Introduction - Flat Roof and Preventive Maintenance

*“If it ain't broke don't fix it” - old US saying (...not for roofs).*



- Complex structure
- Extreme environment (cold, hot, wet, wind)

### Moisture → failure of the roofing system

- Reduces thermal insulation
- Causes corrosion (fastening system / structural deck)
- Cause blistering, splitting, deflection, delamination

### Importance of moisture origin

- From the outside
- Built-in
- Generated internally
- Condensed in roofing system.

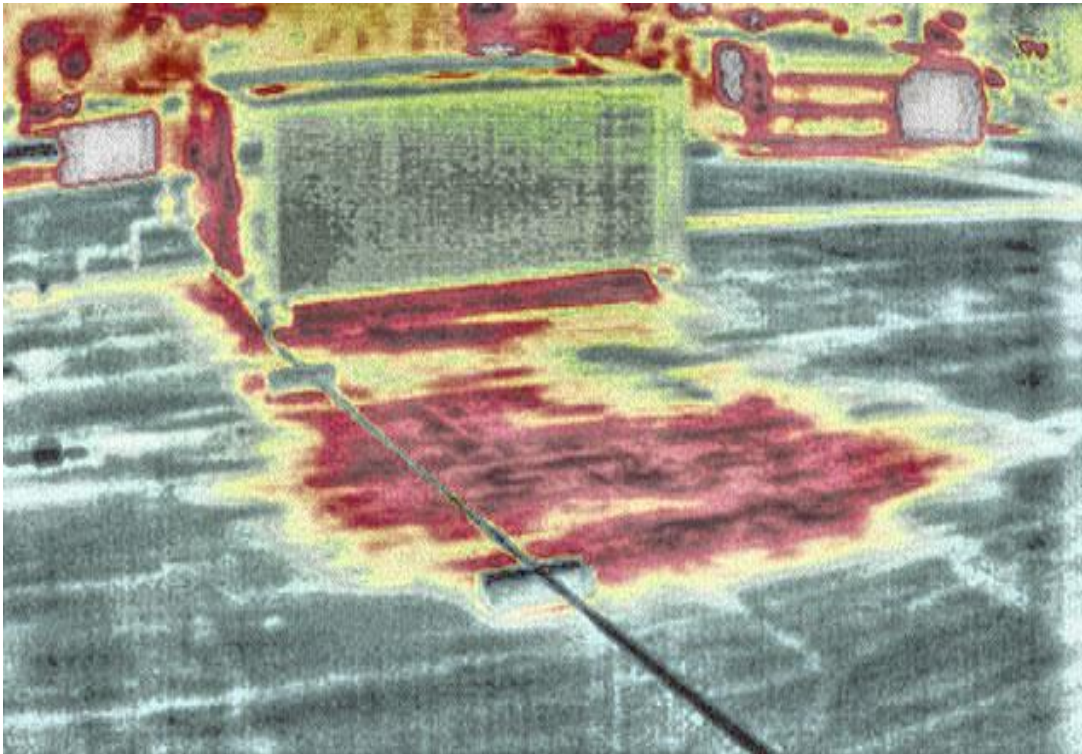
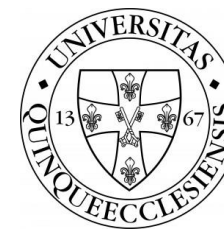
Different  
intervention  
required

**Non-destructive moisture detection → major part in preventive maintenance program.**



- Moisture Detecting Methods**
- Measurement Principle of Permittivity Test
- Principle of Detecting Moisture Distribution

## Detecting Methods 1 - IR Scanning



IR scanning → temperature differentials

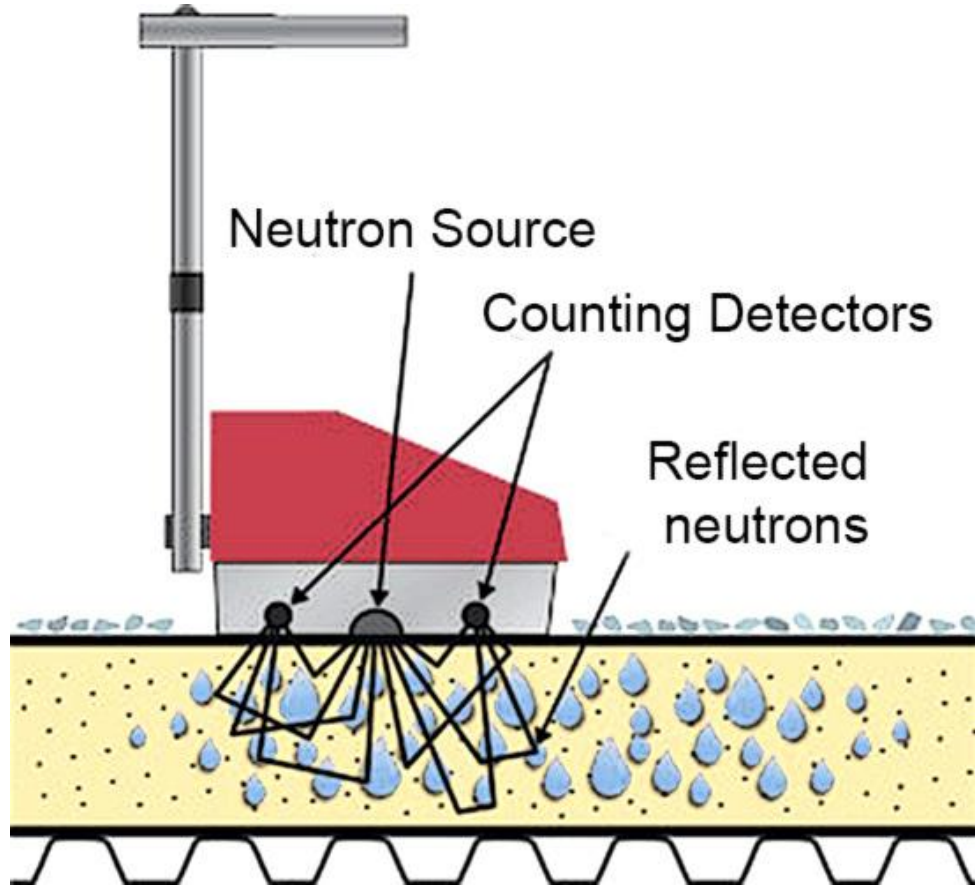
**Effective after sunset!**

- roof system cools quickly at dry areas
- wet insulation or membrane → longer cool (worse heat insulation & larger mass)

**Significant uncertainty!** ('Hot spots' origins: moisture, under deck heating, cooling vents, *etc.*)



## Detecting Methods 2 - Nuclear Scanning



- ❑ Counted neutrons, reflected from hydrogen atoms
- ❑ Wet area → higher level of slowed neutrons
- ❑ Rarely used on roofs in residential environment (because of the applied nuclear technology)

## Detecting Method 3 – Impedance Test



### Measurement of electric conductivity

- Difficult to use  
(membrane system: wrong electric conductivity)

### Measurement of electric permittivity.

- RF signals usually from rubber electrodes
- Significant uncertainty  
(weighted average measurement)
- New test & evaluation method  
(reduced uncertainty)



- Moisture Detecting Methods
- Measurement Principle of Permittivity Test**
- Principle of Detecting Moisture Distribution

## Measurement Principle Using Permittivity Test 1

$$\varepsilon = \varepsilon_s \cdot \left( 1 + 3 \cdot \frac{\varepsilon_w - \varepsilon_s}{\varepsilon_w + 2 \cdot \varepsilon_s} \cdot w_T \right)$$

- $\varepsilon_s$  average permittivity of dry construction (3...5)
- $\varepsilon_w$  permittivity of water (80)
- $w_T$  moisture content (volume %).

Frequency dependency (Debye's complex relaxation model)

$$\varepsilon = \varepsilon(\infty) + \frac{\varepsilon(0) - \varepsilon(\infty)}{1 + j\Omega} \quad \leftarrow \quad \Omega = \frac{\omega}{\omega_R} \quad \varepsilon = \varepsilon' - j \cdot \varepsilon''$$

$$\varepsilon'(\omega) = \frac{\varepsilon(0) + \varepsilon(\infty) \cdot \Omega^2}{1 + \Omega^2} \quad \varepsilon'' = [\varepsilon(0) - \varepsilon(\infty)] \cdot \frac{\Omega}{1 + \Omega^2}$$

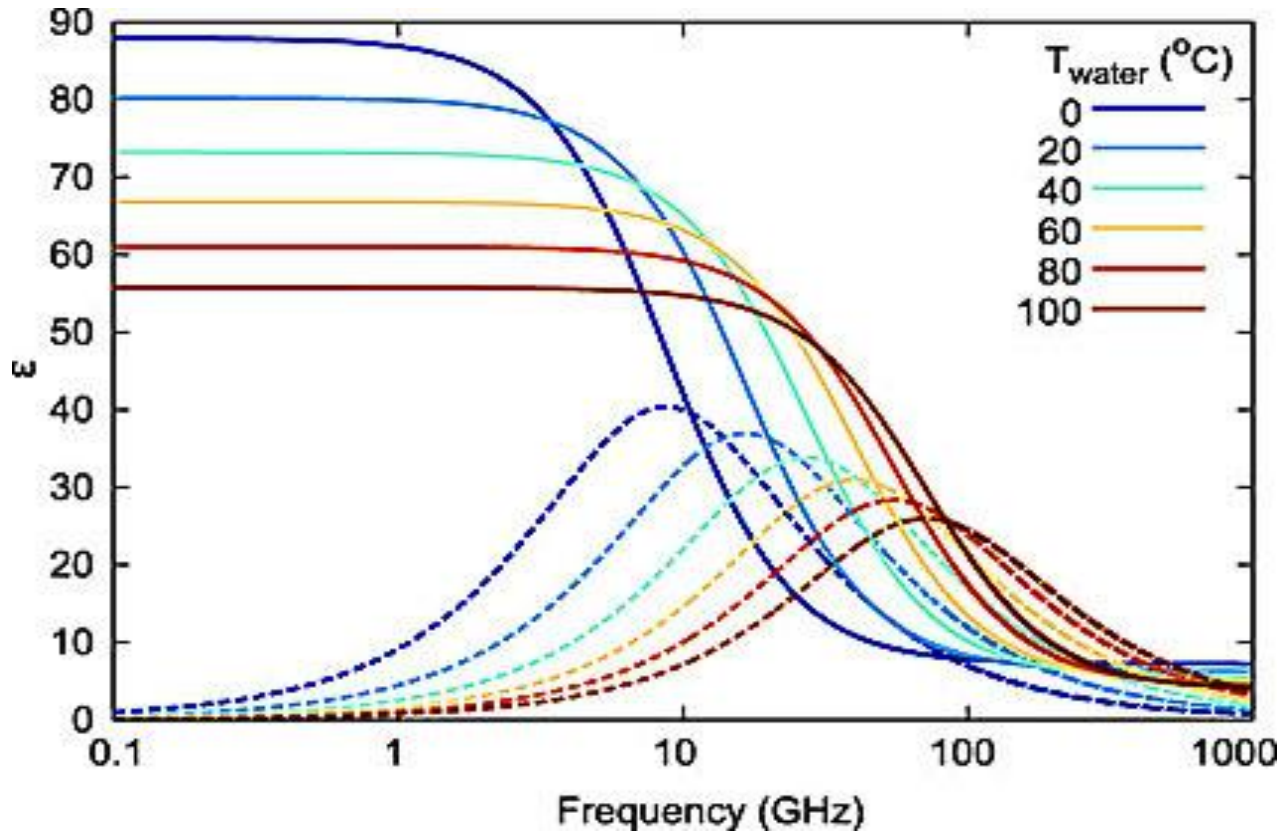
Temperature dependency (Kittel model)

$$\omega_R = \frac{k}{3 \cdot \eta \cdot V_m} \cdot T \approx 2.93 \cdot 10^7 \cdot T$$

- $k$  Boltzmann constant
- $\eta$  viscosity
- $V_m$  volume of the molecule
- $T$  temperature

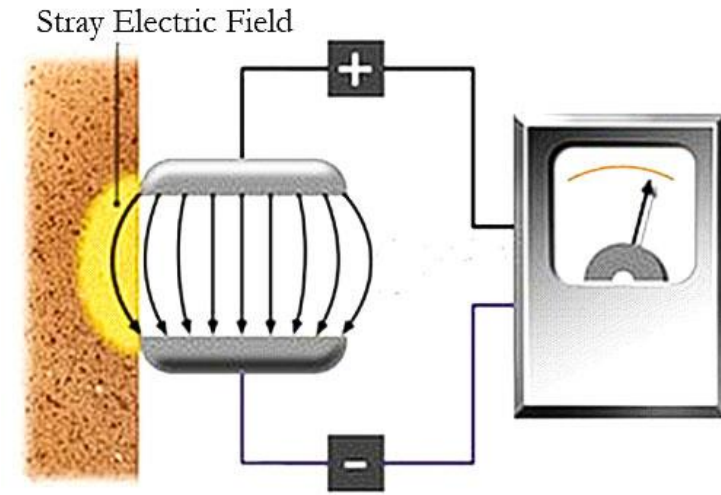


# Measurement Principle Using Permittivity Test 2

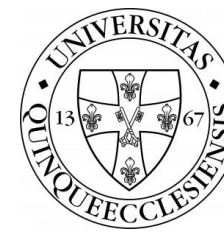


When  $\omega \ll \omega_R$

- Frequency independent real value
- No dielectric loss (no imaginary component)
- No phase delay (no imaginary component)
- Negligible temperature dependency

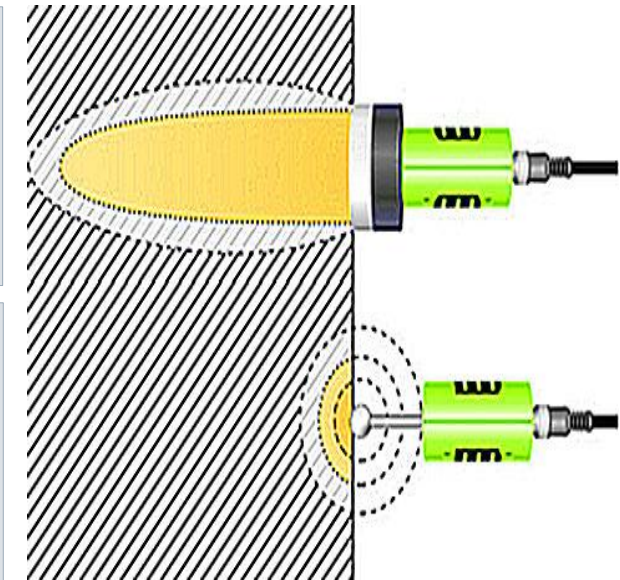


# SWOT Analysis



	<b>Helpful</b> (to achieving the objective)	<b>Harmful</b> (to achieving the objective)
<b>Int. Origin</b> (env. attrib.)	<b>Strengths</b> <ul style="list-style-type: none"> <li><input type="checkbox"/> Mobile scanner</li> <li><input type="checkbox"/> Clear indications</li> <li><input type="checkbox"/> Easy to use</li> </ul>	<b>Weakness</b> <ul style="list-style-type: none"> <li><input type="checkbox"/> Relative detection</li> <li><input checked="" type="checkbox"/> <b>Uncertainty in test</b></li> <li><input checked="" type="checkbox"/> <b>Weighted measurement</b></li> </ul>
<b>Ext. Origin</b> (env. attrib.)	<b>Opportunities</b> <ul style="list-style-type: none"> <li><input type="checkbox"/> Flat roof diagnostic</li> <li><input type="checkbox"/> Instantaneous test</li> <li><input type="checkbox"/> Easy roof inspection</li> </ul>	<b>Threats</b> <ul style="list-style-type: none"> <li><input type="checkbox"/> Inhomogeneous materials</li> <li><input checked="" type="checkbox"/> <b>Small+Close = Big+Distant</b></li> <li><input checked="" type="checkbox"/> <b>Uncertain meaning of test value</b></li> </ul>

$$M = \frac{G_0}{d} \cdot \int_0^d h(x) \cdot w_T(x) \cdot dx$$





- Moisture Detecting Methods
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- Principle of Detecting Moisture Distribution**

## Principle of Detecting Moisture Distribution

Single test value (simple mean)

$$M_k = \frac{G_0}{d} \cdot \int_0^d h_k(x) \cdot w_T(x) \cdot dx$$

Approx. of k-th test value

$$M_k \cong \frac{G_0}{d} \cdot \sum_{i=1}^n h_{ki} \cdot w_{Ti} \cdot \Delta x \rightarrow M_k \cong \frac{G_0}{n} \cdot \sum_{i=1}^n h_{ki} \cdot w_{Ti} \quad (\text{where } d = n \cdot \Delta x)$$

Distribution series

$$\begin{bmatrix} M_1 \\ \vdots \\ M_n \end{bmatrix} = \frac{G_0}{n} \cdot \begin{bmatrix} h_{11} & \cdots & h_{1n} \\ \vdots & \ddots & \vdots \\ h_{n1} & \cdots & h_{nn} \end{bmatrix} \cdot \begin{bmatrix} w_{T1} \\ \vdots \\ w_{Tn} \end{bmatrix} \rightarrow \begin{bmatrix} w_{T1} \\ \vdots \\ w_{Tn} \end{bmatrix} = \frac{n}{G_0} \cdot \begin{bmatrix} h_{11} & \cdots & h_{1n} \\ \vdots & \ddots & \vdots \\ h_{n1} & \cdots & h_{nn} \end{bmatrix}^{-1} \cdot \begin{bmatrix} M_1 \\ \vdots \\ M_n \end{bmatrix}$$

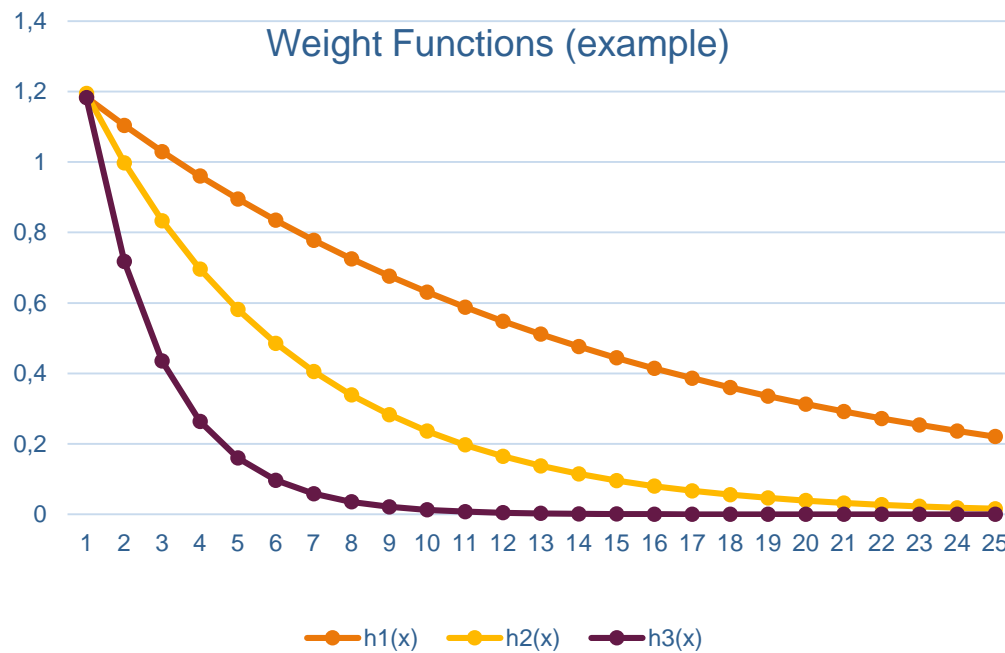


# Simulation Example

$$h_i(x) = G_i \cdot e^{-A_i \cdot x}$$

$i$	1	2	3
$G_i$	1.27	1.43	1.95
$A_i$	0.7	1.8	5

$$\bar{H} = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix} = \begin{bmatrix} 1 & 0.79 & 0.63 \\ 0.78 & 0.43 & 0.24 \\ 0.37 & 0.07 & 0.01 \end{bmatrix}$$



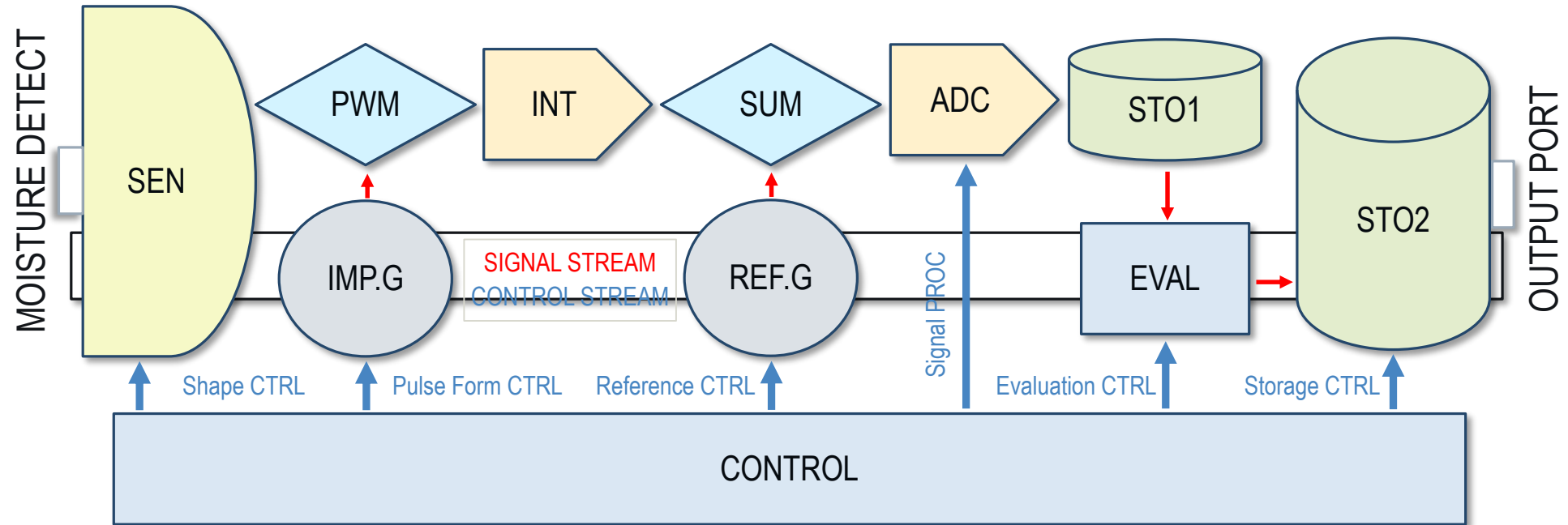
$$\begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix}^{-1} = \begin{bmatrix} 0.70 & -2.18 & 5.44 \\ -5.00 & 14.28 & -16.77 \\ 6.78 & -14.56 & 12.51 \end{bmatrix}$$

$$\bar{w}_T = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \rightarrow \bar{M} = \begin{bmatrix} 1.00 \\ 0.78 \\ 0.37 \end{bmatrix} \rightarrow \bar{w}_{Tcalc} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

$$\bar{w}_T = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \rightarrow \bar{M} = \begin{bmatrix} 0.79 \\ 0.43 \\ 0.07 \end{bmatrix} \rightarrow \bar{w}_{Tcalc} = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$$

$$\bar{w}_T = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \rightarrow \bar{M} = \begin{bmatrix} 0.63 \\ 0.24 \\ 0.01 \end{bmatrix} \rightarrow \bar{w}_{Tcalc} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

# BACKUP: Operation of Device





- Traditional non-destructive moisture detection is accompanied with significant uncertainty due to the moisture inhomogeneity in dept.
- The uncertainty can be reduced by post processing of the measurement values resulted by the non-destructive scanning method.
- The uncertainty depends on the number of partial tests, i.e. the number of weight functions, applied in test.

**Thank you for your time!**