The Acconeer XM125 radar module provides its received data in the form of complex numbers (I/Q data). This is common in radar systems that use pulsed coherent radar (PCR) technology, as the complex representation allows for both amplitude and phase information to be retained.

1. In-phase (I) and Quadrature (Q) Components

   The received signal is split into two parts:

- In-phase (I): The **real** component.
- Quadrature (Q): The **imaginary** component.

   This helps in detecting motion, measuring distance, and determining the Doppler shift.

2. Phase Information

- The phase difference between transmitted and received signals allows for accurate distance measurement.
- The Doppler shift (rate of phase change over time) enables velocity estimation.

3. Signal Processing

- The complex format allows the application of FFT (Fast Fourier Transform) for spectral analysis.
- Phase unwrapping and IQ demodulation help in extracting useful features from the received signal.

Determining the permittivity (dielectric constant, ε_r) of an object using the Acconeer XM125 involves analyzing how the emitted electromagnetic (EM) waves interact with the material. This can be done using **phase shift**, **signal attenuation**, and **reflection properties** from the complex I/Q data.

Breaking Down the Amplitude vs Distance Graph in the Acconeer Exploration Tool

The y-axis (Amplitude) represents the strength of the radar reflections at different distances along the x-axis (Distance in meters).

1. Distance (X-axis, in meters)

- This corresponds to the range bins where reflections are detected.
- Each bin represents a specific time-of-flight measurement converted to distance using the speed of light.
- The bin resolution is dictated by the pulse characteristics and radar processing settings.

2. Amplitude (Y-axis, Unitless or Arbitrary Units)

- The amplitude is derived from the magnitude of the complex IQ signal:

$$A = \sqrt{I^2 + Q^2}$$

- It represents the strength of the reflected signal at each distance.
- The units are arbitrary, meaning they don't correspond to a physical unit like volts or watts.
- Instead, the amplitude values are relative and can be used for comparing different reflections.

3. What the Amplitude Represents

- Higher amplitude means a stronger reflection, which can indicate:
    - A dense or highly reflective object (e.g., metal, water-rich material like wet beans).
    - A closer object that reflects more energy to the sensor.
    - A large surface area reflecting the radar wave.
- Lower amplitude means a weaker reflection, possibly due to:
    - An object being farther away.
    - A material that absorbs or diffuses radar waves.
    - The presence of multiple scattering effects.

4. What the Data Means for Moisture Sensing

- Moisture content affects the dielectric constant of materials, which in turn changes how radar waves reflect and propagate.

- Higher water content typically increases the reflection and attenuation, meaning you should see amplitude changes in the Sparse IQ data when comparing dry vs wet samples.
- By analyzing amplitude shifts at specific distances, you can create a model to correlate radar reflections with moisture content.

Determining the Permittivity of Green Coffee Beans Using the Acconeer XM125: Attenuation-Based & Phase Shift Hybrid Approach

Since green coffee beans are organic and contain moisture, **their permittivity is frequency-dependent and varies based on water content and density**. Given that the XM125 operates at 60 GHz, **the most suitable method would be one that captures both dielectric constant** (ε') **and loss factor** (ε'').

A combination of **attenuation-based analysis** and **phase shift measurement** is ideal for measuring the real and imaginary parts of permittivity in coffee beans.

Coffee Beans Are a Lossy Dielectric

- They contain moisture and organic material that absorbs EM waves, leading to signal attenuation.
- The attenuation can be related to the loss factor ε''.

Bean Density Variation Affects Phase Velocity

- The radar signal slows down inside the material, causing a measurable phase shift.
- This allows us to estimate the dielectric constant ε'.

Measuring Phase Difference

- The radar transmits an EM wave and receives the reflected signal.
- Compute the phase shift $\Delta\phi$ between the signal in free space and after passing through the material.

Steps for Measuring Permittivity Using the XM125

1. Measure Attenuation Through a Known Thickness of Coffee Beans

- Place the coffee beans in a controlled container of known thickness d.
- Transmit the radar signal through the beans.
- Measure the received signal strength after passing through the beans.
- Compare with the signal strength in free space to calculate the attenuation coefficient.

Attenuation-Based Calculation

The transmitted power P_T through the beans is given by:

$$P_T = P_0 e^{-\alpha d}$$

where:

- $P_T =$ received power through the beans
- $P_0 =$ received power in free space
- $\alpha =$ attenuation constant
- $d =$ thickness of the beans

The imaginary part of permittivity ε'' is related to α by:

$$\varepsilon'' = \frac{c\alpha}{2\pi f}$$

where:

- $c =$ speed of light,
- $f =$ frequency (60 GHz for XM125).

2. Measure Phase Shift for Permittivity Estimation

- Measure the phase difference between the received signal in free space and the received signal after passing through the beans.
- The relative permittivity ε_r is related to the phase shift $\Delta\phi$ as:

$$\varepsilon' = \left(\frac{\lambda_0}{\lambda_m}\right)^2$$

where:

- λ_0 = free-space wavelength at 60 GHz (5mm for XM125)
- λ_m = wavelength inside the coffee beans, derived from the measured phase shift

3. Relate Permittivity to Moisture Content

- The permittivity of green coffee beans is strongly correlated with their moisture content.
- By creating a **calibration curve** (mapping measured permittivity to known moisture levels), you can estimate the moisture of unknown samples (we probably will not take this approach).

Extracting Real (ε') and Imaginary (ε'') Parts of Permittivity from XM125 Complex Data

1. Understanding the XM125 Complex Output

   The XM125 provides complex I/Q data in the form:

$$S = I + jQ$$

   where:
   - I = In-phase component (real part),
   - Q = Quadrature component (imaginary part),
   - S represents the received signal at different timestamps.

   This I/Q data is influenced by the permittivity of the material through changes in signal attenuation and phase shift.

2. Extracting Phase Shift and Amplitude

   The **complex values** contain both **amplitude** and **phase** information, which change depending on the material's permittivity.

   - Amplitude (A):

$$A = |S| = \sqrt{I^2 + Q^2}$$

     This represents **signal attenuation**, which relates to ε'' (loss factor)

   - Phase Shift (ϕ):

$$\phi = tan^{-1}\left(\frac{Q}{I}\right)$$

     This represents **how much the wave slows down**, which is linked to ε' (dielectric constant).

3. Converting Phase Shift & Attenuation to Permittivity

The relationship between the **phase velocity**, **attenuation**, and **permittivity** is given by:

$$k_m = \beta - j\alpha$$

where:

- k_m = complex propagation constant in the medium
- β = phase constant (linked to ε'),
- α = attenuation constant (linked to ε'').

From measured **phase shift** and **attenuation**, we estimate:

$$\varepsilon' = \left(\frac{\beta c}{\omega}\right)^2$$

$$\varepsilon'' = \frac{2\alpha c}{\omega}$$

where:

- c = speed of light ($3 \cdot 10^8$ m/s),
- $\omega = 2\pi f$ = angular frequency of the radar (for XM125, $f = 60$ GHz)
- $\beta = \frac{\phi}{d}$ (estimated from phase shift across known material thickness d),
- $\alpha = \frac{ln(A_0/A)}{d}$ (estimated from measured attenuation).

4. Step-by-Step Process to Compute Permittivity

Step 1: Measure Free-Space Reference

- Record I/Q data when no material is present.
- Compute **reference phase shift** ϕ_0 and **amplitude** A_0.

Step 2: Measure Signal Through the Material

- Place the coffee beans in the radar path.
- Collect I/Q data and compute:
  - Measured phase shift ϕ_m,
  - Measured amplitude A_m,

<u>Step 3</u>: Compute Phase Change and Attenuation

- Compute **phase constant**:

$$\beta = \frac{\phi_m - \phi_0}{d}$$

- Compute **attenuation constant**:

$$\alpha = \frac{ln\left(A_0/A_m\right)}{d}$$

<u>Step 4</u>: Compute Permittivity

- Compute **real permittivity**:

$$\varepsilon' = \left(\frac{\beta c}{\omega}\right)^2$$

- Compute **imaginary permittivity**:

$$\varepsilon'' = \frac{2\alpha c}{\omega}$$

Determining Moisture Content of Green Coffee Beans from Permittivity

Since the permittivity ($\varepsilon_r = \varepsilon' - j\varepsilon''$) of green coffee beans is directly influenced by moisture content, we can estimate moisture levels by mapping measured permittivity values to known moisture percentages.

Moisture and Permittivity Relationship

1. Water has a high permittivity

    - At 60 GHz, water has a permittivity of about $\varepsilon_r \approx 5 - j12$
    - Dry organic material has a much lower permittivity (~2-3)
    - More water content **increases permittivity**, especially the **imaginary part** (ε''), which represents energy absorption

2. Empirical models relate permittivity to moisture

    Several empirical relationships exist to relate **moisture content** (MC, in %) to **permittivity**. The most commonly used is the **Lichtensteiger & Shubert model**:

$$MC = A \cdot \varepsilon' + B \cdot \varepsilon'' + C$$

    where:
    - A, B, C are material-specific coefficients found through calibration
    - ε' = real permittivity (dielectric constant)
    - ε'' = loss factor (absorption due to moisture)

Using the RoastRite Capacitive Moisture Sensor as a Baseline for XM125 Model Comparison

1. Establish a Controlled Testing Setup

   To ensure a fair comparison, both the **RoastRite** sensor and **XM125** should measure the **same coffee bean samples** under **identical conditions** (temperature, humidity, bean density, etc.

   - Prepare multiple samples with different moisture levels
   - Ensure consistent packing density in both measurement steps
   - If possible, use **ground truth** moisture values from oven-drying for additional accuracy (we will most likely not be using these values as we may not have access to this information - something to check in with Josh about)

2. Measure Moisture Content with RoastRite (Baseline Measurement)

   - Take readings from the RoastRite for each sample
   - Record the **moisture content** (%) it provides as the baseline truth value

3. Measure Permittivity Using the XM125

   - Use the **XM125** to measure the **real** (ε') and **imaginary** (ε'') parts of permittivity for the same samples.
   - Ensure the same thickness/density of coffee beans is used in each measurement

4. Develop a Correlation Model Between Permittivity and Moisture Content

   Since permittivity is a function of moisture content, we need to map the permittivity values from the XM125 to the moisture values from RoastRite.

- Fit a model of the form:

$$MC = A \cdot \varepsilon' + B \cdot \varepsilon'' + C$$

  where:
  - MC = moisture content (from RoastRite),
  - ε' = real permittivity (XM125),
  - ε'' = imaginary permittivity (XM125),
  - A, B, C = coefficients to be determined via regression.

- Perform a **linear regression** (or nonlinear regression if needed) to fit the XM125 permittivity values to the RoastRite readings.

5. Evaluate the Accuracy of the XM125 Model

    - Compare the predicted moisture content from the XM125 model with the RoastRite moisture readings.
    - Compute the **Mean Absolute Error** (MAE) or **Root Mean Square Error** (RMSE) to quantify the accuracy.

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|MC_{XM125} - MC_{RoastRite}\right|$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(MC_{XM125} - MC_{RoastRite}\right)^2}$$

    - If necessary, refine the correlation model based on the observed error trends

Example Python Script to Calculate Permittivity of Green Coffee Beans

```
# Example program that takes in I/Q data from the XM125 (both the sample and reference)
# Computes phase shift (Δϕ) and attenuation (α)
# Calculates permittivity:
# ε′(real part) from phase velocity
# ε″(imaginary part) from attenuation
# Plots the results

import numpy as np
import matplotlib.pyplot as plt

# Constants
c = 3e8  # Speed of light (m/s)
f = 60e9  # Frequency of XM125 (Hz)
w = 2 * np.pi * f  # Angular frequency

def process_xm125_data(iq_data, ref_iq_data, d):
    """
    Compute permittivity (epsilon' and epsilon'') from XM125 I/Q data.
    :param iq_data: Complex array of I/Q data (measurement with coffee beans)
    :param ref_iq_data: Complex array of I/Q data (free-space reference)
    :param d: Thickness of coffee bean sample (meters)
    :return: epsilon' and epsilon''
    """
    # Compute phase shift
    phase_meas = np.angle(iq_data)
    phase_ref = np.angle(ref_iq_data)
    delta_phi = np.unwrap(phase_meas - phase_ref)  # Phase difference
    beta = delta_phi / d  # Phase constant

    # Compute attenuation
    amp_meas = np.abs(iq_data)
    amp_ref = np.abs(ref_iq_data)
    alpha = np.log(amp_ref / amp_meas) / d  # Attenuation constant

    # Compute permittivity
    epsilon_real = (beta * c / w) ** 2
    epsilon_imag = (2 * alpha * c) / w

    return epsilon_real, epsilon_imag
```

```
# Example data (replace with real XM125 data)
num_samples = 100
iq_data = np.random.randn(num_samples) + 1j * np.random.randn(num_samples)  # Simulated
XM125 data
ref_iq_data = np.random.randn(num_samples) + 1j * np.random.randn(num_samples)  #
Simulated reference
d = 0.01  # Thickness of coffee bean sample (10 mm)

# Compute permittivity
epsilon_real, epsilon_imag = process_xm125_data(iq_data, ref_iq_data, d)

# Plot results
plt.figure(figsize=(10, 4))
plt.subplot(1, 2, 1)
plt.plot(epsilon_real, label="Real Permittivity (ε')")
plt.xlabel("Sample Index")
plt.ylabel("ε'")
plt.legend()

plt.subplot(1, 2, 2)
plt.plot(epsilon_imag, label="Imaginary Permittivity (ε'')", color='r')
plt.xlabel("Sample Index")
plt.ylabel("ε''")
plt.legend()

plt.tight_layout()
plt.show()
```

Handling Variable Thickness (d) in Permittivity Measurements

Since the green coffee beans are irregularly shaped and packed together, the thickness d of the sample won't be constant. This variability can introduce errors when calculating permittivity.

using a stepper motor to rotate the container is an approach that should be considered because:

- It captures multiple angles, reducing bias from non-uniform packing
- It smooths out variations in thickness, leading to a more reliable permittivity estimate
- It allows for averaging across different paths, minimizing errors from gaps between beans

How to Implement the Stepper Motor Approach

1. Rotate the Container & Collect Data at Multiple Angles

- Mount the container on a stepper motor.
- Rotate in small increments (e.g., 5° per step).
- Take multiple XM125 readings at each step.
- Store the I/Q data at each angle.

2. Estimate the Effective Thickness (d_{eff})

- One way is to use a mechanical depth sensor to measure the average depth of beans in the container.
- Another way is to estimate (d_{eff}) statistically by averaging phase-based distance measurements over multiple rotations.

3. Compute Permittivity Using the Average Thickness

- After rotating, computed a weighted average thickness:

$$d_{eff} = \frac{1}{N} \sum_{i=1}^{N} d_i$$

- Use d_{eff} in the permittivity calculations to account for variations