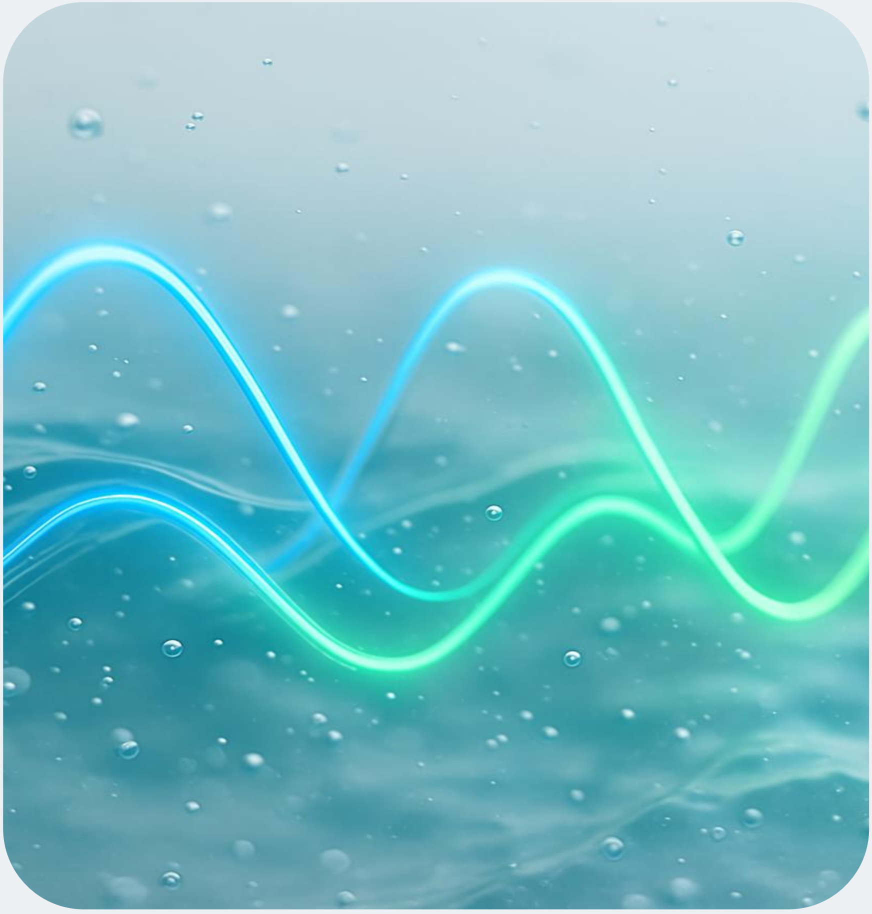
The Science Behind Collo

Measuring Complex Permittivity with Radio Frequency



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1. Dielectricity Quantified: Turning Permittivity into Actionable Data

Collo's measurement principle is built on the phenomenon of dielectricity, which impacts how materials respond when exposed to an electromagnetic field. This well-known and extensively studied effect [1–3] occurs because polar particles, e.g. molecules that are unevenly charged, within the material align with the external electromagnetic field. The degree to which this happens is quantified by *electrical permittivity*, a complex property with real and imaginary components.

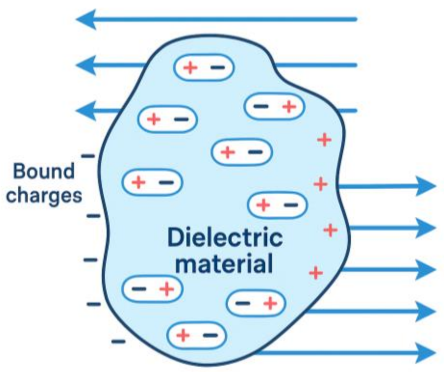

Figure 1 Material with polar molecules align with external electrical field. As the field changes direction, the molecules realign slowing the field.

Traditionally, the complex permittivity of liquids is measured in laboratory environments using *coaxial reflectometry, transmission line methods* or interference-based methods [4]. While these methods provide high accuracy and broad frequency coverage, they often involve significant practical limitations in industrial reactive, fluctuating and dynamic settings and are more suitable for homogeneous, non-reactive liquids in static environments.

Reflectometric methods rely on impedance matching and accurate time-domain or frequency-domain analysis of signal reflections at material interfaces. While highly accurate, they require meticulous calibration, reference standards, and precise sample holder geometries. *Transmission line methods* demand custom-designed test fixtures, precise knowledge of line geometry, and high-frequency instrumentation such as vector network analyzers (VNAs). These setups are sensitive to temperature drift, connector repeatability, and cable losses, making them unsuitable for in-line deployment in environments where conditions fluctuate or where maintenance access is limited. Interference-based methods operating in an extremely high frequency (EHF) range can deliver precise permittivity values but similarly rely on custom fixtures that are impractical outside the laboratory and required sophisticated and custom signal processing, and strict environmental control [5]. In contrast, recent advancements in embedded resonator technology have enabled the real-time measurement of dielectric properties under dynamic, in-line industrial conditions. Salpavaara et al. [7], for instance, demonstrate a passive resonance-based sensor capable of monitoring colloidal particle suspensions in flow, highlighting how resonator-based methods can overcome the constraints of conventional laboratory techniques.

Collo's technology builds on this principle, employing a flat, non-cavity passive resonator that can be seamlessly integrated into pipelines or process vessels. By exciting the system with a broadband signal and tracking resonant frequency shifts and damping behavior, Collo extracts information related to the dielectric properties of the surrounding medium regardless of liquid stability. This approach further eliminates the need for sample preparation, reduces system complexity, and enables automated real-time data refinement for practical use in changing environments.

The sensor hardware, signal processing algorithms, and industrial implementation are built on years of research in electromagnetic resonance and dielectric spectroscopy. Foundational doctoral work by Järveläinen [6] explored how Radio Frequency (RF) fields interact with colloidal liquids, while Salpavaara's dissertation [7] advanced the application of resonator-based measurement in complex liquids. This work has been further validated and expanded through related studies at the same research institution [8–12].

The next section explains how Collo translates permittivity into practical, real-time process data — and how these parameters can be used for liquids monitoring, quality assurance, and process control.

1.1 Radio Frequency Mapping of Dielectric Parameters

Collo's sensing principle builds on years of dielectric and RF resonance research [6][7]. By combining this science with advanced RF resonator design, Collo brings full dielectric analysis out of the lab and directly into the process line — delivering real-time insight into complex liquid systems.

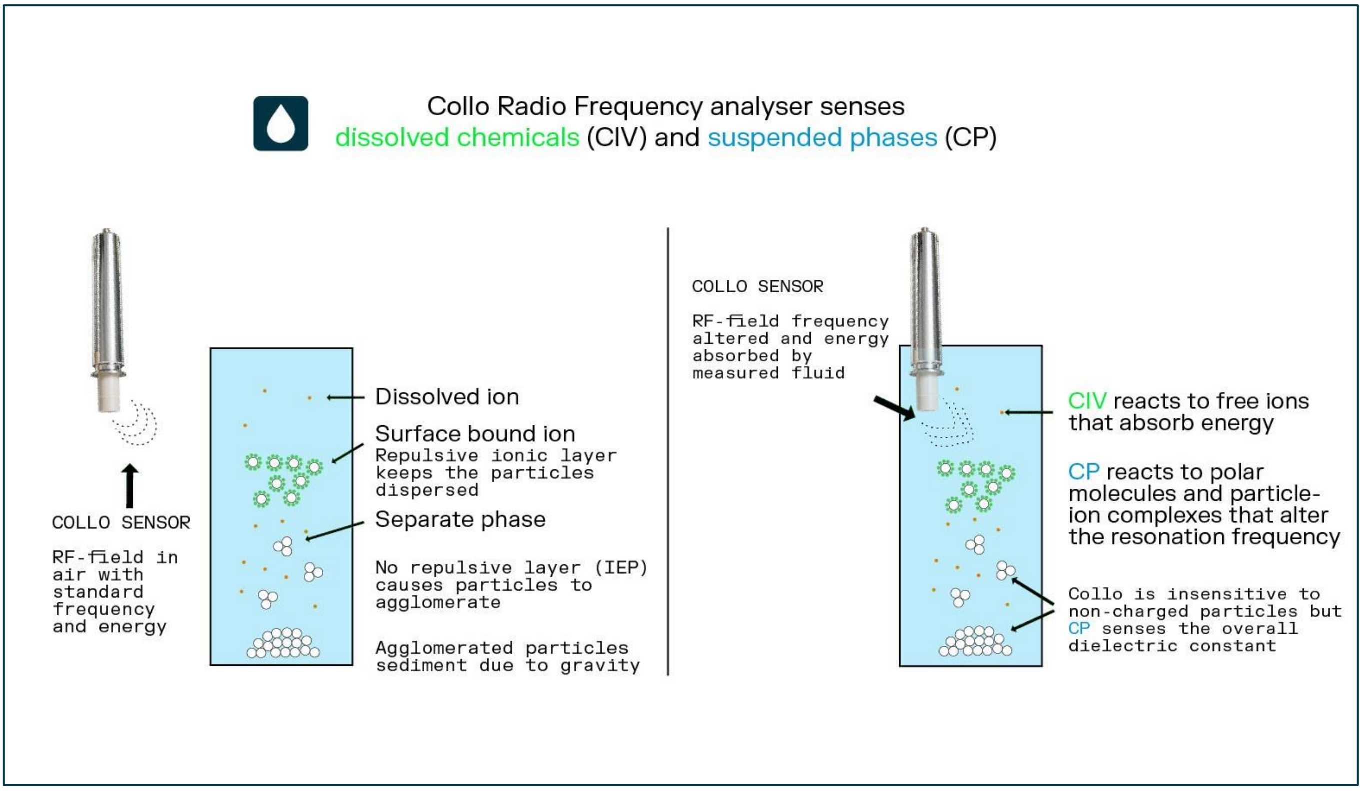

Figure 2 Measuring principle of Collo. On the left: a liquid sample with free ions, particle-ion complexes and non-charged particles. On the right: Collo inserted in the liquid to monitoring the changes in dissolved free ions and suspended particle-ion complexes.

At the heart of Collo's system is a custom-built resonator that operates in the radio frequency (RF) range. This resonator emits an electromagnetic field into the liquid. As the field interacts with the particles and molecules within, it is altered in predictable ways. Collo detects these changes and translates them into clear parameters that update continuously as the liquid's properties shift.

In simple terms, the RF field injects a small amount of energy into the process fluid. Some of this energy is absorbed or dispersed by dissolved or suspended (non-dissolved) matter, and the degree of this interaction reveals the material's dielectric properties — producing a unique, real-time fingerprint for each condition.

Collo captures the fingerprint using two parameters of Complex Permittivity

Complex permittivity (ε^*) is a frequency-dependent function with real (ε') and imaginary components [13]:

(ε''): $\varepsilon^* = \varepsilon' - j\varepsilon''$

Collo Permittivity (CP) — correlates with the real part of the dielectric constant.

CP measures how easily energy passes through the material at a given frequency. Highly polar liquids store more of the RF field energy i.e. they interact more with the field and thus have a higher CP.

CP is particularly sensitive to the physical structure of the liquid — including phase changes, emulsion or dispersion concentration, particle size, and overall stability.

Collo Ion Viscosity (CIV) — correlates with the imaginary part of the dielectric constant.

CIV shows how much energy is lost as charge carriers (ions, molecules) move within the RF field. Lower levels of charge carriers mean lower CIV.

CIV is highly sensitive to chemical composition changes — for example, shifts in ionic content, surface charges of particles, or the presence of impurities.

By analyzing these two dimensions together, Collo offers deeper insight than traditional single-variable probes. Each liquid's electromagnetic response forms a distinctive pattern — or fingerprint — that can be visualized in a plot, where different products, phases, or process states appear as unique clusters.

This multivariable fingerprint is visualized in a plot (such as Figure 3 and Figure 4) where each product or condition forms a distinct cluster based on its spectral features — since the measurement takes place in RF-spectrum even opaque changes or non-transparent liquids or flowing liquids can be analyzed.

2. CP and CIV as Quantities

To make Collo's measurements meaningful and comparable across different liquids, a simple baseline calibration is used during manufacturing:

- **Paraffin oil** is set to CP 10 and CIV 10. It has few charge carriers and low polarity, so it represents the low end of the scale for both parameters.
- **A solution of Potassium Chloride** (10 wt.%) in distilled water is set to CP 1000 and CIV 1000. It contains freely moving ions and is highly polar, placing it at the high end of the scale.

All process liquids will fall between these two reference points. Figure 3 shows an example fingerprint plot with a CP-CIV. For example, when small amounts of sodium chloride are added to a base liquid, they increase the ion content. A 1 PPM addition of sodium chloride shifts the CIV by about one unit within the 0–100 PPM range, demonstrating how sensitive Collo is to low-level changes in chemical composition.

This scale is aimed at helping operators interpret the magnitude of the change in CP or CIV in practice — whether they are monitoring phase shifts, contamination, or recipe deviations.

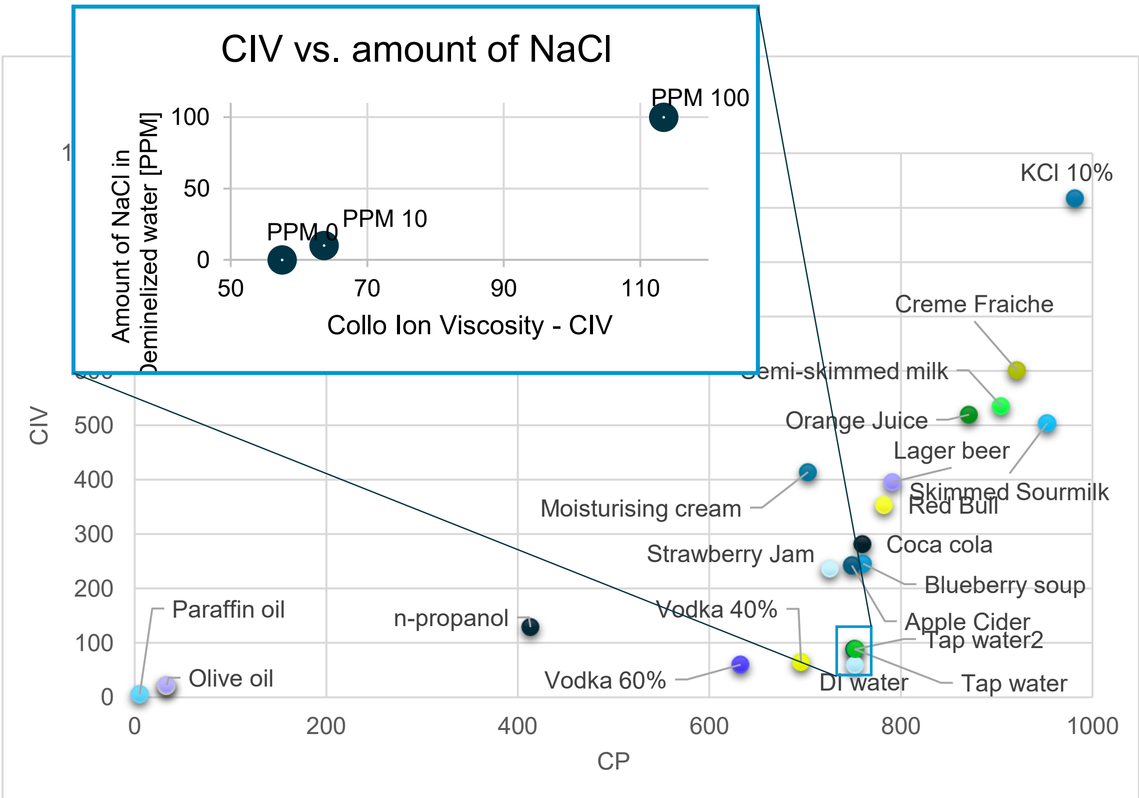

Figure 3 Fingerprint map with a zoom to water and saline solutions.

2.1 Extended Fingerprint

Beyond the two main parameters — Collo Permittivity (CP) and Collo Ion Viscosity (CIV) — the Collo system also calculates six additional variables: T1–T3 and Z1–Z3. These auxiliary parameters are derived in real time from the same RF field data.

The Z parameters are partly influenced by CP, while the T parameters are related to CIV. In practical monitoring, analysis should begin with CP and CIV as they provide the clearest overall insight into dielectric behavior. However, the auxiliary variables can add value, especially in experimental or challenging applications where one of them may show better resolution or less measurement noise for a specific phenomenon.

When Collo's AI builds a custom conversion model to predict a customer's process variable — for example, concentration or phase stability — the algorithm uses the entire fingerprint, combining CP, CIV, and all six additional variables. This multivariable approach improves robustness and accuracy for real-world processes.

2.2 Impact of Temperature

Temperature affects a liquid's dielectric behavior because both ionic activity and the speed of molecular polarization increase as temperature rises. This causes the measured fingerprint to shift: the imaginary part (related to ionic conductivity) typically increases, while the real part (related to permittivity) may decrease slightly for highly polar liquids as they move easier i.e. less energy is needed to turn the polar molecules. [14–16] It's important to understand that this temperature sensitivity is not a defect or error — it's simply how the physics of the liquid works.

Collo comes with a built-in thermometer and a standard temperature compensation model that works well for most liquids and operating conditions. This basic compensation helps remove normal temperature effects so operators can focus on meaningful process changes instead of thermal effect.

If a specific liquid needs to be measured with very high precision — for example, for tight compliance or research applications — a custom temperature compensation can be created and calibrated in the lab to match that product's exact behavior. This ensures Collo remains stable, repeatable, and trusted under all real-world conditions.

3. Using the Fingerprint in Analysis

Collo's liquid fingerprinting gives a versatile toolkit for both identifying and quantifying process changes.

a) Every liquid produces a unique fingerprint — like a signature — that can be stored as a reference. This means you can compare the live fingerprint to the stored one to check whether the liquid in the process matches the expected state or product (Figure 4 A). In practice, this lets you verify product consistency or detect changes, such as contamination, phase separation, or an unexpected shift in composition. Because the fingerprint updates in real time Collo can also be used to monitor dynamic events (Figure 4 B) like reaction endpoints, phase transitions, or gradual buildup of unwanted substances.

b) When the liquids under analysis are known, these changes can be quantified. For example, Collo can calculate the mixing ratio of two liquids based on their distinct fingerprints. In the example graph (Figure 4 C) fingerprints for Liquid A and Liquid B are shown. By applying data-analytical methods, including machine learning, Collo converts this information into a real-time concentration signal (Figure 4 D)

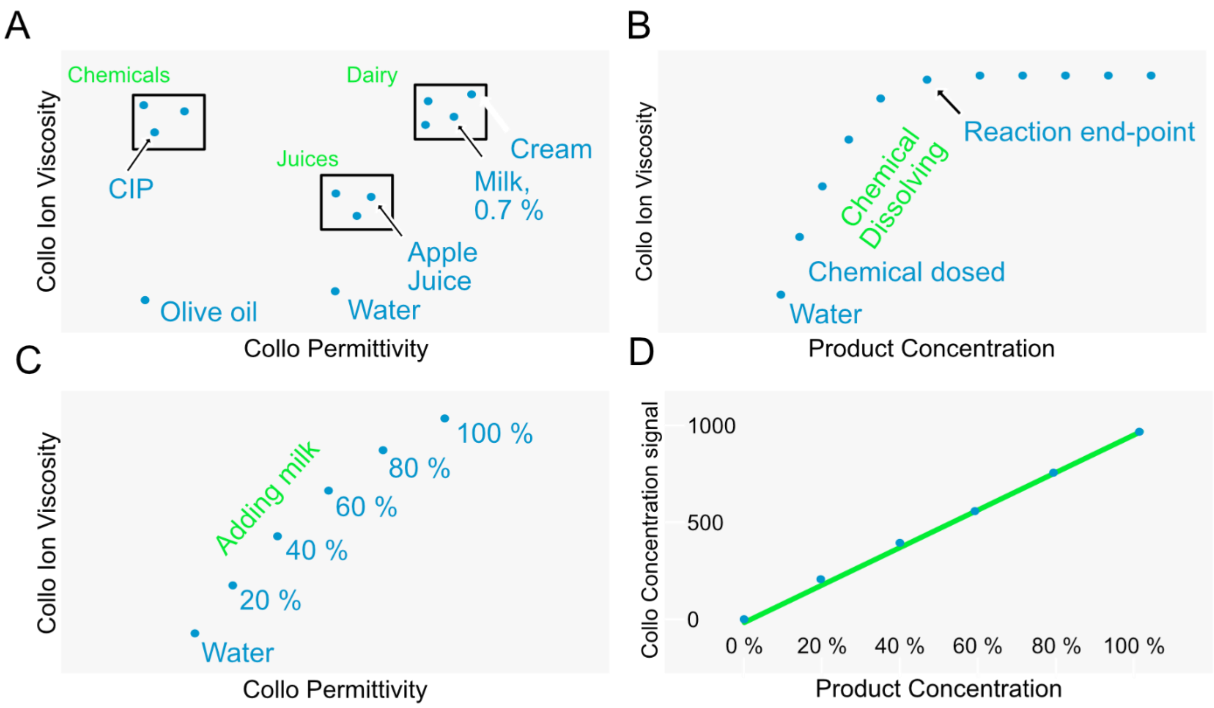

Figure 4 A) A Generic Fingerprint Plot. B) Dynamic change, CIV vs. Time to detect reaction endpoint. C) Fingerprints of water, cream and their mixtures D) Concentration algorithm vs. cream-to-water dilution samples.

Converting the fingerprint into a customer-specific variable — like concentration, purity, or blend ratio — relies on advanced data analysis techniques. This typically involves teaching the system how the fingerprint behaves across different process conditions. With support from Collo's data team:

- Using an existing fingerprint library for similar products (steps 1, 3, and 4 in Figure 5).
- Creating a new, liquid-specific fingerprint dataset experimentally (steps 1–4 in Figure 5).
- If temperature varies during the process, its impact can also be accounted for during this training period to ensure that the final algorithm stays accurate.

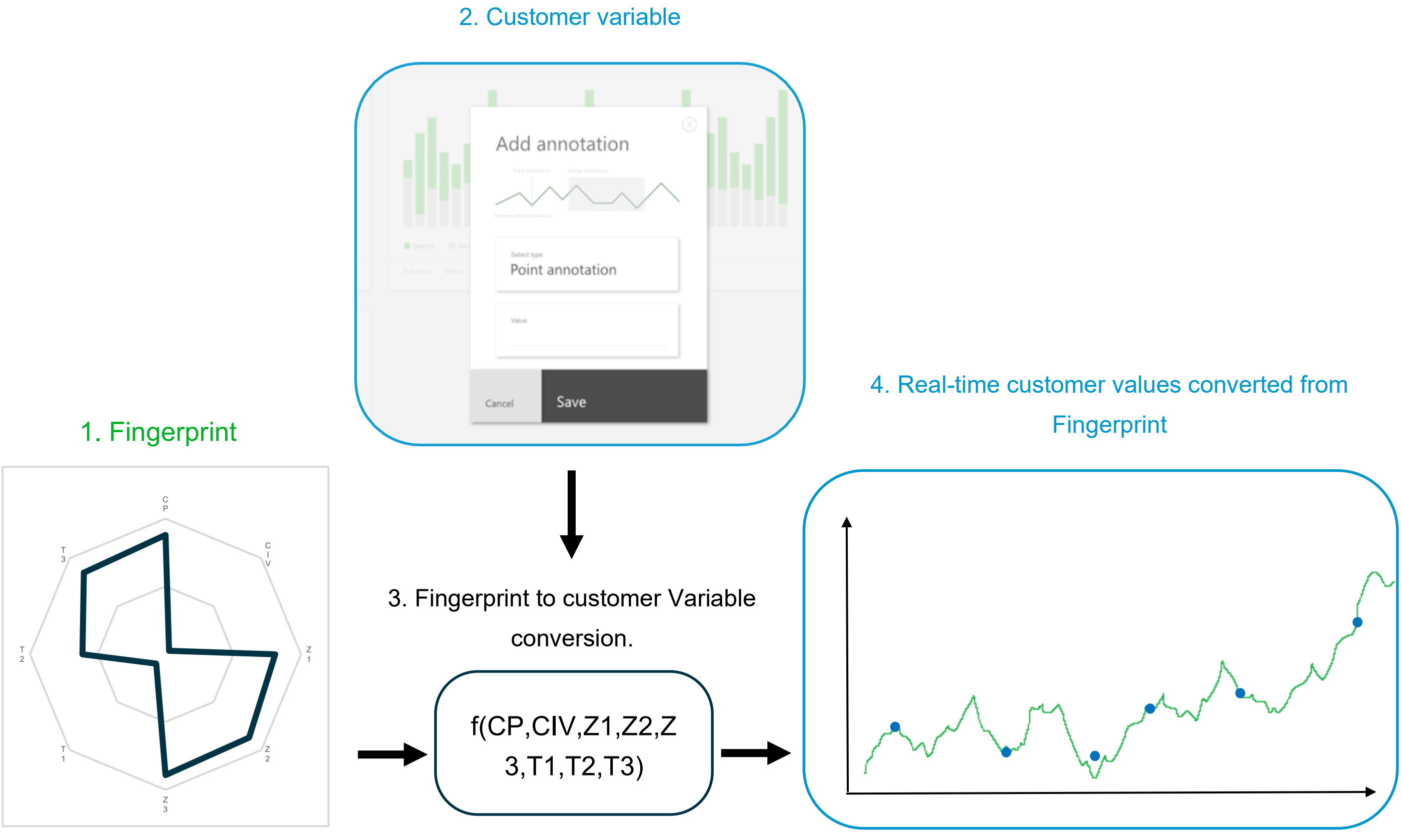

Figure 5 Converting the Fingerprint into a customer variable.

This approach turns Collo into more than just a monitoring tool — it becomes a real-time process control asset that converts complex dielectric data into precise, actionable production insights. For example, in dairy processing, Collo's resonator is used during pushout operations to monitor the transition between water and milk in pipelines. As the dielectric properties of water and milk differ significantly, Collo can precisely detect the interface and convert the fingerprint values into water-to-milk ratio in real time. This enables producers to minimize product losses and optimize product recovery without relying on manual sampling. Similarly, during clean-in-place (CIP) operations, Collo detects changes in the dielectric properties of cleaning fluids, allowing it to quantify acid or caustic concentrations in water. This enables the optimization of rinse cycles to save time and resources.

4. References

[1] C. J. F. Böttcher, O. C. van Belle, P. Bordewijk, and A. Rip, *Theory of Electric Polarization*, 2nd ed., Vols. 1 & 2. Amsterdam, Netherlands: Elsevier, 1973 & 1978.

[2] A. von Hippel, Ed., *Dielectric Materials and Applications*. Cambridge, MA, USA: MIT Press, 1954.

[3] H. Frohlich, *Theory of Dielectrics*, 2nd ed. Oxford, U.K.: Oxford Univ. Press, 1958.

[4] A. P. Gregory and R. N. Clarke, "A review of RF and microwave techniques for dielectric measurements on polar liquids," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 13, no. 4, pp. 727–743, Aug. 2006, doi: 10.1109/TDEI.2006.1667730.

[5] N. A. Andrushchak, I. D. Karbovnyk, K. Godziszewski, Y. Yashchyshyn, M. V. Lobur, and A. S. Andrushchak, "New interference technique for determination of low loss material permittivity in the extremely high frequency range," *IEEE Transactions on Instrumentation and Measurement*, vol. 64, no. 11, pp. 2945–2952, Nov. 2015, doi: 10.1109/TIM.2015.2437631.

[6] M. Järveläinen, Towards In Situ Methods for Characterization of Porous Materials, Tampere: Tampere University of Technology, 2016.

[7] T. Salpavaara, Inductively Coupled Passive Resonance Sensors: Readout Methods and Applications, vol. Publication 1524, Tampere: Tampere University of Technology, 2018.

[8] T. Salpavaara, M. Järveläinen, S. Seppälä, T. Yli-Hallila, J. Verho, M. Vilkko, J. Lekkala, and E. Levänen, "Passive resonance sensor-based method for monitoring particle suspensions," Sensors and Actuators B: Chemical, vol. 219, pp. 324–330, Nov. 2015, doi: 10.1016/j.snb.2015.04.121.

[9] M. Järveläinen, T. Salpavaara, S. Seppälä, T. Roinila, T. Yli-Hallila, E. Levänen, and M. Vilkko, "Characterizing porous ceramics by frequency-response method," in *Proc. 19th IFAC World Congress on International Federation of Automatic Control*, Cape Town, South Africa, Aug. 24–29, 2014, IFAC-PapersOnLine, vol. 19, pp. 10012–10017.

[10] J. Silvonen, N. Järvelä, M. Kopponen, M. Järveläinen, A. Ojuva, and E. Levänen, "Online monitoring of polysaccharide solution concentration by electromagnetic field, electrical conductivity and spectrophotometry measurements," *Chemical Papers*, vol. 75, no. 11, pp. 5885–5894, Nov. 2021.

[11] S. Zakeri, M. Järveläinen, and E. Levänen, "In-line monitoring of ceramic resins used in stereolithography via high-frequency dielectric analysis," in OSA Technical Digest, OSA Optical Sensors and Sensing Congress 2021 (AIS, FTS, HISE, SENSORS, ES), paper AM2D.2, Optica Publishing Group, 2021.

[12] N. Järvelä, *Kolloidisten suspensioiden analysointilaitteen vasteen lämpötilakompensointi*. M.Sc. thesis, Faculty of Engineering Sciences, Tampere University of Technology, Tampere, Finland, 2017. [Online]. Available: https://urn.fi/URN:NBN:fi:tty-201703281231

[13] F. Kremer and A. Schönhals, *Broadband Dielectric Spectroscopy*. Berlin, Germany: Springer, 2003. doi: 10.1007/978-3-642-56120-7

[14] P. Debye, Polar Molecules. New York, NY, USA: Dover Publications, 1929.

[15] A. C. Metaxas and R. J. Meredith, Industrial Microwave Heating. London, U.K.: Peter Peregrinus Ltd., 1983.

[16] J. B. Hasted, Aqueous Dielectrics. London, U.K.: Chapman and Hall, 1973.