Flexible and Reproducible RF Calibration using Google Cloud Workflows

Yunus Emre Keleş
Department of Computer Engineering
Middle East Technical University
06800 Ankara, Türkiye
keles.emre@metu.edu.tr

Anil Cetinkaya
Department of Computer Engineering
İskenderun Technical University
31200 Hatay, Türkiye
cetinkaya@ceng.metu.edu.tr

M. Cagri Kaya
Department of Computer Science and Engineering
Chalmers University of Technology
SE-41296 Gothenburg, Sweden
cagri.kaya@chalmers.se

Halit Oğuztüzün
Department of Computer Engineering
Middle East Technical University
06800 Ankara, Türkiye
oguztuzn@ceng.metu.edu.tr

***Abstract*—Radio frequency measurement device calibration is a critical but often complex multi-step process in metrology. Traditional approaches can be manual and lack standardization, hindering efficiency and reproducibility. This study addresses these challenges by proposing and demonstrating an automated RF calibration process orchestrated by workflow management systems. Google Cloud Workflows is selected for proof of concept of the suggested approach. The methodology involves defining a serverless workflow that manages the sequential invocation of external services for measurement data acquisition and subsequent uncertainty calculation. The results confirm the successful execution of this workflow, including robust input validation, correct data transfer between services, and effective error management. This research validates workflow orchestration platforms as viable tools for automating and simplifying RF calibration procedures, thereby enhancing reproducibility, reducing manual intervention, and contributing to the broader digitalization efforts in metrology. The declarative nature of the workflow definition offers a transparent and maintainable solution for managing complex calibration logic and integrating distinct services.**

Keywords*—*microservices, software architecture, workflows, digitalization, industrial internet of things

I. Introduction

In the field of metrology, radio frequency (RF) measurement device calibration is a critical process that entails a number of interconnected processes, including the preparation of the measuring equipment for setup, data acquisition, uncertainty calculation, and the issuance of a digital calibration certificate (DCC). A DCC is a standardized, machine-readable document that digitally represents calibration results, ensuring data integrity, traceability, and interoperability. For purposes of maintaining metrology standards compliance and ensuring measurement output reliability, these processes need to be performed in a systematic and well-defined manner. However, managing such workflows in a way that is both adaptable to diverse laboratory setups and feasible to automate remains a challenge. The absence of a standard methodology for the description and realization of calibration workflows constrains the efficiency, traceability, and reproducibility of calibration processes [1], [2].

Accurate and reliable calibration is important for maintaining the validity of measurements in RF metrology. Traditional calibration methods often rely on rigid, manual processes that are difficult to standardize and transfer between laboratories. Since laboratories operate under various environments, with different devices and measurement conditions, there is a growing need for an adaptable and versatile approach to define and manage calibration workflows.

A structured and configurable workflow specification can increase efficiency, traceability, and reproducibility in RF calibration as in other industrial operations [3], [4]. By enabling laboratories to define, modify, and execute calibration workflows in a standardized yet adaptable manner, it becomes possible to reduce human errors, improve consistency, and facilitate collaboration between metrology institutions [5]. Furthermore, automation of calibration processes can streamline operations, optimize resource utilization, and support compliance with metrology standards.

Previous research has examined the digital transformation of metrology processes to improve automation, scalability, and interoperability. Çetinkaya et al. [6] presented a cloud-based microservices architecture to manage uncertainty calculation and DCC generation in RF power measurements. They integrate various equipment types and communication technologies, enabling efficient data processing and standardization across different measurement techniques. Similarly, Oppermann et al. [7] proposed the Operations Layer (OP Layer), a distributed microservices architecture that aims to automate metrological processes within Physikalisch-Technische Bundesanstalt (PTB). The OP Layer supports the creation of DCCs while improving data availability, scalability, and security by connecting internal workflows to a central cloud-based infrastructure. These studies demonstrate the potential of cloud-based solutions and microservices architectures in modernizing calibration processes. However, a flexible and adaptable approach that can adapt to different laboratory environments while ensuring ease of configuration and execution remains essential.

This study aims to address these needs by leveraging workflow orchestration platforms to define and automate RF calibration processes. The suggested approach provides a systematic way to orchestrate calibration procedures, ensuring that workflows can be easily adapted to different laboratory setups while maintaining accuracy and reliability, which simplifies user tasks and automates key processes. Google Cloud Workflows (GCW) was selected for its convenience to authors, enabling them to directly define and execute RF calibration procedures. Leveraging the capabilities of GCW, tasks such as measurement setup, data acquisition, uncertainty calculations, and DCC generation can be orchestrated in a structured and automated manner. Workflow definitions, typically expressed in formats like JSON or YAML compatible with GCW, allow for a clear and flexible representation of these complex calibration sequences. The Google Cloud infrastructure ensures the scalable and efficient execution of these workflows, handling task organisation and execution in a robust cloud-based environment. This system will process these workflow specifications, validate their structure where applicable, and execute tasks in a predefined order. It will enable the integration of various calibration-related functions while maintaining adaptability to different laboratory requirements.

This research provides a structured approach to defining and managing RF calibration workflows using GCW, improving efficiency, traceability, and reproducibility in metrology processes. It will enable flexible workflow adaptation to different laboratory environments, reducing manual effort and minimising errors. Additionally, the approach supports collaboration between calibration laboratories by allowing for workflow sharing and standardisation. This, in turn, leads to improved reliability, reproducibility, and traceability of RF metrology practices.

II. Related Work

The digitalization of metrology is transforming calibration practices, aiming to increase efficiency, reduce manual intervention, and enhance data traceability. Traditional calibration workflows, often reliant on paper-based certificates and manual data handling, are being replaced by automated, standardized, and cloud-based solutions that support scalable and interoperable operations [8].

Recent work has explored various architectures to support this transformation. Coelho et al. developed a methodology to automate a previously manual flowmeter calibration procedure using simple digital tools [9]. They demonstrate that even without complex cloud services, automating individual calibration tasks (like data acquisition) can greatly enhance efficiency.

In another work, Oppermann et al. [7] proposed the "Operation Layer" at PTB as a cloud-native infrastructure that employs microservices and REST APIs to integrate and manage metrology services. This approach breaks down data silos and enables complete workflows, including the generation of DCCs, with scalability ensured through Kubernetes. Cetinkaya et al. [6] extended this concept by migrating calibration components to the cloud as microservices, transforming their earlier desktop-based AutoRFPower tool [10] into a modular, scalable platform. Their implementation, based on an enhanced Internet of Measurement Things (IoMT) architecture, includes support for systematic variability, access control, and device compatibility using a Textual Variability Model (TVM). It also incorporates a CI/CD pipeline and supports multiple uncertainty computation methods, demonstrating cloud viability for precision metrology.

Central to these systems is the DCC—a standardized, machine-readable certificate (often in XML format) that ensures traceability, automation, and interoperability across digital systems [11], [12], [13]. Both Oppermann and Cetinkaya integrate DCC generation into their workflows, including features like UUID-based document authentication and QR code verification.

While microservice-based systems inherently offer some orchestration capabilities (e.g., through Kubernetes), they generally lack dedicated high-level workflow management. This gap has led to interest in tools like GCW—a serverless orchestration engine that manages sequences of API-driven operations across cloud services [14]. Unlike lower-level container orchestration, GCW provides a declarative way to define business logic, error handling, and inter-service communication without managing infrastructure.

Commercial calibration software also supports automation to varying extents, often focused on scheduling, asset tracking, and certificate management. However, such platforms may lack the flexibility to integrate seamlessly with bespoke lab automation or programmable workflow tools.

Building on this foundation, our work explores the use of GCW as a dedicated orchestration layer for automating RF calibration processes. By coordinating tasks such as device setup, data collection, uncertainty analysis, and DCC issuance, we aim to deliver a maintainable and reproducible calibration pipeline tailored for cloud-native environments.

Alternative workflow orchestration platforms exist across various cloud providers, such as AWS Step Functions [15] and Azure Logic Apps [16]. Implementing with these alternatives would yield benefits comparable to those offered by GCW. However, as the core contribution of this work lies in automating the calibration process workflows, the most convenient tool for the authors was selected for implementation. Therefore, a comparison of different tools is not within the scope of this work. Besides, GCW was selected due to its declarative syntax, native integration with Google's serverless microservices, and its cost-effectiveness in and research-oriented projects.

III. Methodology

The proposed methodology builds upon the microservice-based architecture introduced in [17], by incorporating GCW to enable end-to-end automation and orchestration of the RF calibration process. Figure 1 presents an expanded view of the overall architecture, highlighting the integration of serverless workflows with the existing cloud-native components. This extension captures not only the microservices responsible for measurement and uncertainty quantification but also illustrates their coordinated invocation through declaratively defined workflows.

Unlike the original system, where API interactions were manually triggered or loosely coupled through client-side logic, the updated architecture introduces an orchestrated

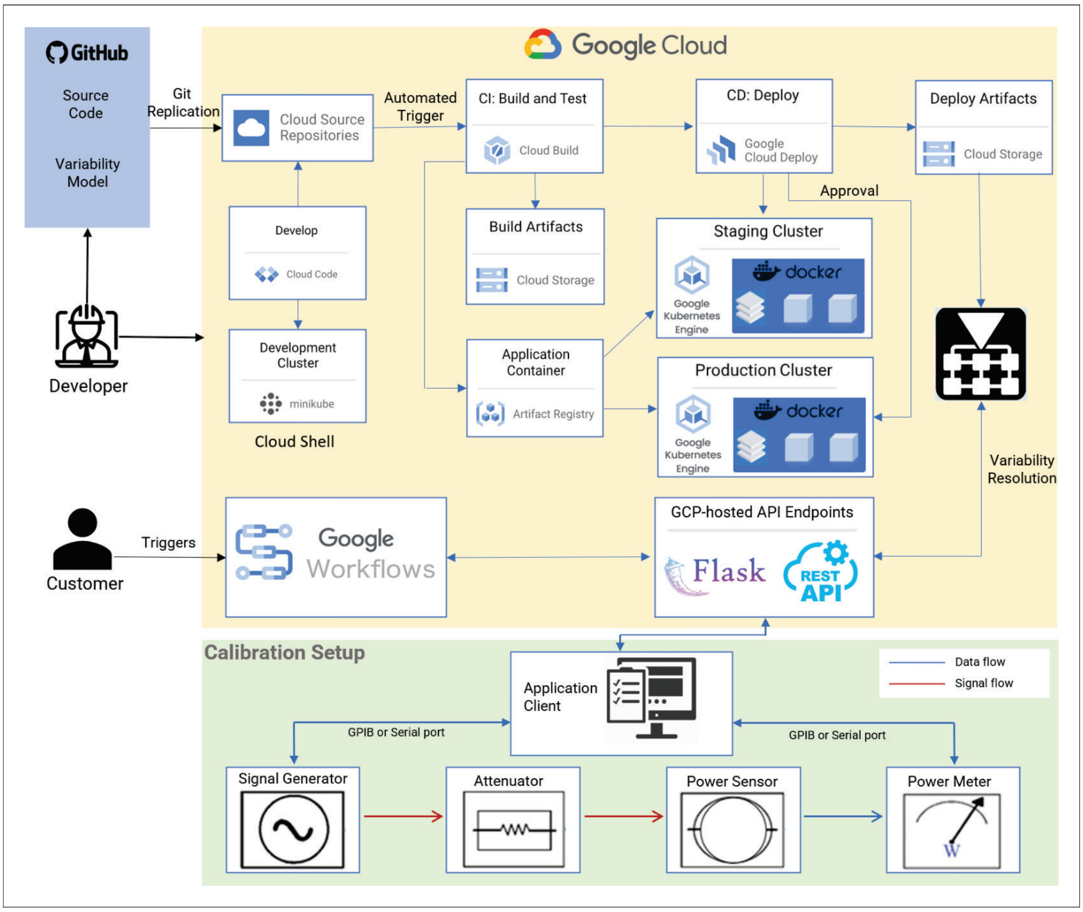

Fig. 1: Overall microservice architecture with workflows and CI/CD pipelines.

control plane using GCW. These workflows serve as the backbone of process automation, enabling a clear, transparent, and maintainable execution model that governs service-to-service communication, data handoff, error handling, and sequential task execution. The architectural improvements also preserve the previously established CI/CD pipeline, which automates the deployment of microservices upon updates to the source configuration or the variability model. By combining orchestration and continuous integration, the system achieves a higher level of automation, traceability, and reproducibility, which are critical for digital transformation in metrology.

This section details the implementation of these enhancements and describes how the workflow-driven methodology simplifies the RF calibration process by coordinating the interactions between external APIs, validating inputs, managing calibration state, and enforcing measurement logic embedded within the digital infrastructure.

We employ GCW, a serverless orchestration service, to automate the RF calibration process. Workflows are defined declaratively in YAML or JSON. Also, GCW was chosen for its ability to reliably integrate services, manage state, and handle errors without requiring any underlying infrastructure management.

The core of our methodology is a defined workflow that automates the RF calibration procedure by interacting with two key external API endpoints: one to perform the measurement and the other to calculate the uncertainty. The workflow is designed to be triggered with a set of input parameters detailing the calibration setup.

A. *Workflow Definition and Execution*

Figure 2 demonstrates a sample workflow that is defined for a process starting with conducting measurements on a RF power measurement setup consisting of a signal generator, an attenuator, a power sensor and a power meter. After the measurements are gathered from the test setup, the process automatically continues with the quantification of uncertainty calculations and finally ends with the creation of a DCC. The realization of such a setup is presented in Figure 3.

Upon invocation, the workflow initializes necessary variables, such as API network addresses, and performs a critical input validation. It checks for all essential parameters, including measurement settings and device details. If any mandatory information is missing, the workflow immediately enters an error handling step, returning a 400 status code with a specific error message.

The workflow is configured to interpret semantic tags that define the uncertainty model to be applied during the calibration process. It determines whether the uncertainty evaluation should rely on linear parameters such as the Reflection Coefficient Index (RCI) or on vectorial parameters such as those derived from the Standing Wave Ratio (SWR) present in device calibration certificates, depending on the measurement configuration. These model selection tags guide the workflow in orchestrating the appropriate uncertainty calculation technique, specifically by invoking either the Law

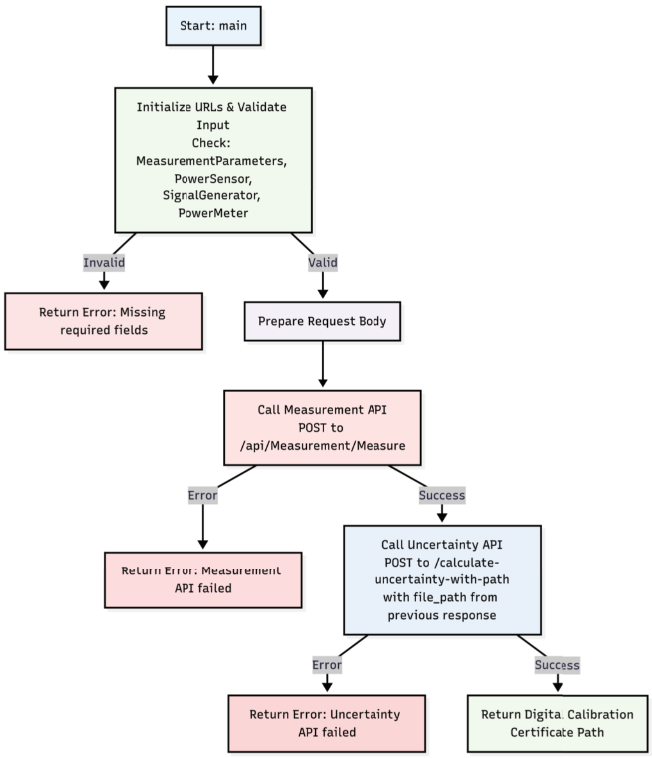

Fig. 2: The implemented workflow (simplified)

of Propagation (LoP) or Monte Carlo Simulation (MCS) methodologies. The selected computational pathway subsequently determines the structure and numerical content of the DCC, which reflects both the chosen uncertainty model and the metrological assumptions embedded within the calibration scenario. The selected computational pathway determines the structure and numerical content of the DCC.

After successful validation, the workflow constructs a detailed JSON payload from all relevant input parameters and dispatches it to the Measurement API via an HTTP POST request. The workflow then checks the response's status code, transitioning to an error-handling routine if a failure is detected. Upon a successful call, it captures the returned file path, which points to the stored measurement data, for use in the subsequent phase.

Using the file path obtained from the successful execution of the Measurement API, the workflow then orchestrates the uncertainty calculation. It prepares a new JSON data payload containing this file path.

An HTTP POST request is made to the designated Uncertainty Calculation API address with this new payload. Given that uncertainty calculations can be computationally intensive, a longer timeout of 900 seconds is configured for this second API call. The response from the Uncertainty Calculation API is stored for the final step.

Similar to the first API call, the workflow checks the status code of the uncertainty calculation response. If an error is detected (status code 400 or higher), the workflow branches to a dedicated error handler. If this call is successful, the body of the response, which presumably contains the results of the uncertainty calculation, is returned as the final output of the entire workflow.

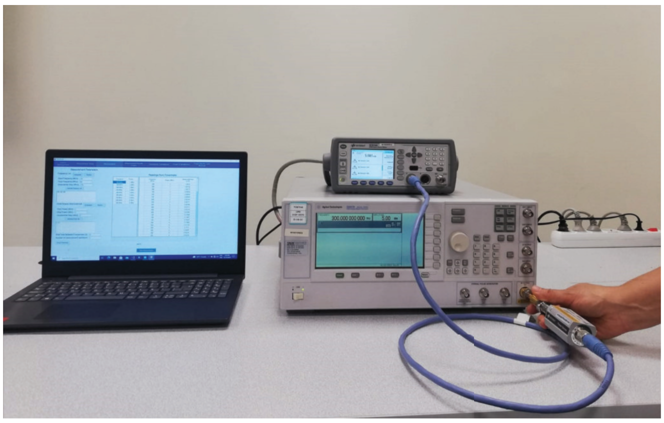

Fig. 3: An example of a realized RF power measurement setup.

B. Data Flow and API Interaction

The workflow manages the flow of data between its steps and the external APIs. Input data, consisting of calibration device details and measurement parameters, is provided in JSON format when the workflow is invoked. This data is then transformed and used to construct JSON request bodies for the HTTP POST calls to the external Measurement and Uncertainty Calculation APIs.

The first API, responsible for measurements, is expected to perform the physical measurement or data acquisition and return a string representing a file path. This file path acts as the crucial piece of data linking the first part of the process to the second.

The second API, for uncertainty calculation, consumes this file path (sent within a JSON structure) to access the necessary measurement data and perform the uncertainty calculations. The final output of the workflow includes a machine-readable DCC.

C. Error Handling

The workflow uses error handling at multiple stages:

- Input Validation: Missing parameters trigger a JSON error response with a 400 status code.
- Measurement API: Failures (status $\geq$400) return a JSON error containing the status code and API response for easier diagnosis.
- Uncertainty API: Similar handling provides targeted troubleshooting data for the uncertainty service.

This structured error handling ensures that failures are caught and reported informatively. Beyond basic error detection, GCW supports advanced fault-tolerance strategies such as *automatic retry policies with exponential backoff and jitter*. These can be configured per step to re-attempt failed API calls in the event of transient issues like network instability or service unavailability. While the current implementation focuses on explicit error propagation and logging, future workflow versions will incorporate conditional retry logic, timeout customization, and alternative endpoint fallback mechanisms to improve reliability. Such fault-tolerance enhancements are particularly important in production deployments where consistent uptime and autonomous recovery are essential.

GCW acts as the orchestrator, ensuring these services are called in the correct sequence and that data is passed appropriately between them.

IV. Results

The implementation of the RF calibration process using GCW, as detailed in the Methodology section, yielded a successfully operational automated system. The workflow was deployed and tested by invoking it with representative input parameters, simulating a typical RF calibration scenario.

Upon execution, the workflow consistently demonstrated its ability to orchestrate the defined sequence of operations. The initial input validation step correctly identified the presence of all required parameters and appropriately handled flags by assigning default values when not provided. This ensured that the workflow proceeded with a valid and complete set of configuration data.

The first major phase, Measurement Process Automation, was successfully executed. The workflow correctly constructed the JSON payload from the input parameters and dispatched it to the designated Measurement API. The API call was observed to complete within the configured timeout period. In successful test runs, the Measurement API returned a response containing a file path, which the workflow correctly captured. This file path, representing the location of the stored measurement data, was then reliably used as input for the subsequent phase.

The second major phase, Uncertainty Calculation Process, also demonstrated successful orchestration. The workflow utilized the file path obtained from the Measurement API to construct a new JSON payload for the Uncertainty Calculation API. This API was invoked, and in successful test runs, it processed the data from the provided file path and returned a response containing the uncertainty calculation results. The workflow then successfully returned this final response as its output, fulfilling the end-to-end process.

The workflow successfully orchestrated the two major phases of the process: Measurement Automation and Uncertainty Calculation. It correctly constructed and dispatched the necessary data to the Measurement API, which returned a file path to the measurement results. The workflow seamlessly used this file path to invoke the Uncertainty Calculation API, which processed the data and returned the final uncertainty results. The workflow successfully delivered this response as its final output, fulfilling the end-to-end process.

The error handling mechanisms were tested by simulating error conditions, such as providing incomplete input parameters or simulating an error response (HTTP status code 400 or higher) from one of the external APIs. In these scenarios, the workflow correctly identified the error condition and returned the appropriate error message and status code, as defined in the error handling routines. This confirmed the robustness of the workflow in managing and reporting operational failures.

The final response from the Uncertainty Calculation API included computed uncertainty values and a machine-readable DCC (XML format). This DCC is structured according to the PTB DCC Schema 2.0, aligning with ISO/IEC 17025. The system provides a secure link to a rendered PDF version of the DCC. This final step completes the automated calibration pipeline, validating successful end-to-end RF calibration and certification.

V. Discussion

The successful implementation and execution of the RF calibration process orchestrated by GCW, as presented in the Results section, demonstrate a significant step towards more flexible, automated, and reproducible calibration procedures in metrology, culminating in the generation of standards-compliant DCCs. This approach effectively addresses the challenges of managing complex, multi-step operations involving disparate services, a common scenario in modern calibration laboratories.

The primary significance of these results lies in the validation of GCW as a viable and effective tool for high-level process orchestration in a metrology context. While existing solutions, such as those proposed by Oppermann et al. [7] and Cetinkaya et al. [6], focus on comprehensive microservice architectures for managing calibration data and services, this study specifically highlights the utility of a dedicated serverless workflow engine. GCW complements such microservice-based approaches by providing a clear, declarative way to define the logic that connects these services, without the overhead of managing the orchestration infrastructure itself. For instance, where Cetinkaya et al. [6] utilize Kubernetes for orchestrating their containerized microservices, our approach shows how GCW can manage the higher-level business logic that invokes such services, potentially including those hosted on Kubernetes or other platforms.

A key advantage demonstrated is the simplification of complex process logic. The workflow's ability to sequentially invoke the Measurement service and then the Uncertainty Calculation service, ensuring proper data handoff between them, and managing conditional logic showcases the power of a dedicated orchestration tool. This declarative approach, using YAML for workflow definition, makes the calibration process more transparent and easier to maintain or modify compared to embedding such logic within individual service components or custom scripts. The built-in error-handling capabilities of GCW, tested in this study, offer inherent robustness to the overall process, which is crucial for reliable calibration operations.

Compared to traditional manual or semi-automated calibration processes, the implemented workflow significantly reduces the potential for human error in sequencing tasks and transferring data. It also enhances reproducibility, as the workflow definition ensures that the same sequence of operations is followed for every execution with given inputs. This aligns with the broader goals of digitalization in metrology, aiming for greater consistency and traceability, as also emphasized by the work on DCCs [11], [13].

However, certain limitations and considerations arise from this approach. The current implementation relies on the availability and correct functioning of two external, custom-developed APIs for measurement and uncertainty calculation. The performance and reliability of the overall workflow depend on these external services. While the workflow includes error handling for API failures, the root cause of such failures would lie outside the workflow itself. Future enhancements could involve more sophisticated error recovery strategies within the workflow, such as conditional retries with backoff, or invoking alternative services if primary ones fail, capabilities that GCW supports.

Another aspect to consider is external API management. While the workflow orchestrates their interaction, their development, deployment, and maintenance are separate concerns. For a complete end-to-end automated solution, robust CI/CD pipelines and monitoring would be necessary for these API components, similar to Cetinkaya et al.'s [6] microservices CI/CD pipeline. Furthermore, while the workflow handles the orchestration, the complexity of device interaction for measurement and the intricacies of uncertainty calculation algorithms are encapsulated within the external APIs. This modularity is an advantage, but it also means that the adaptability of the system to different calibration scenarios or equipment depends heavily on the flexibility of these external APIs. The current workflow passes parameters to these APIs; a more advanced setup might involve the workflow dynamically selecting different API endpoints or versions based on the input parameters, further enhancing adaptability.

The use of a file path as the intermediary data between the two API calls is a practical solution but might introduce dependencies on a shared file system or storage mechanism that both APIs can access. In a more distributed or cloud-native architecture, passing data via other mechanisms, such as direct data payloads (if feasible for size) or through managed messaging queues or cloud storage events, could also be considered to further decouple the services.

Despite these considerations, the study successfully demonstrates the utility of GCW for orchestrating a core metrology process. It offers a scalable, serverless approach that can simplify the automation of complex, multi-step procedures, reduce manual intervention, and improve the reliability and traceability of RF calibrations. This approach provides a valuable alternative or complementary layer to existing microservice architectures in the field.

VI. Conclusion

This study successfully demonstrated the application of GCW for orchestrating a multi-step RF calibration process. The developed workflow effectively managed the sequence of operations, including input validation, invocation of external measurement and uncertainty calculation services, and data handoff between these services. The results confirm that GCW provides a robust and serverless solution for automating complex calibratioEarphonesn procedures, thereby enhancing efficiency, reproducibility, and traceability in metrology.

The declarative nature of the workflow definition simplifies the management and modification of the calibration logic. By leveraging a dedicated orchestration service, this approach reduces the potential for manual errors and provides a clear framework for integrating various components of a calibration system. The inherent error-handling capabilities of GCW further contribute to the reliability of the automated process.

While the current implementation relies on specific external APIs, the principles demonstrated are broadly applicable. This work contributes to the ongoing efforts in digitalizing metrology by showcasing a practical method for automating calibration workflows. It serves as a valuable alternative or complement to existing microservice architectures by focusing on the high-level orchestration of processes.

Future work could explore the integration of more sophisticated error recovery mechanisms, dynamic service selection based on calibration parameters, and alternative data transfer methods between orchestrated services to enhance the system's flexibility and resilience. Additionally, extending this workflow to incorporate the automated generation and management of DCCs would represent a significant advancement towards a fully digital and automated metrology ecosystem.

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