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Checking Traceability by Analyzing DCC Blockchain Transactions

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***Abstract* – Traceability is essential in metrology, linking measurement results to primary standards through documented calibration chains. While blockchain ensures secure, immutable storage of Digital Calibration Certificates (DCCs), retrieving traceability paths remains complex. This paper proposes a method to reconstruct calibration traceability by analyzing blockchain transactions recorded in a private, permissioned network. We describe an architecture combining PHP-based asset management, LabVIEW DCC generation, and recursive graph analysis to extract calibration dependencies. Realistic scenarios illustrate the approach, demonstrating improved auditability, reduced reliance on physical certificates, and secure, decentralized traceability management that aligns with modern digital metrology requirements.**

I. INTRODUCTION

Metrological traceability, defined as the unbroken and documented chain of calibrations that links a measurement result to a reference standard, is a cornerstone of confidence in measurement systems [1]. Ensuring traceability is fundamental, not only for scientific reproducibility but also to industrial quality control, trade, legal metrology, and healthcare. Traditionally, this traceability chain has been maintained using physical or semi-digital calibration certificates stored in local metrology labs, or more often, in isolated, non-interoperable databases.

The recent digital transformation of metrology is oriented toward Digital Calibration Certificates (DCCs) and machine-interpretable representations of measurement metadata. Initiatives such as SmartCom [2], EMPIR 17IND02 (SmartCom project) [3], and the Digital SI framework proposed by the BIPM [4] emphasize the importance of using structured data standards (e.g., XML, JSON, RDF) to increase the automation, portability, and auditability of calibration information.

Despite these advances, the verifiability and long-term integrity of DCCs remain a problem, especially when data must be exchanged across organizational or national boundaries. In this context, blockchain technology, with its properties of distributed consensus, cryptographic immutability, and decentralized trust, has gained significant attention as a mean to prove calibration data in a much safer and transparent way [5]. Prior work, including our own system for blockchain-enabled calibration data management [6], has shown that calibration certificates can be securely registered on a proprietary blockchain network by referencing their content via cryptographic hashes and metadata, providing immunity to data manipulation and timestamping.

However, immutability alone does not equate to traceability. While blockchain ensures that data cannot be altered later on, it does not provide mechanisms to semantically connect and reconstruct the traceability chain from an instrument under test to its ultimate reference standard. This interpretive layer is essential in metrological contexts, where traceability must be demonstrated, verified, and validated, for example, during audits or regulatory inspections.

Several researches have explored the use of blockchain networks to record calibration activities in a tamper-resistant manner, thereby reinforcing the traceability of measurement results. Takatsuji et al. [7] introduced a blockchain-based system for visualizing the entire calibration chain, facilitating end-to-end traceability from measurement instruments to primary standards. Building on this concept, Takegawa et al. [8] proposed a traceability management system leveraging Ethereum smart contracts to allow users instant access to calibration data, thus improving transparency and reliability. Miličević et al. [9] further developed the idea of a digitally transformed traceability pyramid, underlining the role of blockchain in maintaining trust in hierarchical calibration structures. In a previous paper [6] we presented a system that automates the calibration workflow and records the DCCs in a private blockchain, claiming the possibility for ensuring the traceability. These advancements demonstrate the possibility of integrating blockchain technology into metrological infrastructures. The present paper addresses the problem of tracing and validating calibration dependencies across our private blockchain network, thereby enabling interpretable and verifiable metrological traceability.

II. BLOCKCHAIN NETWORK ARCHITECTURE

In a previous paper we implemented a dedicated blockchain network which integrates Digital Calibration Certificates (DCCs) into transactions.

The architecture employed is a private, permissioned blockchain network composed of several nodes, an application programming interface (API) layer and a web-based smart asset management platform. Each node functions as a decentralized server that stores a synchronized copy of the blockchain ledger, validates new transactions, and participates in the consensus protocol. Once a transaction is validated, it is recorded into a data block, which contains a hash of the previous block, a timestamp, and the transaction data. These blocks are chained together sequentially, forming a verifiable and unchangeable timeline of calibration events. The consensus mechanism is based on the X15 algorithm, which combines features from both Proof-of-Work (PoW) and Proof-of-Stake (PoS). This dual mechanism provides a balance between energy efficiency and security and the use of 15 chained hashing algorithms in the X15 model increases resistance to cryptographic attacks while allowing deployment even on less powerful platforms as Raspberry Pi 2.

The security and the traceability are further enhanced by the use of native blockchain wallets. These wallets provide full access to transaction history, monitoring, and asset management. The network operates over designated ports—peer-to-peer communication on port 10218 and remote procedure calls via port 20208—adding an additional layer of operational control.

For the integration of instrument calibration, a web-based asset management tool was developed and a LabVIEW-based calibration application. Through a dedicated function, a unique blockchain address is generated for each instrument using the "*getnewaddress*" command. This address, along with DCC's metadata is used to create a digital identity that is securely identifes the device. During calibration, the LabVIEW application formats the DCC data into an XML structure, which is then embedded into a Blockchain transaction. The transaction is initiated using the "*sendtoaddress*" command, while the metadata is stored within the optional comment field.

Each calibration event results in a transaction that is permanently recorded on-chain. The traceability chain is possible to be retrieved by querying the blockchain through wallet functions, which enables users to search for previous calibration records of the same instrument. This mechanism allows the system to retrieve the complete history of verifications and measurements associated with a specific device.

III. METHODOLOGY AND SCENARIOS

This present work introduces a methodology designed to reconstruct and verify the metrological traceability chain of a measuring instrument by analyzing calibration events that have been digitally recorded and stored in a private blockchain network. Each Digital Calibration Certificate (DCC) corresponds to a calibration event, which is stored as blockchain transaction and cryptographically signed by an accredited calibration laboratory. The central hypothesis of this approach is that the relationships between measuring instruments and their calibration references, as recorded through these transactions. Each DCC serves as a directed connection between two instruments: the instrument under test (IUT) and the reference standard used during calibration. Each calibration transaction is thus formalized as a record containing the identifiers of both the IUT and the reference instrument, the timestamp of the calibration event, and associated metadata defining a directed dependence in the traceability graph, pointing from the calibrated instrument toward the reference standard, indicating a dependency of metrological quality.

The traceability application is built in PHP as a modular architecture consisting of five functional components that work together to provide the complete traceability verification. For testing it several scenarios were possible, as described in the following.

A. Simple linear scenario

The simplest scenario is a simple calibration chain from the working instrument (VM1) to the national standard (REF0), via a secondary standard (REF1). For this case, 2 transactions are recorded in the network (Table 1).

Table 1. Simple linear scenario

DCC ID	Instrument ID	Standard ID	Date
T 001	REF1	REF0	12.12.2024
T 002	VM1	REF1	15.02.2025

The software should trace from VM-A to REF-1 to REF-0, building a traceability graph with depth 2.

B. Multiple calibration scenario with diverging standards

This scenario is presented in Table 2.

Table 2. Diverging standard scenario

DCC ID	Instrument ID	Standard ID	Date
T 001	REF1	REF0	12.12.2023
T 002	VM1	REF1	15.02.2024
T 003	REF2	REF0	15.09.2024
T 004	VM1	REF2	1.02.2025

In this case, the instrument has been calibrated with 2 different standards for last 2 times. First time VM2 was calibrated with secondary standard REF1 and second time with REF2. Both standard instruments were calibrated with national standard REF0. Both chains trace back to the same national standard REF0. The last calibration must be filtered by the date.

C. Branching Tree with Intermediate Levels

In this scenario an intermediate standard is used for multiple instruments calibration. Several instruments VM1, VM 2 and VM 3) were calibrated with diferent intermediate standards (REF2 and REF3). These were calibrated with an secondary standard REF1, which was at its turn calibrated with the national standard REF0. Table 3 presents this scenario.

Table 3. Branching tree scenario

DCC ID	Instrument ID	Standard ID	Date
T 001	REF1	REF0	12.12.2024
T 002	REF2	REF1	15.12.2024
T 003	REF3	REF1	1.01.2025
T 004	VM1	REF2	1.02.2025
T 005	VM2	REF3	5.04.2025
T 006	VM3	REF2	7.06.2025

All 3 instruments trace back to REF0. The standard REF1 acts like a shared note. If we want to check its backward traceability we will find 2 branches, but in real applications could be many branches.

D. Full scale metrological chain

The working instrument (VM1) is calibrated with an working standard (REF3). This was calibrated several times with secondary standards (REF2 and REF1). These are, at their turn, calibrated with the national standard REF0. The national stadard was calibrated based on an international travelling standard ITS. At its turn, this was part of an interlaboratory comparison campaign ILCC. This is presented in Table 4.

Table 4. Full scale metrological scenario

DCC ID	Instrument ID	Standard ID	Date
T 001	ITS	ILCC	12.12.2024
T 002	REF0	ITS	15.12.2024
T 003	REF1	REF0	1.01.2025
T 004	REF2	REF1	1.02.2025
T 005	REF3	REF1	5.03.2025
T 006	VM1	REF2	7.06.2025
T007	VM1	REF3	10.12.2025

IV. IMPLEMENTATION OF PHP BLOCKCHAIN TRACEABILITY VERIFICATION SYSTEM

This chapter presents the implementation and architectural details of the PHP-based blockchain traceability verification system designed to validate and track Digital Calibration Certificates (DCCs) stored on distributed ledger infrastructure. The system serves as a critical component in the proposed blockchain-enabled metrology framework, providing comprehensive verification capabilities for calibration hierarchies and certificate authenticity.

The PHP Traceability Checker implements a modular architecture consisting of five core functional components that work synergistically to provide complete traceability verification. The system employs a recursive traversal algorithm to construct calibration hierarchies while maintaining security through comprehensive input validation and error handling mechanisms.

Each module serves specific roles in the traceability validation process. The primary processing engine coordinates between transaction retrieval mechanisms, chain construction algorithms and device certification validation protocols. The application flow diagram is presented in Figure 1.

The main processing function (*processTraceabilityCheck()*) serves as the system's orchestration layer, accepting blockchain addresses, maximum traversal depth parameters, and network configuration objects. This component implements comprehensive address validation protocols before initiating transaction retrieval and chain construction processes. The function returns structured data containing complete traceability information and certified device listings.

The transaction retrieval component (*getAddressTransactions()*) implements an optimized data access layer capable of processing up to 2000 transactions per blockchain address. The module incorporates intelligent caching mechanisms to minimize redundant network requests while maintaining data freshness. Error handling protocols ensure system resilience when encountering network failures or malformed transaction data.

The chain construction module (*buildTraceabilityChain()*) implements a sophisticated recursive algorithm designed to traverse calibration hierarchies from individual devices to primary measurement standards. The algorithm employs depth-limited traversal with cycle detection mechanisms to prevent infinite recursion while ensuring complete hierarchy mapping. The function utilizes advanced pattern matching to identify calibration relationships through transaction comment analysis, specifically targeting "DCC:calibrated by" patterns that indicate hierarchical relationships.

The recursive implementation maintains a visited

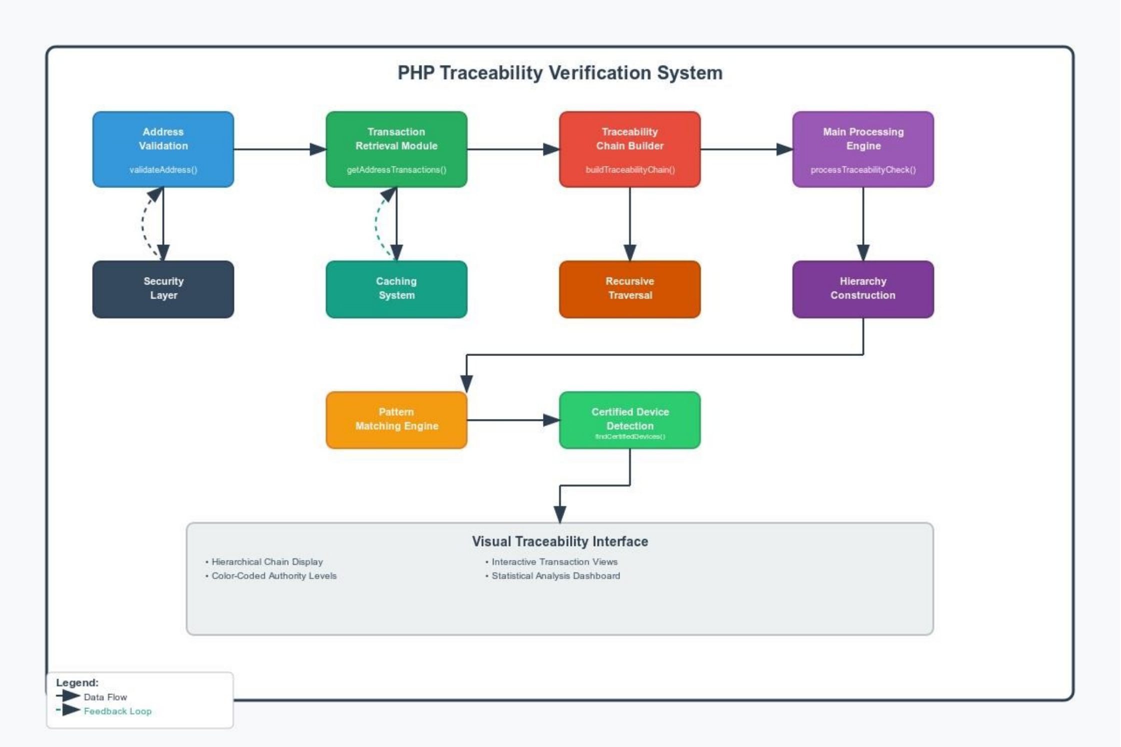

PHP Traceability Verification System
Address Validation
validateAddress()
Transaction Retrieval Module
getAddressTransactions()
Traceability Chain Builder
buildTraceabilityChain()
Main Processing Engine
processTraceabilityCheck()
Security Layer
Caching System
Recursive Traversal
Hierarchy Construction
Pattern Matching Engine
Certified Device Detection
findCertifiedDevices()
Visual Traceability Interface
• Hierarchical Chain Display
• Color-Coded Authority Levels
• Interactive Transaction Views
• Statistical Analysis Dashboard
Legend:
Data Flow
Feedback Loop

Fig. 1. Flow diagram.

address registry to prevent circular references while constructing a comprehensive authority hierarchy. Each iteration processes transaction data to identify upstream calibration authorities, creating a complete genealogy of measurement traceability that extends to primary national standards.

The device certification detection module (*findCertifiedDevices()*) implements enhanced logic for identifying measurement instruments that have been certified by specific calibration authorities. The system applies multi-criteria validation protocols that evaluate transaction amounts, comment pattern matching, and confirmation status to determine certification validity.

Certification criteria include transaction amount thresholds exceeding unity values, presence of "DCC:SerialNo" patterns in transaction metadata, and satisfaction of minimum blockchain confirmation requirements. The module processes both outbound and inbound transaction types to provide comprehensive coverage of certification activities.

The address validation component (*validateAddress()*) implements comprehensive security protocols through regex-based format validation and input sanitization mechanisms. This module serves as the primary defense against injection attacks and malformed input data, ensuring system integrity throughout the verification process.

The system incorporates sophisticated regular expression engines for transaction analysis, implementing specialized patterns for DCC serial number identification and calibration relationship detection. These patterns enable precise extraction of metrology-specific information from blockchain transaction metadata.

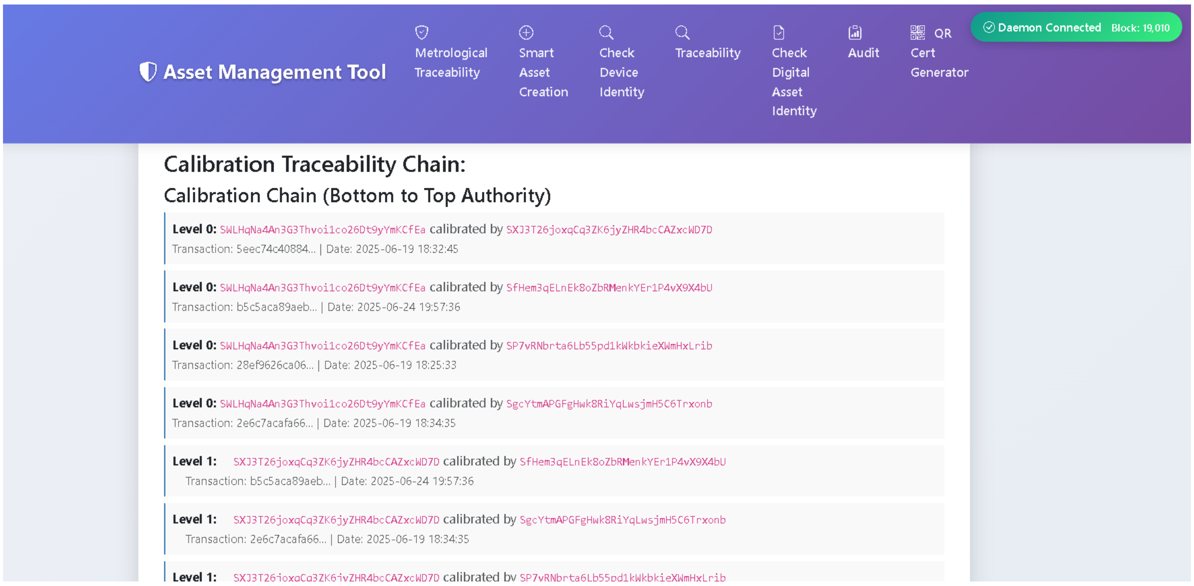
The verification system provides detailed transaction analysis capabilities including statistical summaries, confirmation status monitoring, temporal analysis, and quantitative calculations. This comprehensive approach ensures complete visibility into calibration activities and their associated blockchain records.

The system implements a visualization framework featuring hierarchical chain displays with color-coded authority levels distinguishing between primary standards and intermediate calibration devices. Interactive elements provide detailed transaction examination capabilities while statistical dashboards offer quantitative analysis of calibration activities (Figure 2).

V. CONCLUSIONS

The PHP verification system serves as a critical component in the proposed blockchain-enabled metrology framework, providing essential capabilities for DCC authenticity verification, calibration authority tracing, certified device monitoring, and comprehensive audit trail generation. This integration ensures regulatory compliance and quality assurance in metrology applications.

The implementation incorporates comprehensive error



Calibration Traceability Chain:

Calibration Chain (Bottom to Top Authority)

Level 0: SWLHqNa4An3G3Thvoi1co26Dt9yYmKCfEa calibrated by SXJ3T26joxqCq3ZK6jyZHR4bcCAZxcWD7D
Transaction: 5eec74c40884... | Date: 2025-06-19 18:32:45

Level 0: SWLHqNa4An3G3Thvoi1co26Dt9yYmKCfEa calibrated by SfHem3qELnEk8oZbRMenkYEr1P4vX9X4bU
Transaction: b5c5aca89aeb... | Date: 2025-06-24 19:57:36

Level 0: SWLHqNa4An3G3Thvoi1co26Dt9yYmKCfEa calibrated by SP7vRNbrta6Lb55pd1kWkbkieXWmHxLrib
Transaction: 28ef9626ca06... | Date: 2025-06-19 18:25:33

Level 0: SWLHqNa4An3G3Thvoi1co26Dt9yYmKCfEa calibrated by SgcYtmAPGFgHwk8RiYqLwsjmH5C6Trxonb
Transaction: 2e6c7acafa66... | Date: 2025-06-19 18:34:35

Level 1: SXJ3T26joxqCq3ZK6jyZHR4bcCAZxcWD7D calibrated by SfHem3qELnEk8oZbRMenkYEr1P4vX9X4bU
Transaction: b5c5aca89aeb... | Date: 2025-06-24 19:57:36

Level 1: SXJ3T26joxqCq3ZK6jyZHR4bcCAZxcWD7D calibrated by SgcYtmAPGFgHwk8RiYqLwsjmH5C6Trxonb
Transaction: 2e6c7acafa66... | Date: 2025-06-19 18:34:35

Level 1: SXJ3T26joxqCq3ZK6jyZHR4bcCAZxcWD7D calibrated by SP7vRNbrta6Lb55pd1kWkbkieXWmHxLrib

Fig. 2. The web application – traceability function

handling, intelligent caching mechanisms, confirmation-based validation and detailed logging systems to ensure robust operation in production environments. These features collectively provide the reliability and performance characteristics required for critical metrology applications.

The PHP Blockchain Traceability Verification System represents a comprehensive solution for validating Digital Calibration Certificates within distributed ledger environments. Through its modular architecture, advanced algorithms, and robust security framework, the system provides the verification infrastructure necessary to support blockchain-enabled metrology applications while maintaining the highest standards of reliability and regulatory compliance.

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