Toward a Measurement Information Infrastructure

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Abstract

This paper examines the manual processes by which calibration and testing laboratories produce, communicate, and consume technical measurement and quality data–calibration certificates, accreditation scopes, instrument specifications–and describes a global measurement information infrastructure around which the industry might automate those processes. It illustrates the ways MII-aware software might correct the shortcomings inherent in manual processes, improve measurement traceability, and increase the value of measurement services. The paper compares the design requirements to available technologies and concludes that the technology exists to construct an MII comprising normative standards, semantic data structures, and web services to enable and motivate MII-aware software development and implementation.

1. Introduction

In the test and measurement field, automation as a concept brings to mind computer-driven test and calibration systems that free humans from meticulous, error-prone, and time-consuming instrument configuration and control, data collection, conformance decisions and instrument adjustments. Such automation examples exist at all levels in the measurement hierarchy from national measurement institutes (NMIs) [1, e.g.] to factory production floors [2, e.g.].

At that point, however, the automation typically hits a paper wall. Though the automated system may capture the measurement results in a temporary or more permanent file or database, the data elements likely have no rigorous relation to any file structure the end user's software would recognize, and so some process, manual or automated, transfers the information to a paper document or perhaps an electronic version thereof, from which someone manually extracts the information and feeds it into succeeding processes. Besides the cost and obvious transcription error opportunities at one or both ends, inserting humans into the process encourages shortcuts that may compromise the data product and its traceability [3, 4].

A regular informal column [5] has begun exploring ideas to rectify this situation by applying computer science and related technology to close the predominantly overlooked gaps between automated measurement processes. The column aims to discuss, promote and perhaps loosely design a measurement information infrastructure (MII) composed of semantic data formats, communication protocols and normative standards and thereby motivate MII-aware software development and implementation.

This paper summarizes that effort to date. Section 3 reviews current manual metrology information production, communication and consumption processes and highlights some inefficiencies. Section 4 proposes automated alternatives, illustrates potential advantages, and examines MII requirements. Section 5 samples the available technology for meeting those requirements and some previous work that illustrates successes. First though, Section 2 reviews the typical documents that convey measurement information between its producers and consumers.

2. The Metrology information economy

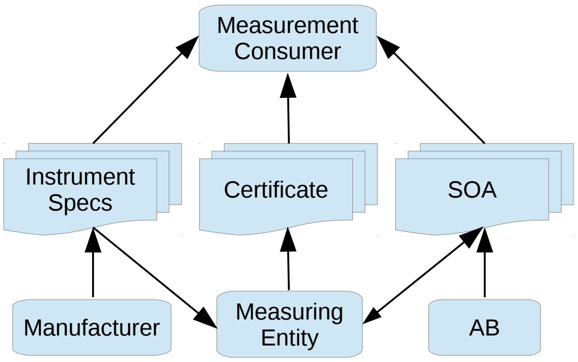

Figure 1: Partial information flow in the metrology economy.

As Figure 1 sketches, three primary vehicles conduct measurement information between entities: instrument specifications, statements of accreditation (SOAs), and test and calibration certificates. All three carry information that revolves around measured quantities. For meaning and value, the data includes the commensurate qualifiers, conditions, measuring intervals and influence quantities to adequately communicate the measurand and measurement quality metrics (MQMs) such as maximum permissible error (MPE) or uncertainty. Note that Figure 1 approximates only one step in a traceability network; each entity ultimately produces and consumes measurement information such that a given measured quantity and its descriptors circulate repeatedly through different instances of all three vehicles in a complex network. The following sections consider each vehicle in turn.

2.1 *Instrument specifications*

Instrument[1] specifications communicate measuring equipment's designed and warranted performance to the manufacturer's potential customers and instrument users. Manufacturers or re-specifiers produce the data, equipment vendors may broker it, specifiers and instrument users consume it. The information influences instrument selection prior to use and flows into certificates' traceability data afterward via the uncertainty analyses that draw on specifications and prior calibrations.

2.2 *Accreditation scopes*

An SOA specifies a measuring entity's (ME) accredited services, known as calibration and measurement capabilities (CMCs). An ME may produce the data, though an accreditation body (AB) actually certifies and publishes the SOA to establish trust and recognition for the claimed CMCs. Other MEs, instrument owners, and certificate customers consume the SOA data. The SOA information influences ME selection and constrains the information appearing in the ME's certifications. For brevity, this paper generalizes the SOA's meaning to include 1) the CIPM mutual recognition arrangement (MRA) and key comparison database (KCDB) for national metrology institutes (NMIs) and their CMCs, and 2) "scopes of capability" [6] that MEs may declare independent of ABs for interested parties that do not require accredited measurements.

2.3 *Certificates*

Certificates convey an instrument's measured performance to an owner or user. A ME produces the data for the instrument user's consumption. The certified MQMs draw on the instrument's own specifications as well as the certificates and specifications of the instruments the ME uses. The corresponding CMC information from the ME's SOA constrains or provides data that the certificate also incorporates. In succeeding measurements the certificate information will flow into other certificates.

3. The manual information economy

Employing these three vehicles and supporting systems, measurement professionals engage in a metrology information economy in which they

- Define measurement requirements for tasks,
- Acquire candidate spec sheets from vendors,
- Analyze specifications to select instruments,
- Search AB web sites to obtain SOAs,
- Examine CMCs to find suitable MEs,
- Augment SOAs as they expire,
- Determine calibration or verification points,
- Validate certificates against SOAs,
- Reconcile certificate content against requisitions,
- Copy calibration results to measurement software,
- Update data files and uncertainty budgets,
- Summarize measurement results on certificates,
- Verify measurement results vs. specifications,
- Initiate non-conformance notices,
- Send certificates to customers,
- Transform uncertainty analyses into SOA CMCs,
- Transfer test results to software systems,
- Archive and retrieve documents,
- Etc.

As mentioned, computers sometimes handle or facilitate these operations; once primed with the appropriate data for example, an automated measurement system may generate a certificate and flag out-of-tolerance results. By and large however, humans currently perform the operations, thus sustaining a primarily *manual information economy*.

3.1 *Cost consequences*

The manual information economy demands *human-targeted* vehicles–paper documents or their electronic equivalents, e.g. PDF files. Human-targeted documents both fulfill the demand and enable the economy's inherent costs. These metrology operations consume significant labor input from subject matter experts whose time might return more value if invested in less routine tasks. This implies economic loss. Even small losses accumulate significantly over the volume of global measurement transactions. The vehicle medium and content both drive manual intervention and hence three consequent costs.

First, the human-targeted medium itself separates entities and automated systems. Transmitted by post or by the Web, the document requires human handling to use and propagate the data, adding not only labor costs but also bottlenecks that dam the data flow between entities.

Second, human-targeted content assumes expert interpretation and so has relatively little standard formatting, terminology, or structure. The expertise assumption may lead to inconsistency or ambiguity that incurs costs to clarify the content. Even content successfully targeting

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[1] This paper uses the term instrument or equipment to include any object of interest subject to measurement

experts, however, may not convey the correct meaning to non-experts. This creates a costly self-perpetuating feedback cycle in which expertise enables a level of imprecision that requires expertise to interpret. In other words, the current vehicles require experts to identify and disambiguate equivalent measured quantities in order to compare results and MQMs in different instances of the same vehicle, not to mention different vehicles.

For example, CMC descriptions for the same measured quantity vary from AB to AB and from SOA to SOA, confounding searches. Furthermore, an SOA's CMC may state "AC voltage measurement", a corresponding certificate's measurement result "output flatness", and the instrument spec sheet "leveled sine amplitude". Complications such as omitted or vaguely stated qualifiers, conditions and influence quantities (e.g., "RMS", "into $50\,\Omega$", "relative to amplitude at $1\,\mathrm{kHz}$", $f \leq 1\,\mathrm{MHz}$) compound the problem.

Finally, human-targeted vehicles carry a further and more subtle cost. Compared to machines and automated processing, humans and manual processing favor simplicity over complexity, summary over detail. Manual operations shift the economic operating point toward data omission as the processing cost exceeds the diminishing return of further information. So certificates commonly omit digits of precision, correlations between reported results, upstream uncertainty components and error correlations, and degrees of freedom in spite of guidance and requirements to the contrary:

> *...to err on the side of providing too much information rather than too little* [7],
>
> [Certificates] *shall include all the information requested by the customer and necessary for the interpretation of the test or calibration results and all information required by the method used* [8].

The human-targeted data comes bound with deficiencies that introduce error in both the measured values and the measurement uncertainties, both of which increase costs. Overestimated uncertainties incur higher equipment and maintenance expenditures plus lost marketplace opportunities; underestimated uncertainties and errors in measurement results increase consequence cost risk [9].

3.2 Key inefficiencies

These key inefficiencies drive losses in the manual information economy:

1. Weakly standardized taxonomies,
2. Labor-intensive processing,
3. Economically compromised data.

The key inefficiencies inter-depend; in fact, they all stem from the same cause: information vehicles without formally defined semantic content.

4. An automated information economy

Suppose the measurement world successfully applied computer science to create a *metrology information infrastructure* (MII) that enabled all measurement-related software to produce, exchange and consume standardized semantic measurement information directly, and to generate human-readable summaries for monitoring and auditing. Practitioners might define a measurement and then direct automated systems to perform all the tasks in Section 3, intervening only to make procurement decisions from machine-optimized instrument and ME choices.

By definition, such an MII would reduce or eliminate the key inefficiencies Section 3.2 identified. Searching, comparing, linking, and transferring measured quantities and MQMs would become trivial (#1). With widespread adoption, few people would touch a paper document or transcribe a number (#2). Human-driven shortcuts and simplified analyses and reporting might then cease, shifting the economic operating point toward higher quality data (#3).

4.1 Further potential

Just as automated measurement frees technician time, an MII would likely free other measurement professionals for such beneficial activity as business management, measurement design, research and development, process refinements and further automation. Presumably, a functional and extensible MII would foster further development and advantages as other technologies have. No one will predict some developments but routine metrology operations today suggest that MII software might

1. Validate data in MII documents, e.g., administrative content, dates, ID numbers, traceability, vendor accreditation status, CMC range and uncertainty, AB security signatures, AB MRA status and scope;
2. Locate any suitable instrument or ME on the market rather than simply those familiar to the practitioner, thus improving competition and value;
3. Discard convenient piecewise linear MQM specifications in favor of specifying closer to actual performance;
4. Correct every measurement result for known bias, identify results with high false accept risk.
5. Generate automated measurement procedures from instrument models and control protocols;
6. Propagate measurement uncertainty through calibrated instrument models rather than estimating it from market-driven MPE specifications;
7. Identify optimal test point sets, evaluate results and logistical deviations in terms of MQMs;
8. Record traceability data back to the SI, itemize each intermediate calibration process uncertainty contributor, account for upstream correlations.

Concepts 6 and 7 bear elaboration. They refer to applying the usual GUM [7, with annexes] techniques to instrument measurement models as defined in the *VIM* [10]. Automated measurement model implementation would make uncertainty propagation through instruments as straight forward as conformance testing, providing unquestioned traceability for further calibration. Instrument modeling methods would connect point-by-point measurement results to an instrument's MPE conformance status, measurement uncertainty, measurement reliability, or other MQM at any usage point, adjusted for time after test or calibration, thus allowing advanced analysis and optimization of test point selections. In calibration interval analysis, measurement models would close the current disconnect between test point in-tolerance probability and instrument reliability, allowing further interval optimization.

4.2 MII requirements

What would a functional MII implementation require? This section takes the previous automation benefits and potential functionality as goals and matches the goals to requirements, taking software development and the existence of raw data network transmission protocols for granted. The first three goals correspond to the key inefficiencies Section 3.2 identified.

Relieving inefficiency 1 requires data structure definitions with the requisite taxonomies to allow MII documents to represent equivalent measured quantities sufficiently alike and to semantically include the appropriate identification and administrative data. Recovering losses from inefficiency 3 simply requires that the structure definition include data elements to fully represent and distinguish measured values and uncertainty parameters, use arbitrary precision numeric data types and extend this structure to arbitrary length so as to encapsulate all upstream traceability data.

Reducing inefficiency 2, however, requires a standard file format for reading, writing, exchanging, and processing MII documents to enable automating tasks such as Section 3 itemizes. An MII would not define the application software but rather leave developers to provide market-driven solutions. Local systems might store, retrieve and interchange data without reference to the standard file format if desired, but MII software would use the same format for measurement data exchange outside the "in-house" envelope. Automated exchange also requires some method to advertise, register, or otherwise locate available MII documents on a network.

Early on, Section 4 mentioned generating human-readable documents from MII vehicles. MII software should allow practitioners to monitor operations and view results as desired, even going so far as to reproduce official documents as currently used. Since such documents may include plots and other figures depicting measurement characteristics, MII document structures require data elements for storing graphics or methods for rendering graphics from the measured quantities and MQM descriptors.

In the general case, some instruments and CMCs and their corresponding certifications have multi-parameter measurement spaces or complex MQMs (e.g., to replace piecewise linear specifications) or reference conditions. Simple pre-defined data structures will not likely anticipate all calculation and measurement restriction variations. Therefore, MII documents will likely require facilities for defining Boolean and numeric equations, their parameters and variables, and linking those variables to measured, influence and input quantities. In order to propagate uncertainty through instruments and evaluate MQMs for test point selections, the same calculation and parameter interface system should robustly handle general instrument measurement models. The parameter interface should also tie to instrument control protocols so that MII software may construct instrument commands from quantity values.

An MII should design data security into the model up front, not only to validate signatures, accreditation marks and the like, but also to protect confidential information, if any. Ideally, all MII documents remain fully transparent, including fully visible measurement detail in the entire chain linking certified measurements to the SI. If valid confidentiality requirements arise, up front security features will help prevent weak patches later.

Finally, to facilitate widespread adoption and universal compatibility, normative standards should delineate all MII elements. In summary then, a functional MII requires

1. Complete data structure definitions and taxonomies, including a robust calculation, parameter interface and graphics methodology,
2. A designated file format,
3. Defined network data exchange service protocol,
4. Secure data protection and validation,
5. Normative standards for all of the above,

yielding an MII definition:

> A set of normative standards that define data structures, taxonomies, service protocols and security for locating, communicating and sharing measurement information.

5. Available technology

What MII-relevant technology exists now and what remains for the measurement world to develop? This section takes the Section 4.2 requirements one at a time to answer that question and also discusses the enabling roles of application software and metrology research.

5.1 Semantic data models

Data either in a defined structure or carrying descriptive meta-data provides the basic semantics the MII requires.

Facilities to encapsulate calculable equations and generate graphics on the fly seem less obvious but the *Metrologist* articles [5] have outlined conceptual MII data structures and posted the data models for download [11]. The models leave basic data types and other detail unspecified but they lack only implementation and refinement. Other projects and industries, however, have demonstrated the concepts:

- The *VIM* [10] lays a suitable ontological foundation for metrology, and norms such as the *ISO 80000* series [12] provide measurement taxonomies.
- The *IEEE 1671* family [13] defines automatic test markup language (ATML), a set of structures describing systems, instruments, objects, configurations, requirements and results for testing. Other proposals exist, e.g. [14, Ch. 9].
- The Object Management Group created a general systems modeling language (SysML) [15] which includes modules implementing the *ISO 80000-1* quantity kinds and measurement units taxonomy.
- NASA demonstrated automatic ATML generation from both LabVIEW virtual instrument panels and SysML equipment descriptions [16].
- National Instruments created a tool that translates ATML test descriptions to executable code [17].
- The Manufacturing Joint Working Group has established an infrastructure allowing process industries to encode operations and maintenance data for exchange [18].
- The METBENCH [19] laboratory management software allows instrument specifications of arbitrary complexity via interpreted equations and a parameter interface bound to measurement quantities at calibration time.
- The Swiss metrology institute METAS designed a data structure [20] that retains upstream correlation information; [3] outlines an alternative.
- The GUM Tree Calculator (GTC) [21] also tracks upstream correlation. It propagates uncertainty via *uncertain number* objects coded in Python, a scripting language that MII documents might easily store for MII software to execute under almost any operating system.

5.2 File formats

The *Metrologist* articles have briefly mentioned file format options but have not yet investigated the options. Since many similar projects, including working ATML systems, use XML (eXtensible Markup Language), at least one viable file format exists.

5.3 Network services

An MII requires automated network services for locating and requesting MII documents, querying their content and responding to requests. Though they operate below most people's radar, such network services exist now based on technologies such as REST (representational state transfer) and SOAP (Simple Object Access Protocol).

As one existing infrastructure example from a multitude, consider an air flight booking service. The service site understands air travel data based on the Open Travel Alliance's Open Travel Model, it uses a predefined airport taxonomy and it communicates with nearly all airline travel systems to locate flight data that matches a request's parameters, all without ambiguity. Compare that infrastructure to manually querying multiple AB databases for SOAs using ad hoc search terms and no taxonomy of measured quantities.

5.4 Security

Applicable security technology exists as encryption based on passwords, key generation and exchange schemes, or public certificates. The latter should apply well to validating an entity's signature or trademark to prevent fraud. Networks already encrypt transmissions on demand so the MII requires nothing new there. The Manufacturing Joint Working Group [18] has applied existing technology to handle its security concerns. Confidentiality requirements, if any, for partial document contents may require encoding additional data identification and ownership elements but no new technology. If MII documents embed executable scripts, limiting the scripting language to a subset à la GTC [21] would prevent arbitrary code execution, though at the expense of versatility.

5.5 Normative standards

Tying and holding MII technology together will require normative standards in the long run. Metrology and commerce in general revolve around standards–measurement standards, normative standards, standard measurement practices, etc. so an MII requires nothing new in principle.

Subject to other endeavor-unique variables though, standards emerge more often as the number of suppliers, the diversity of solutions and the opportunity for simplification increase [23]. The number of manufacturers, ABs and MEs issuing spec sheets, SOAs and certificates appears very large. On the surface, diversity seems low–paper, PDF, and few file structures–but underneath, the measured quantity descriptions diverge significantly. SOA search complexity looks ripe for simplification due to unpredictable measurement descriptors and keyword-based algorithms, amplified considerably for U. S. users and those operating across borders who search multiple AB databases. Practitioners who frequently compare instrument specifications or certificates from multiple vendors may have similar difficulty but this appears less urgent. If SOAs drive the standards though, the structure they share with spec sheets and certificates should lead to norms for all three vehicles.

5.6 Application software

Though not part of the MII definition per se, an MII will benefit no one without MII-aware application software. A successful MII depends on measurement software with the features to manipulate MII documents. Moreover, ubiquitous MII-aware software should engender features and functions that drive demand for wider MII adoption. Beyond replacing manual operations, automation makes impractical measurement refinements practical and would thus help eliminate convenient approximations such as ignoring correlation, selecting inappropriate error distributions, dispensing with degrees of freedom, truncating traceability and upstream correlation, etc., thereby improving quality and further increasing MII demand. Standard calculation libraries specific to analytical metrology for a variety of integrated development environments would likely help software developers proceed, as would MII application programming interfaces (APIs)–libraries for processing and exchanging MII documents.

5.7 Metrology research

Automation encourages more sophisticated metrology by changing the economics, so like software development, metrology research would play an important ongoing MII role, primarily perhaps in developing and implementing instrument measurement models and requirements and procedures for their validation. Openly available libraries of extensible instrument models would facilitate model development for similar instruments in bootstrap fashion. MII instrument spec sheets and certificates would contain the models, the latter parametrized from the measurement results; therefore, MII software might extract a model from one document to modify and install in a new spec sheet. As with routine uncertainty propagation, MII document structures might implement measurement models via either GTC-like technology [21] or an equation and parameter interface [3, 5].

6. Conclusion

MII technology exists today. The measurement world lacks only a motivation and consensus for building an MII. An MII definition would empower developers to incorporate MII data processing features into future versions of already ubiquitous measurement-related software, which in turn would raise opportunities to simplify and streamline many tedious and error-prone tasks, improve traceability and generally increase the value and quality of testing, calibration and measurement.

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References

[1] M. A. Lombardi, A. N. Novick, J. M. Lopez, J.-S Boulanger, R. Pelletier, "The inter-American metrology system (SIM) common-view GPS comparison network", in *Proc. of the 2005 IEEE Int. Frequency Control Symposium and Exposition* (IEEE), pp. 29-31, 2005.

[2] M. Dobbert, "Metrology in Manufacturing", in *Proc. NCSL Int. Workshop & Symposium* (NCSLI), 2015.

[3] M. J. Kuster, "Metrology: Standardize and Automate!", *Cal Lab: The Int. J. of Metrology*, **20.2**, pp. 26-34, 2013.

[4] R. Willink, "An inconsistency in uncertainty analysis relating to effective degrees of freedom", *Metrologia*, **45**, pp. 63-67, 2008.

[5] M. J. Kuster, "Toward a Measurement Information Infrastructure", *Metrologist*, **6.1-pres.**, 2013-pres.

[6] NCSLI RP-9: *Measurement Capability Description, Recommended Practice RP-9*, 2014.

[7] JCGM 100: *Evaluation of measurement data – Guide to the expression of uncertainty in measurement*, 2008.

[8] ISO/IEC 17025: *General requirements for the competence of testing and calibration laboratories*, 2005.

[9] NCSLI RP-18: *Recommended Practice RP-18: Estimation and Evaluation of Measurement Decision Risk*, 2014.

[10] JCGM 200: *International vocabulary of Metrology–Basic and general concepts and associated terms (VIM)*, 2012.

[11] NCSL International, Measurement Information Infrastructure (MII) Community Forum, http://www.ncsli.org.

[12] ISO 80000-1, e.g.: *Quantities and units-Part* $\cdots$, 2011.

[13] IEEE Std 1671: *IEEE Standard for Automatic Test Markup Language (ATML) for Exchanging Automatic Test Equipment and Test Information via XML*, 2010.

[14] C. Nadovich, *Synthetic Instruments: Concepts and Applications: Concepts and Applications* (Elsevier Science), 2004.

[15] Object Management Group, OMG Systems Modeling Language (OMG SysML$^{\mathrm{TM}}$), Version 1.3, http://www.omg.org/spec/SysML/1.3/, 2011.

[16] C. A. Lansdowne, C. Gorringe, P. McCartney, "Experimental applications of Automatic Test Markup Language (ATML)", in *AUTOTESTCON* (IEEE), pp. 318-323, 2012.

[17] National Instruments, ATML – The Standard for Interfacing Test System Components Using XML, http://www.ni.com/white-paper/3893/en/.

[18] Manufacturing Joint Working Group, MIMOSA OpenO&M, Condition Based Operations for Manufacturing, http://www.mimosa.org/whitepapers/condition-based-operations-manufacturing, 2004.

[19] ATS Metrology, METBENCH, http://atsmetrology.com/metbench/.

[20] M. Zeier, J. Hoffmann and M. Wollensack, “Metas.UncLib-a measurement uncertainty calculator for advanced problems”, *Metrologia*, **49**, pp. 809-815, 2012.

[21] B. D. Hall, “Object-oriented software for evaluating measurement uncertainty”, *Measurement Science and Technology*, **24**, 055004, 2013.

[22] Open Travel Alliance, Open Travel Model, www.opentravel.org.

[23] A. Sill, “Socioeconomics of Cloud Standards”, *IEEE Cloud Computing*, **2.3**, pp. 8-11, 2015.