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A FACTS–SEM Framework for National Radiosonde Standardization in Indonesia under Tropical Operating Conditions

Hogan Eighfansyah Susilo[1*], **Iqbal Vernando**[2], **Amy Reimessa**[3]

1- Researcher at Research Centre for Satellite Technology, National Research and Innovation Agency (BRIN), Bogor, Indonesia

2- Policy Analyst at Directorate for Policy Formulation of Research, Technology, and Innovation, National Research and Innovation Agency (BRIN). Jakarta Indonesia

3- Policy Analyst at National Research and Innovation Agency (BRIN), Jakarta, Indonesia

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ABSTRACT

Indonesia's dependence on imported radiosondes poses challenges for ensuring data consistency, calibration traceability, and operational resilience in tropical meteorological conditions. This study proposes an integrated framework combining the Framework for Analysis, Comparison, and Testing of Standards (FACTS) with Structural Equation Modelling (SEM) to develop a stakeholder-driven national radiosonde standard. The FACTS methodology was applied through a five-phase workflow standards inventory, comparison, gap analysis, requirements translation, and validation to systematically benchmark 45 technical clauses from WMO, ITU-R, and ETSI against Indonesia's tropical operating conditions, while SEM was used to quantitatively validate adoption drivers across 80 respondents from government agencies, research institutions, and industry. The PLS-SEM results confirm that measurement accuracy ($\beta = 0.58$, $p = 0.011$) is the most significant determinants of standard acceptance, followed by adaptability, testing reliability ($\beta = 0.34$, $p = 0.008$), technical compliance ($\beta = 0.31$, $p = 0.011$), and radiosonde performance ($\beta = 0.24$, $p = 0.006$). Model robustness is supported by contemporary fit indices (SRMR = 0.067; NFI = 0.934) and PLSpredict cross-validation confirming positive predictive relevance ($Q^2 > 0$). The proposed model successfully explains 76% of the variance in national standard adoption ($R^2 = 0.76$). The integrated FACTS–SEM approach provides a data-validated foundation for designing radiosonde standards compatible with WMO, ITU, and ETSI guidelines, while being optimized for tropical performance and local manufacturing capabilities. This study contributes an actionable framework to strengthen Indonesia's SNI-based meteorological standardization and support industrial self-reliance.

1. Introduction

Radiosonde systems constitute a critical component of national meteorological infrastructure, supplying upper-air observations that support numerical weather prediction, aviation safety, climate monitoring, and disaster risk mitigation [1], [2]. In Indonesia, a tropical archipelago highly exposed to extreme weather events, the reliability and continuity of radiosonde observations are directly linked to public safety and economic resilience [3], [4]. Despite their strategic importance, radiosonde systems deployed in Indonesia remain overwhelmingly imported, with foreign products accounting for almost the entirety of operational units. Based on the 2024 National Budget Planning (RAPBN) for BMKG, the national meteorological network relies heavily on foreign manufacturers, with annual procurements consisting entirely of imported transmitters such as Meisei, Modem, and Intermet to sustain operational flights [5]. This dependence introduces vulnerabilities related to supply-chain continuity, calibration traceability, lifecycle cost control, and long-term technological sovereignty.

*Corresponding author.
Email: hoga001@brin.go.id, Email: hoganefans@gmail.com

From an industrial engineering perspective, technical standards function as system-level instruments that coordinate product design, testing, production processes, regulatory compliance, and stakeholder interaction. Effective standardization reduces uncertainty, improves interoperability, and enables domestic industrial participation across the technology lifecycle [12], [24]. However, the direct adoption of international technical standards without contextual adaptation often proves ineffective in developing economies, where local environmental conditions, regulatory structures, and industrial capabilities differ substantially from those assumed during standard formulation [12], [13]. As a result, standards may become formally compliant yet operationally misaligned, limiting both adoption and industrial impact.

Existing international radiosonde standards issued by the World Meteorological Organization (WMO), the International Telecommunication Union (ITU), and the European Telecommunications Standards Institute (ETSI) establish globally harmonized requirements for measurement accuracy, frequency allocation, and telemetry performance [1], [7], [8]. While these frameworks ensure international data interoperability, they were primarily developed and validated under temperate climatic conditions. In tropical environments such as Indonesia, persistent high humidity, maritime exposure, and elevated ambient temperatures introduce performance degradation mechanisms that are insufficiently addressed by existing test procedures, particularly for humidity sensing and battery endurance [9], [10]. These limitations underscore the need for a national standard that remains internationally compatible while explicitly accommodating tropical operational constraints and domestic regulatory requirements [11].

To address these challenges, this study adopts the Framework for Analysis, Comparison, and Testing of Standards (FACTS) as a structured methodology for industrial standard development [14]. FACTS enables systematic benchmarking against international standards, identification of contextual gaps, and translation of stakeholder requirements into verifiable technical specifications. To quantitatively validate stakeholder priorities and adoption drivers, Structural Equation Modelling (SEM) is integrated into the framework. SEM has been widely applied in industrial engineering and policy studies to analyze complex causal relationships among technical, organizational, and regulatory factors [15], [16], yet its application to meteorological standardization remains limited.

Accordingly, this study proposes an integrated FACTS–SEM framework to support the development of a national radiosonde standard tailored to Indonesia's tropical environment and industrial context. The research objectives are threefold: (1) to identify and prioritize stakeholder requirements relevant to tropical radiosonde operation in Indonesia; (2) to develop a technical standard framework benchmarked against WMO, ITU, and ETSI requirements while accommodating local environmental and regulatory constraints; and (3) to validate the proposed framework using SEM-based stakeholder analysis.

The primary contribution of this research lies in demonstrating how industrial engineering methodologies can be applied to national standardization problems in meteorological instrumentation. By combining a structured standard development framework (FACTS) with quantitative validation (SEM), the study delivers a data-driven and stakeholder-verified approach that supports domestic industrial participation, strengthens calibration traceability, and reduces long-term dependence on imported technologies. Beyond the Indonesian case, the proposed framework offers a replicable model for other tropical and import-dependent countries seeking to align international technical standards with national industrial and environmental realities.

2. Literature Review

2.1. Radiosonde Systems as Industrial Infrastructure

Radiosonde systems are a foundational component of national meteorological infrastructure, providing standardized upper-air measurements required for numerical weather prediction, aviation operations, and climate monitoring [1], [2]. Although often treated as purely scientific instruments, radiosondes operate within a broader socio-technical system that includes manufacturing, calibration, logistics, regulatory approval, and operational maintenance. From an industrial engineering perspective, their performance and reliability are therefore inseparable from the governance structures and standards that regulate their lifecycle.

In developed economies, radiosonde systems are typically supported by mature industrial ecosystems in which domestic manufacturers, calibration laboratories, and regulatory agencies operate under nationally adapted technical standards [10], [18]. These standards facilitate process control, interoperability, and quality assurance, enabling consistent system performance over long operational horizons. In contrast, many developing countries rely almost entirely on imported radiosonde systems validated under foreign standards, resulting in limited control over design parameters, testing procedures, and long-term maintenance strategies [3], [4].

This structural dependency has direct industrial implications. Import reliance increases lifecycle costs, constrains local innovation, and weakens calibration traceability, particularly when instruments must be serviced or certified abroad [6]. Industrial engineering literature emphasizes that national standards play a critical role in mitigating such risks by formalizing design constraints, testing protocols, and interface requirements that enable domestic participation in production and quality assurance [12], [24]. Radiosonde systems thus represent an appropriate case study for examining how industrial standardization can strengthen technological resilience in import-dependent sectors. As illustrated in Figure 1, the diagram identifies the critical payload components, including the GNSS receiver, microcontroller unit, and sensor suite (temperature, humidity, and pressure transducers). In the context of tropical deployment, the physical casing and transmitter antenna require explicit engineering enhancements, specifically, IP67-rated weatherproofing and multi-layer thermal shielding to protect internal electronics from sustained high-moisture environments (>90% RH) and extreme temperature gradients (>60°C at surface altitude) characteristic of Indonesia's equatorial operating conditions.

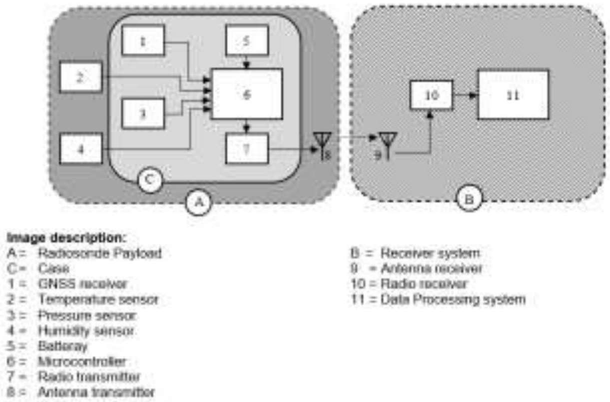

Fig. 1. Schematic of the radiosonde payload and receiver system [6].

2.2. International Standards and Contextual Limitations in Tropical Environments

International radiosonde standards issued by the World Meteorological Organization (WMO), the International Telecommunication Union (ITU), and the European Telecommunications Standards Institute (ETSI) establish harmonized requirements for measurement accuracy, telemetry performance, and radio-frequency usage [1], [7], [8]. These frameworks have been instrumental in enabling global data exchange and interoperability across meteorological networks. As such, they constitute an essential reference point for any national standard development effort.

However, the formulation and validation of these standards were largely conducted under temperate climatic conditions, where environmental stressors differ substantially from those encountered in tropical regions. Empirical studies have shown that sustained high humidity, elevated ambient temperatures, and maritime exposure can accelerate sensor drift, reduce battery endurance, and compromise telemetry stability in radiosonde systems [9], [10]. These degradation mechanisms are not always explicitly addressed in international test procedures, leading to performance gaps when instruments are deployed in equatorial environments [22], [23].

In addition to environmental factors, regulatory and spectrum-management constraints further limit the direct applicability of international standards. National radio-frequency allocations, such as Indonesia's use of the 400–406 MHz band for meteorological applications, require localized compliance mechanisms to avoid interference with aviation and maritime services [11]. Industrial engineering studies highlight that such regulatory-context mismatches necessitate adaptive standardization approaches, in which global benchmarks are retained while test conditions and acceptance criteria are modified to reflect local operational realities [12]. This reinforces the need for nationally contextualized standards that remain internationally compatible yet operationally robust in tropical conditions.

2.3. Standardization Challenges in Developing Economies

Technical standardization is widely recognized as a strategic instrument for industrial coordination, process optimization, and quality assurance [24]. Standards shape production systems by defining interfaces, tolerances, and validation procedures, thereby reducing uncertainty and facilitating interoperability across supply chains. In developing economies, however, the effectiveness of standardization is often constrained by limited testing infrastructure, fragmented stakeholder coordination, and misalignment between international requirements and domestic industrial capacity [12], [13].

The literature consistently reports that the unmodified adoption of international standards can result in low compliance and limited industrial impact. When performance thresholds or testing procedures exceed local manufacturing or calibration capabilities, standards may remain formally recognized but practically unenforceable [12]. This phenomenon has been observed across multiple sectors, including energy systems, medical devices, and transportation technologies, where localized adaptation proved necessary to achieve meaningful adoption [11], [13].

In Indonesia, national standardization efforts coordinated by the National Standardization Agency have demonstrated that participatory approaches improve alignment between regulatory objectives and industrial capability. Successful examples include the adaptation of international standards for electric vehicles and renewable energy systems, where stakeholder engagement enhanced feasibility and accelerated implementation [11], [12]. Despite these advances, meteorological instrumentation has received comparatively little attention within the industrial engineering standardization literature, leaving a gap in understanding how national standards can be systematically developed for this sector.

2.4. FACTS Methodology for Industrial Standard Development

The Framework for Analysis, Comparison, and Testing of Standards (FACTS), developed by the U.S. National Institute of Standards and Technology, provides a structured methodology for developing and harmonizing technical standards in complex industrial environments [14]. FACTS emphasizes systematic comparison of existing standards, identification of contextual gaps, and translation of stakeholder requirements into testable technical specifications. This process-oriented structure aligns closely with industrial engineering principles of systems design and continuous improvement.

FACTS has been successfully applied in domains such as aerospace materials, manufacturing interoperability, and telecommunications, where standards must reconcile international compatibility with sector-specific constraints [26], [27]. These applications demonstrate that FACTS is particularly well-suited to multi-stakeholder contexts, as it explicitly integrates technical benchmarking with stakeholder deliberation and validation. This dual focus addresses a common weakness in developing economies, where standards are often formulated without sufficient industrial input.

Despite its demonstrated utility, FACTS has not been widely applied to environmental measurement systems or meteorological instrumentation. Existing studies tend to focus on hardware performance or regulatory compliance in isolation, rather than on the standard development process as an integrated industrial system [14]. Applying FACTS to radiosonde standardization, therefore, represents an opportunity to extend its use into a new domain while addressing the need for structured, evidence-based national standards in tropical environments. Figure 2 details the national standardization process workflow, explicitly outlining the sequential stages of Indonesia's national standardization cycle. The transition commences with the drafting of the National Standard proposal (PNPS), proceeding through structured stakeholder consultation, e-balloting, consensus verification, and concluding with formal SNI proclamation. Demonstrating the necessary bureaucratic steps, each stage functions as a quality gate that ensures the proposed standard achieves regulatory legitimacy, industrial feasibility, and broad stakeholder acceptance before advancement to the next phase a process directly mirrored in the FACTS-based validation methodology applied in this study.

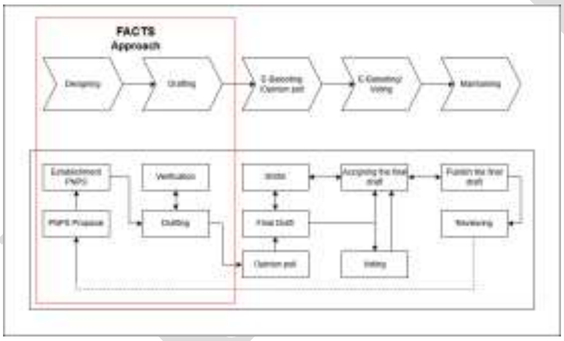

Fig. 2. **Standardization Process workflow and consensus benefits [12].**

2.5. Stakeholder Validation and Structural Equation Modelling

While structured frameworks such as FACTS support systematic standard development, empirical validation of stakeholder priorities and drivers of adoption requires quantitative analytical tools. Structural Equation Modelling (SEM) has been widely applied in industrial engineering and policy research to evaluate complex causal relationships among technical performance, organizational readiness, and regulatory feasibility [15], [16]. SEM enables simultaneous analysis of multiple latent constructs, making it suitable for assessing multi-dimensional standardization problems.

Prior studies have demonstrated that SEM is effective in identifying the relative influence of technical accuracy, testing rigor, and governance mechanisms on standard acceptance and implementation [25], [28]. These findings are consistent with industrial engineering theory, which emphasizes that technical excellence alone is insufficient without institutional alignment and stakeholder support. SEM thus provides a rigorous means of validating whether proposed standards address the factors most critical to adoption.

Despite its widespread use in other industrial domains, SEM has rarely been applied to the standardization of meteorological instrumentation. Integrating SEM within a FACTS-based framework allows qualitative stakeholder inputs to be statistically tested and refined, bridging the gap between framework design and practical implementation. This integration strengthens the methodological rigor of national standard development and supports evidence-based decision-making in complex regulatory environments.

2.6. Synthesis and Research Gap

The reviewed literature indicates that radiosonde systems are essential industrial infrastructure, yet existing international standards insufficiently address the environmental and regulatory conditions characteristic of tropical developing countries. While global frameworks ensure interoperability, their limited contextual sensitivity can reduce operational reliability and hinder domestic industrial participation. Industrial engineering research underscores the importance of adaptive, stakeholder-driven standardization to overcome these challenges.

Furthermore, although methodologies such as FACTS and analytical tools such as SEM have been independently applied across various industrial sectors, their combined use for developing and validating national technical standards remains underexplored. This gap is particularly evident in the domain of meteorological instrumentation, where standardization has traditionally been treated as a purely technical or regulatory exercise rather than an industrial systems problem.

This study addresses these gaps by integrating FACTS and SEM to develop a national radiosonde standard tailored to Indonesia's tropical and industrial context. By embedding stakeholder participation within a structured development framework and validating outcomes quantitatively, the proposed approach contributes to industrial engineering practice and offers a replicable model for other import-dependent nations seeking to localize international standards without sacrificing global compatibility.

3. Research Methods

This study employed a mixed-method research design integrating qualitative framework development with quantitative validation to construct a national standardization framework for radiosonde systems adapted to tropical conditions. The methodological foundation combines the Framework for Analysis, Comparison, and Testing of Standards (FACTS) with

Structural Equation Modelling (SEM), enabling both conceptual rigor and empirical reliability [13][14].

The research workflow consisted of four sequential phases: (1) exploratory review and comparison of existing international standards, (2) adaptation of the FACTS methodology to radiosonde standardization, (3) stakeholder-based data collection, and (4) SEM validation and model refinement. The initial stage involved an extensive benchmarking of forty-five technical clauses extracted from the World Meteorological Organization, International Telecommunication Union, and European Telecommunications Standards Institute guidelines. These clauses were categorized into five performance domains: measurement accuracy, telemetry and frequency reliability, environmental durability, calibration traceability, and regulatory compliance. Expert consultations were then conducted with representatives from the Meteorological, Climatological, and Geophysical Agency (BMKG), the National Standardization Agency (BSN), and local manufacturers to evaluate the relevance of these parameters under tropical operational conditions. This process identified several context-specific adaptations, such as humidity sensor recalibration thresholds, battery endurance limits, and frequency interference mitigation requirements [9][11]. The outcome of this stage was a preliminary FACTS-based framework comprising five primary constructs and twenty-one measurable indicators that formed the basis for quantitative validation.

To make the FACTS application transparent and demonstrable rather than merely descriptive, Table 1 presents the complete FACTS process workflow as applied in this study, including the key activities, input sources, and specific outputs produced at each phase. This workflow table directly corresponds to the four-phase sequence described above and provides the decision logic underlying the gap analysis and standards mapping documented in Tables 2 and 3.

To ensure practical feasibility and stakeholder alignment, a stakeholder-based survey was conducted to gather expert input on the proposed framework. A total of eighty respondents were purposively selected, representing four groups critical to standardization: government and regulatory agencies (BSN and BMKG, n = 20), calibration and testing laboratories (n = 20), research institutions and academia (n = 20), and industry representatives involved in meteorological instrumentation (n = 20). This distribution reflects the multi-sectoral nature of standardization and ensures balanced representation across technical, regulatory, and industrial domains [12][13]. The questionnaire was structured based on the indicators derived from the FACTS framework and used a five-point Likert scale (1 = strongly disagree to 5 = strongly agree) to assess each item's importance and adequacy. Prior to full deployment, a pilot test with ten participants was conducted to confirm construct clarity and reliability. The collected responses were screened for completeness, coded, and analyzed, ensuring that the final dataset accurately captured stakeholder priorities and perceived challenges in radiosonde standardization. This participatory data collection phase not only strengthened the validity of the framework but also reflected the importance of multi-stakeholder collaboration in standard development [24].

The quantitative validation of the proposed framework was performed using Partial Least Squares Structural Equation Modelling (PLS-SEM), an approach well-suited for exploratory research with moderate sample sizes and non-normal data distributions [15][25]. The model included five latent constructs corresponding to the domains identified through FACTS analysis: Technical Compliance, Radiosonde Performance, Testing Reliability, Measurement Accuracy, Regulatory Feasibility, and Standard Adoption. Each construct comprised three to five observed variables, resulting in twenty-one measurable indicators [16]. The data were analyzed using SmartPLS 4.0. Reliability and validity were assessed through Cronbach's alpha (>0.70) and composite reliability (>0.80), while convergent validity was verified using average variance extracted (AVE > 0.50). Discriminant validity was confirmed using the Fornell–Larcker criterion, and model fitness was evaluated through the Standardized Root Mean Square Residual (SRMR < 0.08) and Normed Fit Index (NFI > 0.90) [25][28]. Predictive relevance was assessed through PLSpredict using a tenfold cross-validation procedure; positive Q^2 prediction values for all endogenous constructs confirm that the model possesses predictive accuracy beyond a naïve benchmark [25]. Path significance was tested via bootstrapping with 5,000 resamples at the 95% confidence level ($p < 0.05$).

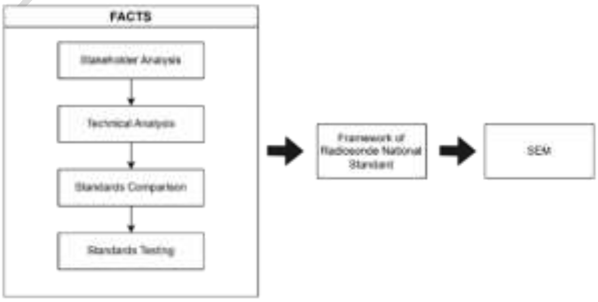

Fig. 3. Integrated FACTS–SEM research framework for radiosonde standard development.

The iterative integration of FACTS and SEM established a feedback mechanism whereby qualitative findings structured the initial model, and quantitative validation refined and confirmed key relationships among factors. This methodological synthesis ensured that the resulting FACTS–SEM framework is both technically grounded and empirically verified, offering a robust, stakeholder-validated foundation for Indonesia's tropical radiosonde standardization and a replicable model for other developing, import-dependent nations. A summary of the research methodology is presented in Figure 3. The figure illustrates the integrated FACTS–SEM methodological workflow comprising four sequential phases: (1) exploratory benchmarking against WMO, ITU-R, and ETSI reference standards using the FACTS clause inventory; (2) contextual gap analysis identifying tropical-specific performance deficiencies not addressed by existing international test procedures; (3) stakeholder-driven technical specification synthesis translated via the Zachman Framework and 5W1H analytical model; and (4) quantitative Structural Equation Modelling (SEM) validation of adoption drivers using SmartPLS 4.0. Furthermore, the bidirectional feedback arrows between the FACTS and SEM phases indicate the iterative refinement mechanism, whereby empirical model results inform the revision of technical specifications prior to formal standard submission, ensuring that the theoretical standard is empirically validated.

Tab. 1. FACTS Process Workflow Applied to Radiosonde Standardization.

FACTS Phase	Key Activities	Inputs / Sources	Outputs / Decision Logic
Phase 1: Standards Inventory	Catalogue all applicable clauses from WMO, ITU-R, and ETSI. Classify clauses into performance domains. Identify national regulatory requirements (KOMINFO).	WMO-No. 8 (2018); ITU-R RS.1165-3; ETSI EN 302 054-1; KOMINFO Regulation No. 5/2014	Annotated clause inventory: 45 technical clauses across 5 performance domains (measurement accuracy, telemetry, RF, environmental durability, calibration)
Phase 2: Standards Comparison	Cross-map equivalent clauses across WMO, ITU-R, and ETSI. Identify overlaps, contradictions, and omissions. Map national regulatory provisions (frequency allocation, flight permits).	Clause inventory (Phase 1); expert consultation with BMKG and BSN	Comparative standards matrix (Table 4): 16 technical parameters mapped across all reference bodies; alignment status coded for each parameter-standard pair
Phase 3: Gap Analysis	Evaluate each parameter against Indonesia’s tropical context. Assess whether international thresholds are sufficient, insufficient, or absent for equatorial performance. Apply decision logic: Align / Augment / Adapt.	Comparison matrix (Phase 2); tropical performance data [9][22][23]; stakeholder survey (n=80)	Gap analysis with clause mapping and decision logic (Table 2): 3 parameters augmented (humidity RH range → 100% RH; battery thermal endurance → ≥60°C; frequency stability → ±10 ppm); 13 parameters aligned with international thresholds
Phase 4: Requirements Translation	Map gap-response decisions to quantifiable SNI specifications. Apply Zachman Framework and 5W1H analytical structure. Conduct FGDs to validate specification feasibility.	Gap analysis (Phase 3); FGDs with BSN, BMKG, academia, and industry representatives	Draft SNI technical specifications (Appendix A): 21 measurable indicators across 6 latent constructs; stakeholder requirement traceability matrix (Table 1)
Phase 5: Validation and Testing	Validate draft specifications via PLS-SEM stakeholder analysis (SmartPLS 4.0). Conduct laboratory environmental chamber tests and intercomparison field flights. Refine specifications based on empirical feedback loop.	Draft specifications (Phase 4); survey data (n=80); physical prototype test results; intercomparison flight data	Validated FACTS–SEM framework: SRMR=0.067, NFI=0.934; $Q^2>0$ for all constructs; hardware meets all specification thresholds (±10 ppm, ≥12 dB S/N, ≥180 min battery at 60°C); proposed SNI radiosonde standard submitted for BSN review

4. Results and Discussions

This section presents the core findings of the study, organized into five interrelated components: stakeholder requirements, technical specification development, international benchmarking, validation through consensus and Structural Equation Modelling (SEM), and the discussion of practical implications. Together, these results demonstrate how the proposed FACTS–SEM framework enables the development of a radiosonde standard that is technically rigorous, contextually adapted for Indonesia’s tropical environment, and compatible with global meteorological practices.

4.1. Stakeholder Analysis Outcomes

Stakeholder analysis served as the foundation for identifying the parameters necessary to design a radiosonde standard relevant to Indonesia’s climatic, regulatory, and industrial conditions. Input was collected from eighty participants representing five stakeholder groups government regulatory agencies, research and development (R&D) units, radiosonde manufacturers, operational users, and testing laboratories through structured surveys, interviews, and literature reviews. The integration of diverse viewpoints ensured that both technical and governance considerations were addressed [12][13].

Tab. 2. Requirements based on stakeholder needs.

No	Stakeholder	Requirements
	Government	• Radio frequency settings specifically for meteorological activities based on the Regulation of the Indonesian Minister of Communication and Informatics (KOMINFO) 400.15 MHz - 406 MHz and 1668.4 MHz - 1700 MHz. • Transmitter Power: <250 mW • Minimum S/N Ratio: 12 dB • Flight Permit: Required (NOTAM/NOTMAR)
	R&D Radiosonde	• Radio frequency settings specifically for meteorological activities based on the Regulation of the Indonesian Minister of Communication and Informatics (KOMINFO) 400.15 MHz - 406 MHz and 1668.4 MHz - 1700 MHz. • Transmitter Power: <250 mW • Minimum S/N Ratio: 12 dB

		• Modulation: No restrictions • Battery Life: At least 180 minutes • Antenna: Not regulated, omnidirectional recommended • Measurement Range: Up to 30 km altitude • Radiosonde packaging: Weatherproof • Receiver Software: Must display measurement data
	Consumer/user	• Measurement Range: Up to 30 km altitude • Sensor Accuracy & Range: Must meet WMO requirements • Data Availability: 97% • Operating Procedure: Required for radiosonde operation
	Radiosonde manufacturers	• Radio Frequency Bandwidth: ≤200 kHz • Sensor type: Not specified for each parameter • Radiosonde type: Analog or digital Receiver Gain: Not specified
	Testing laboratory	• Frequency Error/Tolerance: ≤ ± 20 kHz for a 200 kHz bandwidth • RF Bandwidth Emissions: < -30 dBm • Antenna VSWR: 1.2:1 with 50 Ohm impedance • Receiver sensitivity: 12dB S/N at <-100 dBm • Transmission Stability: ±10 ppm in extreme conditions • Operational Reliability: Functions normally under extreme temperature and pressure

Table 2 summarizes the primary requirements obtained from this analysis. Government agencies emphasized compliance with KOMINFO's radio frequency allocation (400.15–406 MHz and 1668.4–1700 MHz), transmitter power limits below 250 mW, and mandatory flight permits in accordance with national aviation regulations [11]. R&D teams prioritized extended battery endurance (≥ 180 minutes), weatherproof packaging, and real-time data visualization, whereas users focused on sensor accuracy, reliability, and 97 % data availability. Manufacturers underscored production flexibility allowing analog or digital types while testing laboratories demanded precise calibration metrics, including RF tolerance ± 20 kHz, transmission stability ± 10 ppm, and antenna VSWR ≤ 1.2:1.

Across stakeholder groups, three convergent themes emerged:

1) regulatory compliance with local radio-frequency laws,
2) robustness under tropical environmental stress, and
3) precision in sensing and telemetry performance.

These findings reinforce the conclusion that radiosonde standardization must balance technical reliability with regulatory legitimacy and environmental adaptability a pattern consistent with earlier studies on stakeholder-driven standard development in developing economies [24]. International frameworks such as those of the World Meteorological Organization and the International Telecommunication Union provide useful baselines, yet they often lack detailed provisions for tropical conditions. Hence, stakeholder-derived insights provide the necessary contextual validation for a nationally grounded standard that still maintains interoperability with global meteorological networks.

Beyond informing the technical specification development process, the stakeholder requirements summarized in Table 2 also served as the basis for constructing the latent variables employed in the SEM validation stage. Requirements related to sensor capabilities, data transmission, and operational duration were grouped under Radiosonde Performance. Parameters governing RF output power, frequency bandwidth, and emission standards were consolidated into Technical Compliance. Laboratory, field testing, and calibration traceability requirements were represented by Testing Reliability, while sensor precision and frequency stability formed the Measurement Accuracy construct. Regulatory provisions concerning frequency spectrum compliance, operating procedures, and flight authorization were grouped under Regulatory Feasibility. These constructs were subsequently used to quantitatively evaluate the ultimate outcome of Standard Adoption.

4.2. Technical Specification Development and Justification

Following stakeholder analysis, the prioritized requirements were translated into quantifiable technical specifications using the Zachman Framework and the 5W1H (What, Why, Where, When, Who, How) analytical model. These tools have been widely applied in industrial systems engineering to ensure traceability between qualitative needs and measurable design parameters [14][26]. The resulting specifications were grouped into four interrelated domains: performance criteria, specification thresholds, measurement tolerances, and testing guidelines each contributing to a coherent radiosonde performance profile.

Performance criteria establish baseline operational capability: radiosondes must achieve at least 97 % data availability, maintain continuous operation for ≥ 180 minutes, and remain functional at altitudes up to 30 km. These requirements directly address the need for sustained measurement reliability during high-humidity monsoon and equatorial conditions [22].

Specification thresholds ensure compliance with domestic and international RF regulations. Transmitter power is limited to < 250 mW, frequency operation confined within 400.15–406 MHz, and total bandwidth constrained to ≤ 200 [7][11]. These values maintain interoperability while minimizing interference with maritime and aviation communications.

Measurement tolerances were defined through reference to WMO and ETSI standards, supplemented by stakeholder input: temperature accuracy ± 0.5 °C, humidity accuracy ± 5 % RH, and pressure accuracy ± 0.6 hPa [1][8]. These thresholds align with global expectations yet incorporate adjustments for tropical drift behavior observed in humidity sensors [9].

Finally, testing guidelines specify environmental and RF validation protocols. Radiosonde prototypes must withstand –90 °C to 60 °C, maintain transmission stability within ± 10 ppm, and meet emission limits below –30 dBm. These procedures ensure resilience under high temperature and moisture stress typical of Indonesia's maritime climate. Collectively, these specifications transform stakeholder expectations into a verifiable set of national standard parameters while preserving full compatibility with WMO and ITU benchmarks.

The comprehensive translation of stakeholder requirements into technical specifications covers four primary domains: performance criteria, specification thresholds, measurement tolerances, and testing guidelines. Due to the high density of these parameters, the complete mapping matrix detailing specific parameters such as the -90°C to 60°C thermal endurance and the 400.15 MHz - 406 MHz frequency bounds derived from flight and durability tests is provided in Appendix A. This extensive matrix forms the baseline for the subsequent comparative analysis against international benchmarks.

4.3. Benchmarking Against International Standards

Benchmarking was performed against the WMO Guide to Instruments and Methods of Observation (2018), the ITU-R RS.1165-3 recommendations, and ETSI EN 302 054-1, enabling cross-validation of Indonesia’s proposed parameters with globally recognized requirements. This comparison confirmed that the national framework achieves near-complete alignment on key indicators, including frequency allocation (400.15–406 MHz), transmitter power (< 250 mW), and bandwidth usage (≤ 200 kHz). Such conformity ensures interoperability of locally produced radiosondes with international telemetry and data assimilation systems [4].

Nevertheless, benchmarking also identified several context-driven enhancements introduced to address tropical operational challenges. These include:

(1) Enhanced humidity tolerance for sensors performing under > 90 % RH to mitigate drift and condensation errors;

(2) Battery-life assurance of ≥ 180 minutes at 60 °C to compensate for accelerated electrolyte degradation in hot climates; and

(3) Stricter frequency stability (± 10 ppm) to ensure signal integrity under rapid pressure and temperature fluctuations.

Rather than deviations, these modifications represent contextual augmentations that enhance the resilience of Indonesia’s radiosonde systems. Similar adaptive localization has been observed in the development of standards for other tropical technologies, such as photovoltaic durability testing and marine telemetry [20][23]. Consequently, the Indonesian specification emerges as both globally credible and locally responsive, satisfying international compliance while addressing previously unregulated tropical stress factors.

To explicitly demonstrate the FACTS decision logic and shift from conceptual description to empirical application, Table 3 presents an example of the clause mapping and gap analysis process. This matrix details how specific international guidelines (from WMO, ITU, and ETSI) were systematically analyzed against tropical operational gaps, leading directly to the contextually adapted SNI requirements.

These adjustments are not deviations from international standards but enhancements to ensure robustness in equatorial regions. Table 4 summarizes these comparisons, showing clear alignment with global standards while demonstrating thoughtful tailoring to Indonesia’s operational landscape. This benchmarking exercise confirms that the national standard is both globally credible and locally responsive. The following section presents the validation of this framework through stakeholder consensus and SEM analysis.

Tab. 3. FACTS Clause Mapping and Decision Logic Example.

Standard Parameter	International Reference	Identified Gap for Tropical Condition	Proposed SNI Requirement	Decision Logic / Gap Analysis
Battery Life & Thermal Endurance	WMO Handbook (2018) / ETSI EN 302 054-1	Standard tests do not fully account for accelerated electrolyte degradation experienced in persistently hot equatorial climates.	Battery must sustain continuous operation for ≥ 180 minutes and withstand extreme temperatures up to 60°C.	Augmentation: Baseline operational duration adopted, but thermal endurance bounds explicitly augmented for tropical daytime resilience.
Frequency Stability & Error Tolerance	ITU-R RS.1165-3 / ETSI EN 302 054-1	Rapid pressure and temperature fluctuations during tropical ascent risk telemetry loss and signal integrity degradation.	Stability must be strictly maintained at ±10 ppm under extreme conditions during measurement.	Contextual Tightening: ITU/ETSI frequency bands (400.15 MHz - 406 MHz) adopted, but stability tolerance tightened to mitigate drift under rapid gradient shifts.
Humidity Sensor Resilience	WMO CIMO Guide (2014)	High maritime exposure and monsoon profiles cause severe sensor drift and condensation errors when operating in environments > 90% RH.	Measurement capability across 0% RH to 100% RH with an enhanced accuracy tolerance of ±5% RH.	Adaptation: WMO sensor thresholds adapted to enforce stricter recalibration and tolerance limits against continuous high-moisture stress.

4.4. Validation Through Consensus and SEM Analysis

Based on the stakeholder requirements analysis, FACTS-derived technical specifications, and international standards benchmarking results, six constructs (one exogenous and five endogenous) were established for SEM analysis: Technical Compliance, Radiosonde Performance, Testing Reliability, Measurement Accuracy, Regulatory Feasibility, and Standard Adoption. These constructs represent the principal dimensions identified throughout the standard formulation stages. Their influence was subsequently evaluated against Standard Adoption using SEM to quantitatively assess the primary drivers of radiosonde standard implementation.

Validation of the proposed framework proceeded through two complementary stages: stakeholder consensus and quantitative SEM analysis. The focus group discussions (FGDs) involved representatives from the initial stakeholder categories, including BSN, BMKG, academic institutions, and manufacturers. These sessions confirmed the practical relevance and feasibility of the proposed requirements, particularly the specifications governing temperature accuracy and flight operations. Feedback was used to refine the draft standard before formal validation.

the The consensus achieved during the FGD sessions also informed the refinement of indicator definitions and construct relationships subsequently evaluated in the SEM model. This ensured that the quantitative validation process remained grounded in stakeholder priorities while maintaining consistency with the FACTS-derived standardization framework.

To eliminate ambiguity regarding the validation phase, the proposed SNI framework strictly mandates that testing beof actual physical hardware rather than relying on computer simulations. While Hardware-in-the-Loop (HIL) methodologies may be employed by manufacturers as internal developmental tools, the formal compliance validation required by this standard consists of two mandatory physical stages, mirroring the rigor of WMO certification.

First, Laboratory Environmental Chamber testing is conducted to verify the physical endurance and sensor accuracy of the actual radiosonde unit under extreme atmospheric profiles (e.g., thermal-vacuum cycling down to -90°C and pressures approaching 3 hPa). Second, the framework requires Operational Field Testing via Intercomparison Flights. In this final validation stage, the prototype hardware must be launched alongside a reference standard radiosonde on a single balloon to evaluate real-time system performance, telemetry stability, and actual sensor behaviour against metrics, physical atmospheric stressors (such as icing and extreme humidity) that cannot be fully replicated by simulation models.

Within the proposed framework, physical validation is performed against a set of predefined performance criteria, including frequency stability (±10 ppm), signal-to-noise ratio (≥12 dB), and environmental endurance requirements such as a minimum battery life of 180 minutes under elevated temperature conditions. These validation criteria were derived from stakeholder requirements, international , standards, and operational considerations specific to tropical environments. Compliance with these requirements provides objective evidence that a radiosonde system satisfies the technical and operational expectations necessary for standard adoption.

causal relationships. The SEM analysis was conducted using SmartPLS 4.0 to quantitatively validate the relationships among the proposed latent constructs and assess their contribution to radiosonde standard adoption. The measurement model demonstrated satisfactory reliability and convergent validity**,** as detailed in Table 5, with all indicator loadings exceeding 0.70, composite reliability values above 0.84, and average variance extracted (AVE) values greater than 0.50.

In accordance with contemporary PLS-SEM practices, global model fit evaluation prioritized the Standardized Root Mean Square Residual (SRMR = 0.067) and the Normed Fit Index (NFI = 0.934). Furthermore, predictive evaluation was performed using PLSpredict with a tenfold cross-validation procedure. The results yielded positive Q^2 prediction values for all endogenous constructs (e.g., Standard Adoption $Q^2 = 0.61$), confirming that the model's predictive accuracy exceeds a naïve benchmark.

The coefficients of determination (R^2) demonstrated substantial results. The Standard Adoption variable yielded an $R^2 = 0.76$, indicating that the model accounts for 76% of the variance in national standard adoption. The other endogenous constructs also exhibited solid explanatory power: Testing Reliability ($R^2 = 0.56$), Radiosonde Performance ($R^2 = 0.50$), Measurement Accuracy ($R^2 = 0.42$), Regulatory Feasibility ($R^2 = 0.34$).

To elucidate these structural findings, Figure 4 presents a comprehensive SEM path diagram. Addressing rigorous analytical requirements, this diagram explicitly details the standardized path coefficients (β), significance values (p-value), and coefficients of determination (R^2) for each construct relationship.

Path analysis revealed that Measurement Accuracy exerted the strongest direct influence on Standard Adoption ($\beta = 0.58$, $p = 0.$by 011 < 0.05. Subsequent significant determinants included Testing Reliability ($\beta = 0.34$, $p = 0.008 < 0.05$), Technical Compliance ($\beta = 0.31$, $p = 0.011 < 0.05$), Radiosonde Performance ($\beta = 0.24$, $p = 0.006 < 0.05$), and Regulatory Feasibility ($\beta = 0.21$, $p = 0.028 < 0.05$). These results consistent with SEM-based infrastructure standardization showing theory, which emphasizes that measurement precision and testing rigor are primary determinants of framework standard acceptance. The model also Feasibility, captured strong inter-construct dynamics; for instance, Technical Compliance significantly influenced Radiosonde Performance ($\beta = 0.71$, $p = 0.011 < 0.05$), which in turn served as a major driver for Testing Reliability ($\beta = 0.46$, $p = 0.004 < 0.05$). Overall, the integration of FACTS and SEM provides a statistically validated, stakeholder-approved model capable of guiding the national standardization process in a transparent and data-driven manner.

Tab. 4. Comparison of standard framework with reference standards.

No	**Technical Requirements**	**Reference Standard Comparison**				
		National radiosonde standards [6]	WMO Handbook (2018) Use of Radio Spectrum for Meteorology: Weather, Water and Climate Monitoring and Prediction [1]	CIMO Guide 2014 Part 1 Chapter 12 [21]	ITU Recommendation ITU-R RS.1165-3 [7]	ETSI EN 302 054-1 [8]
1	Radio Frequency	✓	✓	✓	✓	✓
2	Frequency stability and error tolerance	-	✓	✓	-	✓
3	Frequency Emission	-	-	-	✓	✓
4	Power Output	✓	✓	✓	✓	✓
5	Receiver Sensitivity	-	-	-	✓	✓

6	Bandwidth Radio	✓	✓	✓	✓	✓
7	Antenna Parameters	✓	✓	-	✓	✓
8	Battery Performance	✓	✓	✓	✓	✓
9	Sensor performance	✓	✓	✓	-	✓
10	Radiocommunication Test	✓	✓	✓	✓	✓
11	Flight Test/Field test	✓	✓	✓	✓	-
12	Battery Life Test	✓	✓	✓	✓	✓
13	Weather resistance test	✓	✓	✓	✓	✓
14	Air Pressure Sensor Performance Test	✓	-	✓	-	-
15	Temperature and humidity performance test	✓	-	✓	-	-
16	Operating procedure	✓	-	-	-	-

4.5. Practical Implications, Limitations, and Future Directions

The validated FACTS–SEM framework presents significant industrial and policy implications for Indonesia's meteorological and manufacturing sectors. Technically, the framework supports the development of domestically produced radiosonde systems that maintain global interoperability while being optimized for tropical performance. This advancement can reduce dependence on imports currently exceeding 95 % of deployed radiosondes and potentially decrease procurement costs by 30–40 % [5]. The standard also facilitates traceable calibration infrastructure by defining uniform testing procedures, thereby strengthening the reliability of national upper-air observation data [3]. From an engineering-process standpoint, integrating FACTS with SEM enhances decision transparency and allows continuous performance monitoring across the radiosonde lifecycle, from design to validation.

At the policy level, the framework provides a clear pathway for BSN and BMKG to establish a National Tropical Radiosonde Standard (SNI-RS). This could position Indonesia as a regional hub for tropical meteorological technology, similar to how Japan localized its Meisei RS-11G and Malaysia adapted its humidity-sensor calibration facilities [10][20]. Furthermore, adopting a stakeholder-validated approach ensures that policy implementation is supported by both industry and end-users, reducing resistance and improving long-term sustainability [24].

However, several limitations remain. The stakeholder sample, while diverse, may not fully represent regional variations across Indonesia's 17,000 islands, and prototype validation was conducted under controlled laboratory conditions rather than extended field operations. Future research should include real-time field validation campaigns across contrasting climatic zones (maritime, highland, and equatorial forest) to verify operational resilience under real meteorological stress. , the present study already incorporated primary fit indices (SRMR and NFI) alongside PLSpredict cross-validation to strengthen model credibility; future work may extend this further by reporting Comparative Fit Index (CFI) and Tucker-Lewis Index (TLI) robustness to align with covariance-based SEM reporting conventions and facilitate cross-study comparisons [25].

Three key directions are recommended:

(1) Conduct multi-season field campaigns to validate radiosonde reliability under variable humidity and wind-shear conditions;
(2) Undertake longitudinal assessments of the standard's impact on forecasting accuracy and domestic manufacturing capability; and
(3) Extend the FACTS–SEM approach to other meteorological instruments, such as weather radars and GPS water-vapor sensors, to establish a cohesive tropical instrumentation standardization ecosystem.

Tab. 5. Measurement Model Assessment.

Construct	Cronbach's Alpha	Composite Reliability (CR)	AVE
Technical Compliance	0.89	0.92	0.69
Radiosonde Performance	0.91	0.93	0.66
Testing Reliability	0.84	0.90	0.74
Measurement Accuracy	0.81	0.88	0.70
Regulatory Feasibility	0.79	0.87	0.69
Standard Adoption	0.86	0.91	0.77

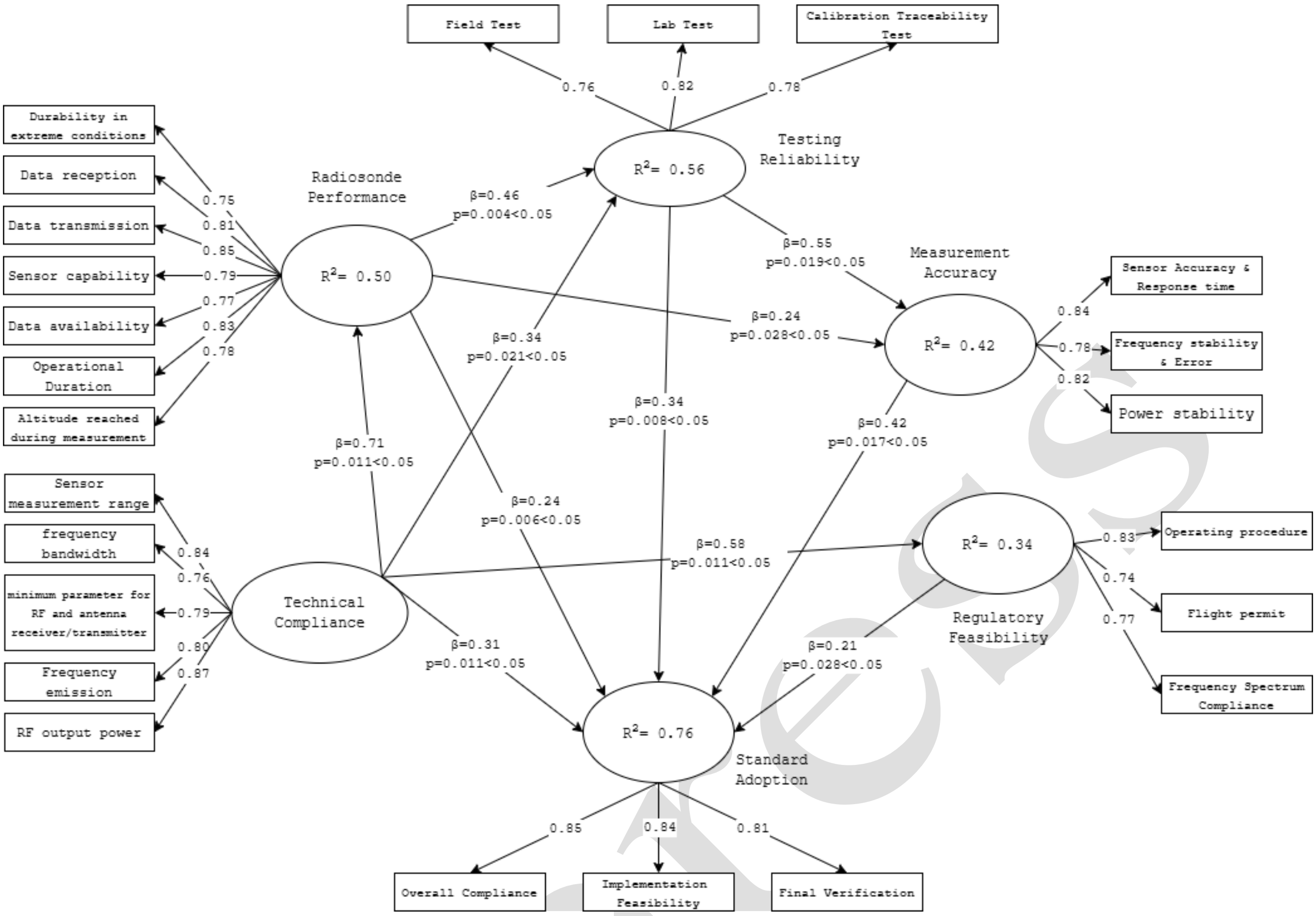

Fig. 4. Structural Equation Modeling (SEM) path diagram illustrating the causal relationships among latent constructs and their influence onon radiosonde standard compliance.

4.6. Discussion

The integration of the FACTS methodology with Structural Equation Modelling represents a novel contribution to meteorological standardization research. Previous studies have applied FACTS primarily in aerospace and telecommunications contexts [13][26], whereas this study demonstrates its adaptability to environmental measurement systems. Critically, the FACTS application here is not merely described but fully demonstrated through a five-phase workflow (Table 1), an explicit clause mapping and decision logic table (Table 3), and a comparative standards matrix (Table 4), addressing a gap in prior FACTS-based studies where process transparency was limited. The hybrid FACTS–SEM model advances from traditional “top-down” standardization dominated by international agencies to a bottom-up, evidence-driven framework grounded in stakeholder participation and empirical validation.

A key insight is that measurement accuracy, testing reliability, and technical compliance are the pivotal determinants of and standard adoption. The statistically significant influence of measurement tolerance ($\beta = 0.58$, $R^2 = 0.76$ for Standard Adoption) underscores that radiosonde systems must sustain high precision under tropical humidity and temperature variability conditions, where many imported systems exhibit performance degradation [9]. The model’s multi-index validation SRMR = 0.067, NFI = 0.934, and positive Q^2 values across all constructs via PLSpredict collectively confirm both structural robustness and predictive relevance beyond a naïve benchmark, lending confidence to these findings. This reinforces the importance of context-specific testing and calibration protocols. Additionally, the significance of regulatory feasibility confirms that successful standardization requires institutional coordination as much as technical excellence [16].

Beyond Indonesia, this study offers a replicable model for other developing nations such as those in Southeast Asia, Central Africa, and the Caribbean, where climatic extremes and limited industrial capacity constrain the direct adoption of temperate-region standards. Specifically, the framework can be adapted by following the five-phase FACTS workflow (Table 1): beginning with a clause inventory against WMO/ITU-R/ETSI, generating a comparative standards matrix (Table 4), performing a structured gap analysis with explicit decision logic (Table 3), and translating results into locally calibrated SNI requirements. Meteorological agencies in other tropical or archipelagic regions can replicate this method to systematically adjust specific test thresholds, such as thermal endurance bounds at 60°C and humidity sensor drift tolerances to reflect their unique operational stressors, ensuring environmental resilience without sacrificing international data interoperability. By demonstrating a transparent and validated pathway for adapting global benchmarks to local contexts, Indonesia's radiosonde framework contributes to global efforts in equitable technology standardization.

Finally, the research reflects a broader shift in industrial engineering toward performance-based standardization, emphasizing empirical testing and continuous validation over static procedural compliance. This transition strengthens accountability, fosters innovation, and aligns with international quality-assurance trends in aerospace and environmental instrumentation [25]. Overall, the findings confirm that integrating FACTS and SEM creates a robust, adaptive mechanism for developing standards that are both scientifically sound and socially legitimate, an essential step toward technological sovereignty and enhanced national meteorological resilience.

5. Conclusion

This study developed a FACTS–SEM–based framework to support national radiosonde standardization under Indonesia's tropical environmental and regulatory conditions. By integrating the Framework for Analysis, Comparison, and Testing of Standards with Structural Equation Modelling, the research combined stakeholder-driven qualitative inputs with quantitative validation to ensure technical rigor and practical feasibility. The FACTS methodology was operationalized through a five-phase workflow standards inventory, comparison matrix, gap analysis, requirements translation, and empirical validation (Table 1) producing explicit clause mappings and decision logic (Table 3) that demonstrate how international WMO, ITU-R, and ETSI requirements were systematically adapted to Indonesia's local operational constraints.

The SEM results confirm that measurement accuracy (β = 0.58), testing reliability (β = 0.34), and durability and technical compliance (β = 0.31) are the most influential direct determinants of standard compliance, while regulatory feasibility and Radiosonde performance also exerts significant positive effects. The robustness of the model is supported by goodness-of-fit indices (SRMR = 0.067; 0.92, NFI = 0.934) and PLSpredict cross-validation, confirming positive predictive relevance for all endogenous constructs. Additionally, the model yields substantial coefficients of determination, explaining 76% of the variance in Standard Adoption ($R^2 = 0.76$), demonstrating the effectiveness of combining structured standard development with empirical validation.

From an industrial and policy perspective, the framework provides a practical foundation for developing an Indonesian National Radiosonde Standard, enabling increased domestic production, improved calibration traceability, and a potential reduction in import dependency. Regulatory agencies such as BSN and BMKG may apply this approach to harmonize industrial capability with international expectations, thereby strengthening technological sovereignty in atmospheric instrumentation.

Future work should include multi-season field validation across Indonesia's diverse climatic regions and broader stakeholder participation to enhance representativeness. Extending the SEM model to incorporate economic and policy-readiness variables would further support adoption analysis. Beyond radiosondes, the proposed approach is transferable to other tropical measurement technologies, offering a scalable pathway for localized yet globally compatible standardization.

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Appendix A: Detailed Radiosonde Technical Analysis and Parameter Mapping

No	Requirements	Technical Analysis	Parameter
	• Radiosonde can measure atmospheric parameters up to a minimum height of 30 km • Data Availability 97% • Radiosonde battery life can work for at least 180 minutes • Radiosonde can work normally in extreme temperature and pressure conditions • Radiosonde Payload Packaging is weatherproof • Battery voltage remains stable in extreme conditions • GNSS used is connected to at least 8 channels during flight • Pressure Sensor can measure in the range of 1070 hPa to 3 hPa • Temperature Sensor can measure in the range of -85 °C to 55 °C • Humidity Sensor can measure in the range of 0 %RH to 100 %RH • The type of sensor for each parameter used is not regulated	• Flight test/Field test [1][4][9][17]	Radiosonde performance specifications
	• The battery can withstand working at temperatures of -90 °C to 60 °C • The battery can withstand working at pressures of 1000 hPa to 50 hPa	• Durability Test [1][9][21]	
	• The radiosonde radio frequency must be 400.15 MHz - 406 MHz	• Radio Frequency Test [7][8][11][21]	
	• Pressure Sensor can measure in the range of 1070 hPa to 3 hPa • Temperature Sensor can measure in the range of -85 °C to 55 °C • Humidity Sensor can measure in the range of 0 %RH to 100 %RH • The type of sensor for each parameter used is not regulated	• Sensor Performance Test [18][21]	
	• Radio frequency bandwidth ≤200 kHz • The modulation used is free • Analog or digital radiosonde type	• Radio bandwidth test [11][7][8]	
	• Radio frequency bandwidth emission <-30 dBm • Transmitter Power Output <250 mW	• Power output and emission test [11][7][8]	
	• Minimum transmitter system S/N 12 dB • Transmitter antenna is not adjustable, omnidirectional type is recommended • Antenna Gain Transmitter > 2 dBi • VSWR is less than 2 at 400.15 MHz -406 MHz bandwidth with connector impedance of 50 Ohm	• Transmitter antenna[11][7][8]	
	• Receiver sensitivity 12dB S/N <-100 dBm • Receiver Antenna is not adjustable, omnidirectional type is recommended • Receiver Gain Antenna is not adjusted • VSWR is less than 2 at 400.15 MHz -406 MHz bandwidth with connector impedance of 50 Ohm	• Receiver antenna[7][8]	
	• Frequency Error or tolerance for the difference between the measured radio frequency and the radio frequency from the manufacturer is no more than ± 20 kHz for a bandwidth of 200 kHz. Radio frequency transmission must be stable under extreme conditions during measurement (±10 ppm)	• Radio frequency stability/error [7][8]	Measurement tolerance/ accuracy
	• Altitude accuracy of 10 gpm at surface pressures up to 100 hPa and 20 gpm in the range ≥ 100 hPa • The accuracy of GPS-derived wind speed is ±1 m/s at surface pressures up to 100 hPa and ±2 m/s in the range ≥ 100 hPa. • Wind direction accuracy of 5°	• Measurement tolerance [9][17][19]	

	• Pressure sensor accuracy ±0.6 hPa on the surface up to < 100 hPa and ±1.0 in the range ≥ 100 hPa • Temperature sensor accuracy ±0.5 °C in the range ≥ 100 hPa and ± 0.8 °C in the range < 100 hPa • Sensor response time <0.5 s at surface pressure • Humidity sensor accuracy ±5%RH • Response time ≤0.5 s (at pressure 1000 hPa and temperature 20 °C) and < 20 s (at pressure 1000 hPa and temperature -40 °C)	• Sensor Accuracy [9][10][18][19]	
	• Response time ≤0.5 s (at pressure 1000 hPa and temperature 20 °C) and < 20 s (at pressure 1000 hPa and temperature -40 °C)	• Operating procedure	Operation [6]
	• Radiosonde flights must be permitted by local aviation authorities.	• Flight Permit	