Air Quality Sensor Technologies: $PM_{2.5}$ Literature Findings

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June 25-26th, 2018
Sensor Performance Deliberation Workshop

Background

In support of the Performance Benchmarks Workshop, a literature review of relevant PM and select gas phase published research findings were investigated. This investigation included:

- **Defined regulatory requirements (US, EU, China)**
- **Peer review journal and proceedings-based literature**
- **Journal focus was 2007-> 2017**
- **Performance characteristics were recovered and categorized**
- **Primary research was conducted by Ian MacGregor and the Battelle group under an EPA-defined task order**
- **The investigation was ultimately limited by resources but is considered informative but not exhaustive or comprehensive**

Literature Review Search Effort

Combination of automated and hand-curated approach with focus on literature published after 2007 and on use of air sensors; databases searched included:

- **Compendex, Scopus, and Web of Science for peer-reviewed literature,**
- **Networked Digital Library of Theses and Dissertations, Open Grey, OpenAIRE, and Worldcat for identification of relevant information sources available in the "grey literature",**
- **Catalog of US Government Publications, the Defense Technical Information Center, and the UN Digital Library for applicable US and international government documents.**

Literature Specifics

- Computer-based search of key words reported ~ 20000 records pertaining to the area of interest
- Reduction in total number of titles to a resource-capable level was performed
- A total of 257 titles were graded for applicability and utility associated with performance characteristics or requirements
- The titles focused on air quality sensors because inclusion of research and regulatory-grade instrumentation would have exhausted the resources
- Each retained article was graded for information pertaining to 10 common performance attributes, then organized into 16 application types and then 4 use categories

Literature Review Quality Assurance

100% of all scored references were reviewed using an independent 2nd party approach regarding:

- **Correct association of scoring with the reference title**
- **Original scoring values (e.g., pollutant/category/data quality indicator)**
- **Transcription of original scores to spreadsheet-based database**
- **Extracted information included in statistical findings (e.g., verified for accuracy in data findings report)**

Key Regulatory Documents

- US Code of Federal Regulations in support of the NAAQS (FRM/FEM requirements)
- US EPA Performance Standard 18
- European Commission for Standardization (CEN) through their Air Quality Directive (2008/50/EC) and EU 2015/1480)
  - Working Group 42 directed to develop sensor-based performance classifications
    - Class 1 (Indicative measurements)
    - Class 2 (Objective estimation techniques)
    - Class 3 (research, environmental education,
- United Kingdom's MCERTS (Monitoring Certification Scheme)
- People's Republic of China (HJ 654-2013,HJ 653-2013, and GB 3095-2012)

Reference Categorization Approach

- Organized performance requirements into four broad categories, irrespective of the application:
  - Spatiotemporal variability, comparison, trend, and decision support
- Categories describe the type of data analysis being performed and the decision sought for the monitoring
- The categorization scheme is based on the work of Lewis et al. (2017), where spatial and temporal variability are combined together and decision support added to capture regulatory monitoring
- Performance requirements stratified in this manner to simplify the reporting matrix to facilitate identifying qualitative trends

Application Categories

- **Air quality forecasting**
- **Air quality index (AQI) reporting**
- **Community near-source monitoring**
- **Control strategy effectiveness**
- **Data fusion**
- **Emergency response**
- **Epidemiological studies**
- **Exposure reduction (personal)**
- **Hot-spot detection**
- **Model input**
- **Model verification**
- **Process study research**
- **Public education**
- **Public outreach**
- **Source identification**
- **Supplemental monitoring**

Performance Descriptors

- **Accuracy/uncertainty**
- **Bias/trueness**
- **Completeness**
- **Detection limit**
- **Measurement duration**
- **Measurement frequency**
- **Measurement range**
- **Precision**
- **Response time**
- **Selectivity**

Variation in use of terms, units and statistical approaches made systematic categorization difficult

Literature by the Numbers

- Of the 257 documents, **48** contained quantitative performance information. A total of 8 contained qualitative performance info. A total of **56** documents provided the primary information shared today.
- Literature most often reported sensors being used for spatio-temporal investigations (n=40)
- Performance requirements were most often reported for ozone (52%) followed by NO2 (46%) and then **PM2.5 (40%)**. SO2 reports were extremely limited (10%)
- Of the primary 48 references, 70% adjusted for measurement artifacts, 8% intentionally retained non-adjusted data. Adjustment for the remainder (22%) was not applicable
- Treatment of erroneous data was discussed in **only 35%** of the sources

Certification Considerations

In the review of existing performance standards:

- **Discovery of current US and foreign-based regulatory technology performance standards for criteria pollutants (with a focus on ambient and near-source)**
- **Were there any non-regulatory technology performance standards for criteria pollutants internationally? What was the justification for how these standards were set, and to what applications/pollutants did they apply?**

Certification Program Requirements

Program	U.S. EPA FRM/FEM Program	European Parliament and of the Council Ambient Air Quality Directive (2008/50/EC)	Monitoring Certification Scheme (MCERTS)
Organization	U.S. EPA	European Committee for Standardization	Environment Agency (UK)
Type	Performance Standards Certification (instruments)	Performance Standards (instruments)	Certification (instruments)
Pollutants	Ambient O_3, NO_2, CO, SO_2, **$PM_{2.5}$**, PM_{10}, and Pb	Ambient **$PM_{2.5}$**, PM_{10}, CO, NO_2, SO_2, and NO_3,	Ambient **$PM_{2.5}$**, PM_{10}, CO, NO, NO_2, SO_2, O_3, benzene, and benzene-like VOCs

Certification Program Requirements

Program	People's Republic of China National environmental monitoring standards	U.S. EPA Performance Standard 18	European Committee for Standardization (CEN) Technical Committee 264 (Air Quality) Working Group 42 (Gas sensors)	People's Republic of China Performance Standards for Air Sensors
Organization	Chinese Ministry of Environmental Protection (MEP)	U.S. EPA	European Committee for Standardization	Chinese Ministry of Environ-mental Protection (MEP)
Type	Performance Standards Certification (instruments)	Performance Standards (instruments)	Technical Specifications (air sensors)	Performance Standards (air sensors)
Pollutants	Ambient **$PM_{2.5}$**, PM_{10}, CO, NO_2, SO_2, and O_3,	Source Hydrogen Chloride (HCl)	Ambient O_3, NO, NO_2, CO, SO_2,O_3, and CO_2	Ambient **$PM_{2.5}$**, PM_{10}, CO, NO_2, SO_2,O_3, and tTVOC

Certification Program Requirements, Cont'd

Program	U.S. EPA FRM/FEM Program	European Parliament and of the Council Ambient Air Quality Directive (2008/50/EC)	Monitoring Certification Scheme (MCERTS)	People's Republic of China National environ-mental monitoring standards
Applications Tiers	Single Tier Designated reference or equivalent method for use in regulatory monitoring for the NAAQS	Three Tiers 1. Fixed measurements (highest quality) 2. Indicative measurements 3. Objective estimation	Two tiers 1. Fixed measurements (highest quality) 2. Indicative measurements	Single Tier

Certification Program Requirements, Cont'd

Program	U.S. EPA Performance Standard 18	European Committee for Standardization (CEN) Technical Committee 264 (Air Quality) Working Group 42 (Gas Sensors)	People's Republic of China Performance Standards for Air Sensors
Applications Tiers	Single Tier Any instrumental technology that can meet performance criteria may be used.	Three tiers Class 1 - meets the DQOs of Air Quality Directive (2008/50/EC) Class 2: meets DQOs of objective estimation Class 3: no mandatory performance level	Single Tier

Certification Program Requirements, Cont'd

Program	U.S. EPA FRM/FEM Program	European Parliament and of the Council Ambient Air Quality Directive (2008/50/EC)	Monitoring Certification Scheme (MCERTS)	People's Republic of China National environ-mental monitoring standards
Test Locations	Laboratory and Field	Laboratory and Field	Laboratory and Field	Field
Outcomes	Designated reference or equivalent method by U.S. EPA	Stamp of approval for the use of specific analyzers (in their tested configuration) in national monitoring networks	Product Conformity Certificate issued for an instrument and concentration range	Unknown

Certification Program Requirements, Cont'd

Program	People's Republic of China National environ-mental monitoring standards	U.S. EPA Performance Standard 18	European Committee for Standardization (CEN) Technical Committee 264 (Air Quality) Working Group 42 (Gas sensors)	People's Republic of China Performance Standards for Air Sensors
Test Locations	Field	Field	Laboratory and Field	Field
Outcomes	Unknown	Any instrumental technology that can meet performance criteria may be used	Unknown	Unknown

Certification Considerations, Cont'd

During the review of research studies and information sources:

- **What were the various purposes of applying the measurement technology (applications such as control strategy effectiveness, source identification, near-source monitoring, emergency response, public outreach, etc.)?**
- **What appeared to be the drivers affecting the air measurement technology employed for specific monitoring purposes (such as cost, performance [accuracy, precision, bias], portability, reliability, etc.)?**
- **What were the expected concentrations and actual measured concentration ranges for specific measurement applications and environments?**
- **How were measurement artifacts addressed, such as impacts on measurement performance related to environmental conditions (adjustment, no adjustment; explanation)?**

Certification Considerations, Cont'd

During the review of research studies and information sources:

a. **What, if any, in-use DQIs or other automated data quality checks were employed to flag and/or adjust data (precision, bias, accuracy, completeness, etc.)?**

b. **If applicable, were the selected measurement techniques compared to FRM/FEM or other regulatory/reference instrument, and if so, what were the outcomes of these comparison(s) (compared to FRM/FEM or other reference standard, yes or no; if yes, indicate degree of agreement as bias range)?**

c. **How were erroneous data handled (not flagged and used; not flagged and not used [discarded/null coded]; flagged and used)?**

d. **What are the commonalities or differences among measurement DQOs within similar studies conducting non-regulatory air quality measurements (e.g., multiple near-road outdoor air quality studies) and between differing purposes of non-regulatory monitoring (e.g., indoor versus outdoor monitoring)?**

In the context of this project the term artifact captures the potential impact of co-collected pollutants and/or temp/RH changes on reported concentrations. An artifact may be manifested as imprecision, bias, change in sensitivity, etc.

U.S., European Union and Chinese Regulatory $PM_{2.5}$ Monitoring Performance Values

Pollutant	Performance Attribute	US	EU	China
$PM_{2.5}$	Accuracy/ uncertainty	R^2: 0.7225-0.9025 [1]		$R^2 \geq 0.8649$ [2]
	Measurement range	Measurement range: 3-200 µg/m^3 [1]	Measurement range: (0-$1000_{24h\text{-}avg}$, 0-$10000_{1h\text{-}avg}$ µg/m^3) [3]	Measurement range: 0-1000 µg/m^3 [2]

[ ] indicates reference citation number

Percentage of Reports of DQOs/MQOs

Pollutant	Comparison	Spatio-temporal Variation	Trend	Decision Support	Other	% All Sources
$PM_{2.5}$	32% (6)	63% (12)	5% (1)	26% (5)	5% (1)	40% (19)

( ) represents the number of references used in the statistic

Frequency of Monitoring Applications

Application	$PM_{2.5}$
Air Quality Forecasting	16% (3)
Air Quality Index Reporting	26% (5)
Community Near-Source Monitoring	42% (8)
Control Strategy	32% (6)
Data Fusion	16% (3)
Emergency Response	21% (4)
Epidemiological Studies	42% (8)
Exposure Reduction	16% (3)
Hot Spot Detection	42% (8)
Model Input	16% (3)
Model Verification	21% (4)
Process Study Research	16% (3)
Public Education	37% (7)
Source Identification	16% (3)
Supplemental Monitoring	68% (13)
Other	11% (2)
% All Information Sources	40% (19)

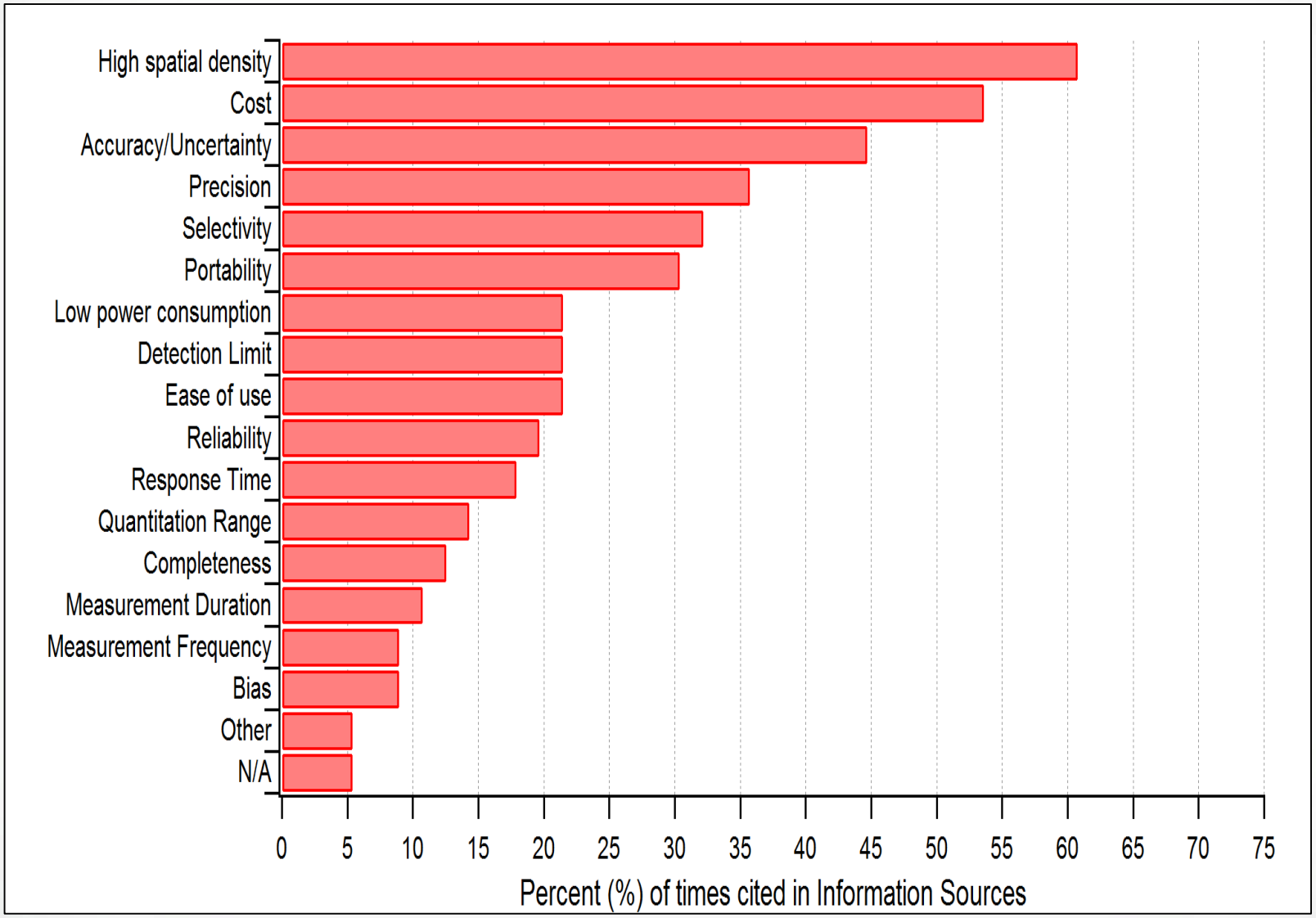
( ) represents the number of references used in the statistic

Frequency of DQOs/DQIs Reported

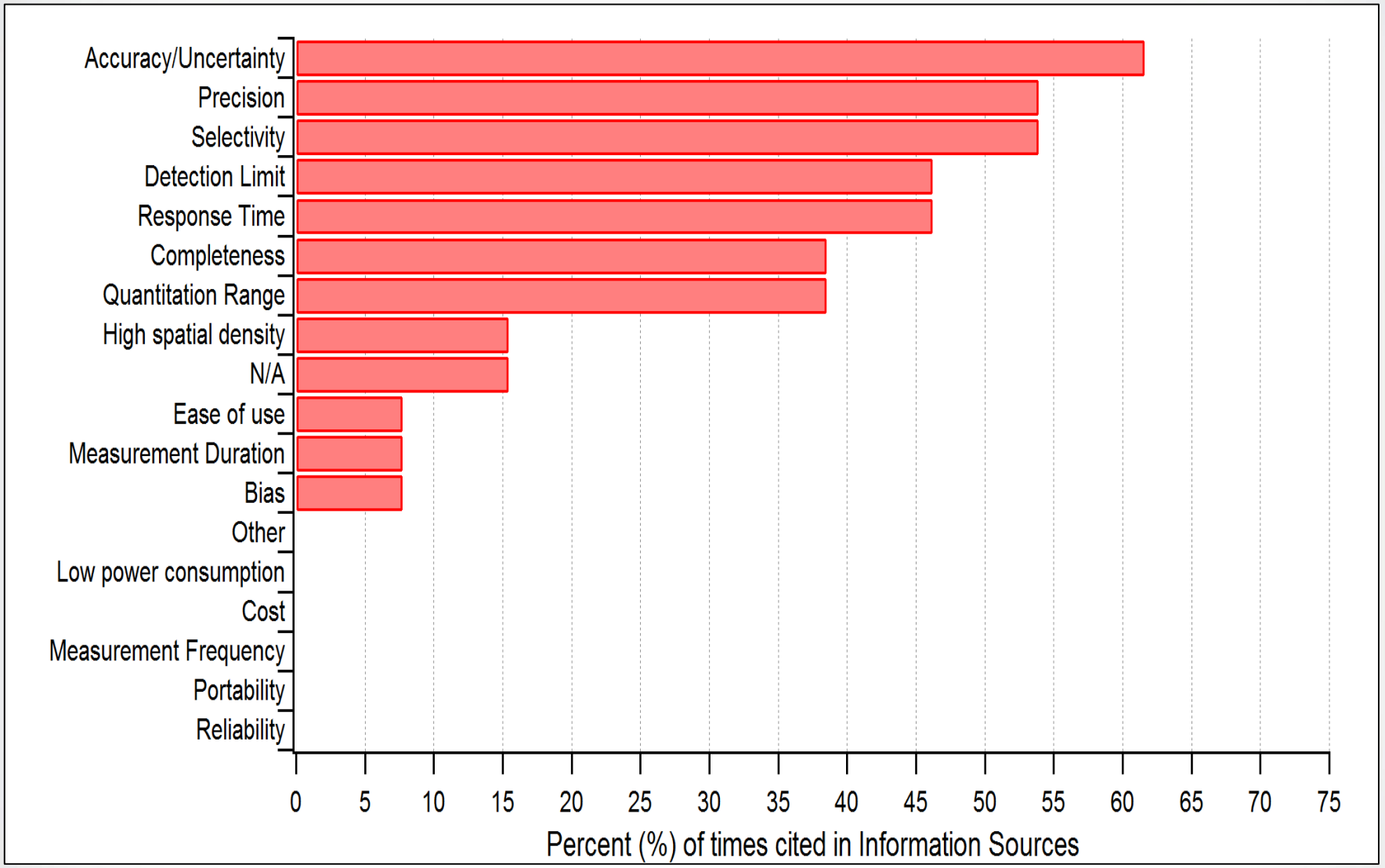
Performance Characteristic/DQI	$PM_{2.5}$
Accuracy/Uncertainty	84% (16)
Bias	5% (1)
Completeness	26% (5)
Detection Limit	26% (5)
Measurement Duration	26% (5)
Measurement Frequency	26% (5)
Measurement Range	47% (9)
Precision	42% (8)
Response Time	0% (0)
Selectivity	11% (2)
Other	5% (1)
% All Information Sources	40% (19)

( ) represents the number of references used in the statistic

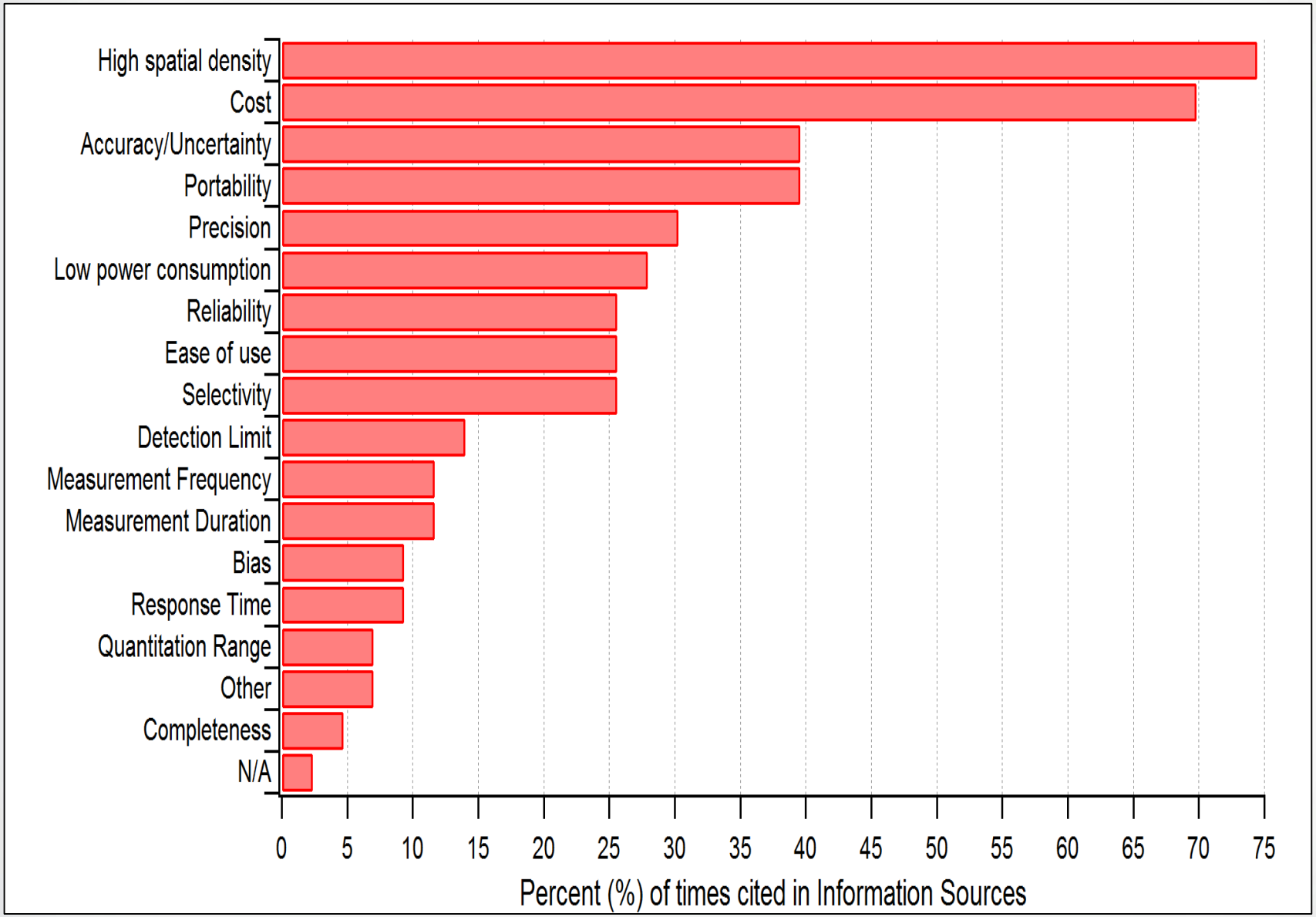
All Application Uses-Based References



Decision Reporting Based References



Non-Regulatory Use-Based References (Spatio-temporal, Comparisons, Trends)

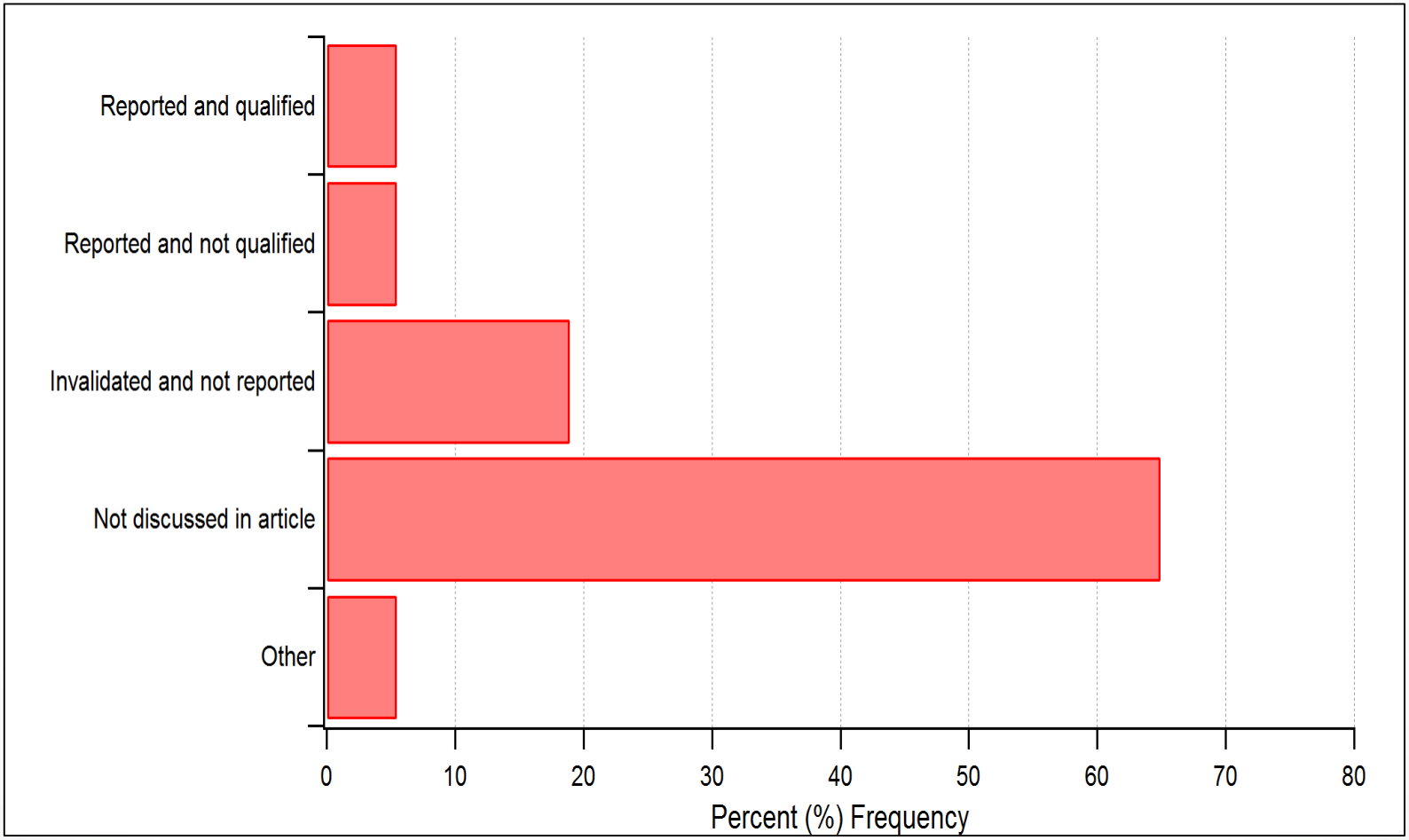


Sensor Comparison with Reference Monitors

$PM_{2.5}$
$R^2 = 0.07\text{-}0.91\ (0.78)$

( ) represents median values

Percentage of Erroneous Data Treatment



PM2.5 DQO/DQIs and Use Category

Performance Attributes/DQIs	Spatio-temporal Variation*	Comparison*	Trend	Decision Support*
Accuracy/ Uncertainty	R^2: (0.4225-0.4356, 0.3969-0.4489) [89], 0.62-0.71 [51], 0.91 [65]	R^2: ≥0.73-0.76 [50]		R^2: ≥*0.8649 [2]*, **(0.7225-0.9025) [1]**
	$\%Diff_{flow}$: ±10% [74]	$\%Diff_{flow}$: ±10% [74]		
	$\%Diff_{zerodrift}$: <20% [74]	$\%Diff_{zerodrift}$: <20% [74]		

*U.S., EU, and China references are shown in **bold**, <u>underline</u>, and *italics*, respectively

PM2.5 DQO/DQIs and Use Category

Performance Attributes/DQIs	Spatiotemporal Variation*	Comparison	Trend	Decision Support*
	σ: 1-10 µg/m^3 [53] %Diff: 9% [63] Relative expanded uncertainty: 50% at 25 µg/m^3 with an averaging period of 1 year [84] Short term drift: <0.5%/24 hours [97] Long term drift: <5%/month [97] RMSE/$\sigma_{reference}$ ≤1 [64]			RPD_{flow}: ≤2% [3] $\%Diff_{specifiedflow}$: **±5% [7],** ±5% [2] $\%Diff_{onepointflow}$: **±4% [7]** $\%Diff_{multipointflow}$: **±2% [7]** T_{amb} (°C): **±2 [85]**, *±2 [2]*, ±2 [3] P_{amb} (mm Hg): **±10 [7]**, *≤ 7.5 [2]*, ±7.5 [3] RH_{amb}: ±5% [3] Clock/timer (sec): **±60 [7]**, *±20 [2]* D_{50}: *2.5±0.2 µm[2]* Collection efficiency: σ_g = *1.2±0.1 [2]* Average flow indication error: *≤2% [2]*

*U.S., EU, and China and is shown in **bold**, underline, and *italics*, respectively

PM2.5 DQO/DQIs and Use Category

Performance Attributes/DQIs	Spatiotemporal Variation	Comparison	Trend	Decision Support*
				Slope: *1±0.15 [2]*, **1±0.10 [1]** Intercept (µg/m^3): *0±10 [2]*, **0±2 [1]** Aerosol transmission efficiency: *≥97% [2]* Expanded uncertainty: <u><25% in 24-h averages [3]</u> Zero level: <u><2.0 µg/m^3 [3]</u> Zero check: <u>0±3 µg/m^3 [3]</u> Maintenance interval: <u><14 days [3]</u>

*U.S., EU, and China and is shown in **bold**, <u>underline</u>, and *italics*, respectively

PM2.5 DQO/DQIs and Use Category

Performance Attributes/DQIs	Spatiotemporal Variation*	Comparison*	Trend*	Decision Support*
Bias	Bias (%): (<20, <50)[10]	Bias (%): (<30, <30, <50) [10]	Bias (%): <50 [10]	
Completeness	Completeness (%): (≥50, ≥80) [10], 75 [54]	Completeness (%): (≥50, ≥75, ≥80) [10], ≥75% [50]	Completeness (%): ≥50 [10]	Completeness (%): *85 [2]*, <u>≥90 [3]</u>
Detection Limit	Detection limit: 10 µg/m^3 [54], 5 µg/m^3 [97]			Detection limit (µg/m^3): <u><2.0 [3]</u>, **2 [7]**
				T_{amb} resolution: **0.1 °C [7]** P_{amb} resolution: **5 mm Hg [7]**

*U.S., EU, and China and is shown in **bold**, <u>underline</u>, and *italics*, respectively

PM2.5 DQO/DQIs and Use Category

Performance Attributes/DQIs	Spatiotemporal Variation*	Comparison*	Trend	Decision Support*
Measurement Duration	Measurement duration: 30 sec [53], 1 hour [54]	Measure-ment duration = 1 min [51], 1 hour [50]		Measurement duration: **60 min [7]**
Measurement Frequency	Reporting interval: 1 second raw sensor output interval [63] Minimum measurement frequency: 10 s [65], 12 h [89] Averaging time: >4 times the sensor response time [84]			Flow rate measurement intervals: **≤30 sec [7]**

*U.S., EU, and China references are shown in **bold**, <u>underline</u>, and *italics*, respectively

PM2.5 DQO/DQIs and Use Category

Performance Attributes/DQIs	Spatiotemporal Variation*	Comparison*	Trend*	Decision Support*
Measurement Range	Concentration range: <100 µg/m^3 [63], 0.1-200 µg/m^3 [74], 0-250 µg/m^3 [97]	Concentration range: 0.1-200 µg/m^3 [74]		Concentration range: *0-1000 µg/m^3 [2]*, (0-1000$_{24h\text{-}avg}$, 0-10000$_{1h\text{-}avg}$ µg/m^3) [3], **3-200 µg/m^3 [1]**
Precision	CV (%): (<20, <50)[10]	CV (%): (<30, <30, <50)[10]	CV (%): <50 [10]	CV$_{conc}$: **≤5%[1]**, *≤15% [2]*
	CV$_{flow}$: ±10% [74]	CV$_{flow}$: ±10% [74]		CV$_{flow}$: **<2% [7],** *≤2% [2]*, (Avg: ≤2%, Inst.: ≤5%) [3]
	CV$_{zerodrift}$: ±10% [74]	CV$_{zerodrift}$: ±10% [74]		
	R^2: 0.95-0.99 [51], 0.9801 [89] Unbiased variance estimate: 12% [54],			σ**: ≤2 µg/m^3 [1]** Precision: <2.5 ug/m^3 [3] RMS: **15% [1]**

*U.S., EU, and China references are shown in **bold**, underline, and *italics*, respectively

PM2.5 DQO/DQIs and Use Category

Performance Attributes/DQIs	Spatiotemporal Variation*	Comparison	Trend	Decision Support*
Response Time				
Selectivity	Temperature impact on sensor sensitivity: <0.3% from -10 to 50 °C [97]			Temperature influence: zero temperature dependence under 2.0 µg/m^3 [3], <5.0% change in min and max temperature conditions [3]

*U.S., EU, and China are shown in **bold**, <u>underline</u>, and *italics*, respectively

PM- Key Findings on Performance Attributes

Particulate Matter ($PM_{2.5}$)

- Precision – lower CV for concentration and flow for decision support
- Accuracy/uncertainty –higher r^2 for decision support compared to spatiotemporal
- Detection limit – lower detection limit for decision support

PM- Key Findings on Performance Attributes

Particulate Matter ($PM_{2.5}$)

- Measurement duration – shorter measurement duration for comparison and spatiotemporal
- Measurement range – smaller concentration range (0-200 µg/m^3) for comparison and spatiotemporal compared to larger ranges (0-1000 µg/m^3) for European Union and China Standards under decision support
- Completeness – higher requirements for completeness for decision support