

Seamless Integration of DAQ Systems into OEM Test Ecosystems: Standards, Interfaces, and Future Trends

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Abstract:

The increasing complexity of aerospace and automotive test environments is driving a fundamental shift in the integration of data acquisition (DAQ), telemetry, and analytics systems. Modern test programs require scalable and flexible architectures that enable seamless integration of distributed instrumentation into OEM ecosystems while maximizing the utilization of expensive test assets.

This paper examines the evolution of DAQ integration from traditional data transport interfaces toward standardized ecosystems that support configuration, diagnostics, and system orchestration. Established protocols such as Modbus TCP and IENA, are compared with more advanced approaches including ASAM XCP on TCP, IPEaeroAPI and iDDS. The paper highlights how standardized interfaces and metadata descriptions transform data recorders from passive logging devices into intelligent systems capable of signal interpretation, event detection, condition-based recording, and automated data quality monitoring.

Building on lessons learned from the automotive industry, the paper further explores the transition from standalone DAQ systems to cloud-connected test ecosystems. Automotive fleet testing demonstrates how cloud-based architectures, intelligent processing, remote monitoring, and centralized data management enable efficient operation of globally distributed test fleets while reducing engineering effort and accelerating validation cycles.

By combining aerospace-specific standards with proven concepts from automotive measurement, calibration, diagnostics, and cloud-based fleet testing, the paper outlines a pragmatic path toward scalable, secure, and future-proof test and telemetry ecosystems. Particular focus is placed on interoperability, intelligent data recording, remote operation, and the role of cloud-native infrastructures in future aerospace validation programs.

Key words: Data Acquisition, Test Instrumentation, Protocol Standardization, Telemetry, Cloud-Based Testing

Introduction

In the 1990s, the automotive industry began transitioning its testing philosophy. Until then, it was common practice — in wind tunnel facilities, for example — to locate the entire data acquisition system (DAQ) in a separate, temperature-controlled room. Before each test, the unit under test had to be wired to the DAQ at the facility. This process could take several days, and any wiring errors had to be traced and corrected before testing could begin, leaving the expensive facility idle.

The first facilities began reversing this concept by mounting the DAQ directly on the unit under test. The key advantage was a significant increase in facility utilization: wiring and functional checks could be performed in a

separate preparation room, while another engine or vehicle was already being tested in the facility. This also introduced a new level of flexibility and scalability. Testing order could be changed at short notice — for instance, if an issue was discovered during preparation. When new measurement signals were required, there was no need to re-configure the fixed facility infrastructure; an additional DAQ module was simply added to the unit under test.

This shift made it necessary to move from rack-mounted, laboratory-grade DAQ systems to mobile, rugged systems capable of operating accurately under harsh environmental conditions — including wide ambient temperature ranges, vibration, and humidity.

The same concept has since been adopted in aerospace engine test cells, and its application is growing rapidly. Engine test cells are extraordinarily expensive assets: GE's facility required a \$50 million investment involving more than 150 suppliers and 700 construction workers; Rolls-Royce's indoor aerospace testbed required a £90 million investment and nearly three years of construction. Given these costs, maximizing facility utilization is of critical economic importance. Engine test cells are also the primary means of validating fuel efficiency and emissions compliance — measurements that directly influence fuel consumption, component lifetime, and regulatory certification.

The traditional approach placed the DAQ in a temperature-controlled room adjacent to the test stand, connected via long sensor cables with multiple connectors running to the engine. This kept DAQ requirements low (stable 23°C, no vibration), but at a significant operational cost: wiring the engine at the test stand could take up to several weeks, during which the cell could not be used. Workers were also required to wire in exposed positions and challenging environmental conditions, raising health and safety concerns. Long cable runs introduced additional measurement uncertainty through connector oxidation and cable resistance.

The modern approach mounts the DAQ directly on the engine pylon inside the test cell. Short sensor cables — without intermediate connectors — run directly from thermocouples and pressure sensors to the DAQ. Wiring and sensor verification are carried out in a preparation room before the engine enters the test cell. Once the engine is moved into the cell, only a single Ethernet cable needs to be connected instead of wiring 1000 sensors like thermocouples and others. This workflow allows multiple engines to be wired simultaneously in the preparation room, testing order to be changed if priority changes, and production and development engines to be intermixed in the schedule — all while the test cell itself remains in continuous use.

The environmental challenge that results from this mounting location is substantial. Ambient temperature in the test cell can range from -20°C in winter to over +40°C in summer, with rapid dynamic changes caused by engine-induced airflow immediately after starting. Vibration, water from rain or water injection tests, and intense acoustic noise are standard operating conditions.

In addition the seamless integration into OEM ecosystems is crucial for flexibility and scalability. This requires standardization and

implementation of protocols where many DAQ devices are compatible with. Then new sensors / measurement can be easily added.

The increasing complexity of aerospace and automotive test environments is driving a fundamental shift in how data acquisition (DAQ), telemetry, and analytics systems are integrated into OEM ecosystems. Modern test programs require seamless data flow from distributed sensors and instrumentation through secure networks into advanced analytics frameworks, digital twins, and AI-based decision systems. Achieving this efficiently remains a major challenge due to the diversity of interfaces, protocols, and legacy infrastructures.

This paper addresses the seamless integration of DAQ products into OEM data acquisition and test software environments, drawing on IPETRONIK's multi-interface strategy. Several established and emerging interfaces will be discussed, including iDDS (the industry standard initiated by Rolls-Royce and adopted by OEMs such as GE Aerospace and MTU Aero Engines), IPEaeroAPI (based on XCP on TCP, Automotive Standard), Modbus TCP and IENA / Airbus Flight Test Instrumentation standards. Each of these interfaces supports data streaming and status monitoring to varying degrees, while configuration capabilities and extensibility differ significantly.

Beside above-mentioned communication protocols, standards for data recording have been established. In defense and flight test IRIG 106 Chapter 10 is well established, while MDF 4.0 – measurement data format - is the automotive correspondent.

The paper highlights that while standardization promises interoperability, every interface still requires substantial implementation effort on both DAQ supplier and OEM sides. iDDS, for example, offers a powerful and flexible framework but comes with high initial integration costs, whereas simpler protocols such as Modbus TCP or IENA offer fast adoption at the expense of configurability for the DAQ.

Beyond classical DAQ protocols, the paper introduces concepts derived from automotive fleet testing and discusses the potential benefits of transferring these approaches to the aerospace industry, especially benefitting applications like urban air mobility (UAM) and unmanned aerial vehicle (UAV) operations. Cloud solutions enable global data availability and analysis immediately after test runs. An asset becoming increasingly important in order to accelerate validation and verification processes in aerospace.

The topics covered include smart operations executed directly on data loggers, secure data acquisition through encryption and cyber-resilient system architectures, cloud-based fleet and data management, as well as the integration of AI-driven analytics.

By combining aerospace-specific standards with proven automotive fleet and cloud concepts, this presentation outlines a pragmatic path toward scalable, secure, and future-proof test and telemetry ecosystems across industries.

Integration into OEM Ecosystem

Seamless integration into an OEM ecosystem is not only a matter of providing an Ethernet interface or a data stream. In modern test cells and flight-test environments, the interface determines how easily an OEM can add channels, exchange hardware, automate setup procedures, validate configurations, and route data into existing real-time monitoring, recording, analysis, and archiving systems. The historical development of DAQ and telemetry protocols therefore shows a clear transition: early interfaces primarily standardized the transport or recording of measurement data, whereas newer approaches increasingly include metadata, configuration, diagnostics, and system-level orchestration.

A first group of protocols can be classified as data-oriented interfaces. These protocols are widely used because they are comparatively simple, robust, and easy to integrate, but they do not provide a complete standardized model for configuring a DAQ system, such as sensor type, measurement range, excitation, sampling rate, scaling, channel naming, or calibration information. In this category, Modbus TCP is one of the oldest and most widely adopted industrial examples. The original Modbus protocol was introduced by Modicon, today Schneider Electric, in 1979, while the open Modbus TCP/IP specification was developed in 1999 to bring the Modbus register model onto standard Ethernet/TCP/IP networks. Modbus TCP is highly established in industrial automation, PLC, SCADA, energy, infrastructure, building automation, and general monitoring applications. Its strength is the simple exchange of register-based process values across multi-vendor systems. However, in a DAQ context, the semantic meaning of each register and the complete DAQ configuration remain project- or vendor-specific; the protocol does not define a standardized instrumentation configuration model. [1]

In aerospace flight-test instrumentation, IENA represents another important data-oriented protocol family. IENA is an Airbus-specific

Ethernet data format for Flight Test Installation networks and was first used for the A380 program. Airbus documentation describes IENA as a format used to transmit test data from acquisition systems to processing units over an Ethernet-based FTI network, typically using UDP/IP, with data such as analog, ARINC, AFDX, CAN, and other acquired parameters encapsulated into a common packet format. The first publicly referenced issue history of the Airbus IENA format document starts in 2007, while its operational introduction belongs to the A380 flight-test generation in the early to mid-2000s. IENA is therefore strongly established in Airbus-related FTI environments and in the supplier ecosystem serving those installations. Its purpose is efficient and deterministic distribution of acquired and computed parameters to recorders and processing systems. With XidML, IENA packages are uniquely described and can be consistently applied to both transmitting and receiving devices. This eliminates the need for manual protocol configuration. However, the configuration of the DAQ front end remains outside the scope of the core IENA data packet concept and is typically managed using DAQ-specific engineering tools. [2]

Besides communication protocols, IRIG 106 Chapter 10 as standard for data recording was established. It emerged from the need, identified in the late 1990s, to replace many unique recorder formats with a common computer-compatible digital data acquisition and on-board recording standard. The original Chapter 10 standard was issued in 2004, and the first IRIG 106 version containing Chapter 10 was IRIG 106-04. It is widely used in military and civil aerospace flight testing, US and allied test ranges, recorder systems, mission recorders, video/data servers, health monitoring, mission planning, debriefing, and other applications where recorded data interoperability is essential. Chapter 10 defines packet formats, time correlation, data types, recorder interfaces, and file structures for many data sources, including PCM, MIL-STD-1553, ARINC 429, analog, video, image, UART, Ethernet, time, and discrete data.[3]

The next integration level of communication protocols is represented by manufacturer-dependent interfaces that combine measurement data transfer with device configuration. An example is IPETRONIK's IPEaeroAPI, which is based on XCP on TCP. XCP itself is standardized by ASAM as the Universal Measurement and Calibration Protocol. It was established as ASAM MCD-1 XCP in 2003 and defines a bus-independent

master-slave protocol for acquiring measurement variables, adjusting parameters, stimulation, programming, and accessing memory-oriented data over different transport layers, including Ethernet via UDP/IP and TCP/IP.[4] The automotive origin of XCP is important because it brings mature mechanisms for configuring DAQ lists, selecting variables, starting and stopping acquisition, reading device information, and handling high-rate measurement data.

In an aerospace DAQ context, an IPEaeroAPI-style interface uses these XCP concepts to expose IPETRONIK devices to OEM software in a structured way. Compared with pure data-stream protocols, this allows the host system not only to receive measurement values but also to configure the measurement setup, verify device status, and control acquisition behavior. The advantage is a high level of functional integration with the supplier's DAQ hardware and software architecture. The limitation is that the object model, supported features, and configuration workflow remain manufacturer-specific. OEMs therefore gain powerful integration capabilities, but they still need a dedicated driver or software adaptation for that supplier interface.

The highest level of ecosystem integration is achieved by manufacturer-independent or OEM-driven standardized protocols that combine data, metadata, configuration, diagnostics, and system orchestration. The most relevant example in aerospace engine testing is iDDS — Instrumentation Data Distribution Service. iDDS was introduced by Rolls-Royce and developed in cooperation with MDS Aero and the iDDS Working Group. It was created as a response to monolithic single-supplier systems that were common in the early 2000s and became difficult to modify, maintain, or upgrade over long test-cell lifetimes. The iDDS ecosystem now includes major engine OEMs, test-facility designers, and instrumentation vendors, including Rolls-Royce, GE Aerospace, MDS Aero, National Instruments, IPETRONIK, Scanivalve, UEI, and others.

Technically, iDDS extends the OMG Data Distribution Service concept toward instrumentation and DAQ applications. It uses a data-centric publisher/subscriber architecture in which nodes can generate, process, and consume measurement data over a real-time backbone. Unlike data-only protocols, iDDS includes channel metadata, IEEE 1588/PTP-based source timestamping, a configuration system, and system-health monitoring. The configuration server manages network setup and sends the required configuration information to the nodes, enabling plug-and-play

interoperability of compliant instrumentation and software. This allows OEMs to build modular, multi-vendor test systems in which hardware can be exchanged or extended with reduced impact on the rest of the ecosystem.

The practical consequence for OEM integration is that no single protocol currently covers all installed bases and all use cases. Modbus TCP is widely supported in legacy infrastructures, while IENA is establishing as standard for Flight Test Instrumentation in Europe. Both are well suited for transmitting measurement values or bus data, but they require additional engineering effort for configuration of data acquisition settings. Manufacturer-specific APIs such as IPEaeroAPI provide deeper configuration and control capabilities, but they tie the integration to a specific supplier implementation. Standardized multi-vendor approaches such as iDDS address the broader OEM requirement: not only moving data, but also making instrumentation configurable, diagnosable, and replaceable across a long-lived test ecosystem.

Therefore, a DAQ platform should not rely on a single interface. It should support legacy data protocols, supplier-specific high-functionality APIs, and emerging multi-vendor standards in parallel, allowing each OEM to integrate new measurement capabilities without redesigning the complete test-cell or flight-test software architecture.

Protocol Capability and Integration Effort Comparison

The discussed protocols address different integration requirements within OEM test ecosystems. While some focus on efficient data transport, others additionally support device configuration and system orchestration. Table 1 provides a qualitative comparison of the most relevant characteristics.

Protocols such as Modbus TCP, and IENA are primarily designed for standardized data transport. They enable interoperability at the data level but provide no support for the configuration and management of the underlying DAQ infrastructure. In contrast, IPEaeroAPI (based on ASAM XCP on TCP) and iDDS extend beyond data exchange by standardizing the interaction with the DAQ system itself. This includes capabilities such as device configuration, health monitoring, diagnostics, and acquisition control. As a result, these approaches enable deeper integration into OEM ecosystems, albeit at the cost of higher implementation effort for both suppliers and OEMs.

Tab. 1: Comparison of selected DAQ integration protocols

Protocoll	Introduced	Capability	OEM Effort	Vendor Effort	Data Rate
Modbus TCP	1999	Data	Low	Low	Medium (Request-Response)
ASAM XCP on TCP	2003	Data + DAQ lists + user command + events	Medium-High (High for multiple Vendors)	Medium	High
IENA	2007+ (public)	Data	Medium	Medium	High
iDDS	~2010	Data + Configuration + Diagnostics	High	High	High* (optimized QoS)
IPEaeroAPI (XCP-based)	2015	Data + Configuration + Diagnostics	Medium-High (High for multiple Vendors)	Medium	High

An interesting observation is the difference in the historical evolution of these standards. ASAM XCP was introduced in 2003, providing a standardized mechanism for measurement, calibration, and configuration of distributed systems. Comparable concepts for vendor-independent instrumentation integration in aerospace only gained broader adoption several years later with the emergence of initiatives such as iDDS. This suggests that the automotive industry recognized the importance of standardized measurement and instrumentation integration earlier, driven by increasing ECU complexity, calibration requirements, and large-scale distributed testing environments. Many of the challenges currently addressed in aerospace test ecosystems—such as scalable DAQ integration, standardized configuration, and seamless data accessibility—have therefore already been explored in the automotive domain for more than two decades.

The automotive industry has established a comprehensive ecosystem of complementary standards such as XCP, A2L, AUTOSAR, UDS, and FIBEX. Together, these standards cover software architecture, measurement, calibration, diagnostics, and network description. In contrast, aerospace test and telemetry environments are only recently moving towards similarly integrated and vendor-independent ecosystems through initiatives such as iDDS

Impact of standardized interfaces on Data Recording

The benefits of standardized interfaces extend far beyond the integration of DAQ systems into OEM ecosystems. They also fundamentally change the role of the data recorder. Traditionally, recorders operated as passive devices that captured incoming data streams without understanding their semantic meaning. Standardized interfaces, combined with standardized metadata descriptions, enable the recorder to interpret measurement channels and operate on a signal level rather than merely storing raw data traces.

A prominent example from the automotive domain is the combination of ASAM XCP and A2L. While XCP standardizes the communication interface, the A2L description file provides a standardized definition of measurement and calibration objects, including measurement variables, engineering units, scaling information, data types, memory addresses, calibration parameters, and functional groupings. The correspondent in IENA is the XidML description file. As a result, the recorder can automatically decode and interpret signals without requiring project-specific decoding software.

Once signals are available in an interpreted form, the recorder can perform significantly more advanced functions. Instead of simply storing all incoming data, it can monitor signal values in real time, detect abnormal behavior, and execute predefined actions. Examples include

generating notifications when limits are exceeded, initiating triggered recordings upon fault conditions, or selectively increasing recording rates during critical events. A practical example is fault-triggered recording, where only relevant pre-trigger and post-trigger data are stored at full resolution, reducing storage requirements while preserving all information required for root-cause analysis.

Signal awareness also enables direct visualization through HMIs, mobile applications, and remote monitoring systems. Furthermore, advanced processing functions—often referred to as Smart Operations—can be executed directly on the recorder. These functions may detect sensor failures, intermittent wiring faults, sensor drift, implausible signal behavior, or other anomalies that cannot be identified using simple threshold monitoring alone. In addition, signals can be converted into engineering units, combined with other measurements, filtered, aggregated, or post-processed before storage or transmission.

Standardized and semantically described measurement data is also a prerequisite for AI-based analytics. Machine learning algorithms can utilize signal-aware datasets to identify anomalies, detect sensor degradation, classify operating conditions, and support automated root-cause analysis.

Consequently, standardized interfaces and metadata transform data recording from a passive logging task into an intelligent measurement management process. The recorder evolves from a device that blindly captures data streams into a system that understands measurement content, identifies invalid or suspicious data at an early stage, supports condition-based recording strategies, and optimizes storage utilization. This significantly improves data quality, accelerates test result analysis, and reduces the effort required for post-processing and troubleshooting.

While automotive measurement systems achieved a high degree of interoperability through the combination of XCP, A2L and also UDS, and AUTOSAR, aerospace test and telemetry ecosystems took a similar way with IENA and XidML – comparable to XCP and A2L respectively. In contrast to automotive standards, configuration of DAQ and sensors relies still on proprietary interfaces. Current initiatives such as iDDS indicate a growing demand for a vendor-independent ecosystem that standardizes not only data transport and recording, but also instrumentation

configuration, diagnostics, and system orchestration.

From DAQ to Cloud-Native Test Ecosystems

The next evolutionary step in test and measurement systems is the integration of DAQ infrastructures into cloud-connected ecosystems. This transition has already become common practice in large-scale automotive validation programs and provides valuable insights for future aerospace test environments.

Automotive development programs typically operate significantly larger test fleets than aerospace programs. Pre-series validation campaigns often involve more than one hundred vehicles operating simultaneously across the globe. These campaigns are designed to expose vehicles to a wide range of environmental and operational conditions, including extreme cold and heat, high-altitude environments, urban traffic, highway operation, and increasingly complex Advanced Driver Assistance Systems (ADAS) and autonomous driving scenarios.

A key challenge is the enormous amount of generated data. In particular, ADAS and automated driving validation can generate multiple terabytes of data per vehicle and day. Recording and transferring all available sensor data continuously is neither technically nor economically feasible. As a result, modern validation programs rely on intelligent recording strategies, event-based data acquisition, edge processing, and cloud-based data management.

The typical architecture consists of distributed DAQ systems connected to a data recorder or logger, which acts as the central gateway between the vehicle and the cloud. Besides recording measurement data locally, the logger provides connectivity via cellular or Wi-Fi networks and performs tasks such as data buffering, compression, event detection, and secure data transfer. This architecture allows measurement data to be collected, processed, and uploaded efficiently without requiring permanent high-bandwidth connectivity.

Cloud integration fundamentally changes the testing workflow. Instead of deploying measurement engineers to every test location, only the vehicle and driver need to be present in the field. Drivers can often be recruited locally, while measurement engineers, calibration specialists, software developers, and validation teams remain at their development centers. Measurement data, diagnostics information, and system status are continuously synchronized with the cloud and become available for analysis by globally distributed teams.

The cloud-connected logger also enables remote interaction with the measurement system itself. Test configurations can be updated over-the-air, recording parameters can be adjusted remotely, and system health can be monitored continuously. This significantly reduces travel effort, shortens reaction times, and increases the utilization of both test vehicles and engineering resources.

Such cloud-based validation ecosystems typically provide:

- Fleet-wide monitoring of vehicles, loggers, and DAQ systems
- Real-time telemetry, diagnostics, and KPI visualization
- Remote configuration and control of measurement systems
- Automated event- and condition-based recording strategies
- Intelligent data compression, packaging, and cloud upload
- Centralized storage and worldwide availability of measurement data
- Automated notifications, alarms, and workflow integration
- Collaboration across globally distributed engineering teams
- Firmware updates

A practical example is IPEcloud2, IPETRONIK's cloud-based platform for fleet testing and measurement data management. Combined with intelligent data recorders, the platform enables centralized fleet monitoring, remote access to DAQ systems, automated data synchronization, project-specific data management, KPI visualization, user and access management, and collaborative analysis workflows. The result is a highly scalable test infrastructure that allows hundreds of vehicles to be monitored and managed from a centralized engineering environment.

As test systems become increasingly connected through Ethernet networks and cloud infrastructures, cybersecurity becomes a critical design requirement. Modern DAQ and recorder architectures therefore require encrypted communication, authentication mechanisms, secure boot concepts, and role-based access control to protect measurement data and test infrastructure from unauthorized access.

The underlying concepts are equally relevant for future aerospace applications. Flight testing in urban air mobility platforms (UAM), and unmanned aerial vehicles (UAV) are

increasingly facing challenges similar to those already encountered in automotive fleet testing: geographically distributed test assets, growing data volumes, globally distributed engineering teams, and pressure to accelerate validation cycles. Consequently, cloud-connected data recorders, intelligent edge processing, and centralized data management are expected to become key enablers for the next generation of aerospace test and telemetry ecosystems.

Summary and Outlook

The evolution of test and telemetry systems has been driven by the need for greater flexibility, scalability, and utilization of increasingly expensive test assets. The transition from centralized DAQ installations to distributed, ruggedized measurement systems mounted directly on the test object has significantly improved operational efficiency in both automotive and aerospace testing environments.

At the same time, the integration of DAQ systems into OEM ecosystems has become a critical success factor. The comparison of interfaces such as Modbus TCP, IENA incl. XidML, ASAM XCP on TCP incl. A2L, and iDDS demonstrates a clear trend: data transport alone is no longer sufficient. Modern test environments increasingly require standardized mechanisms for configuration, diagnostics, metadata management, and system orchestration. Aerospace continues to move from legacy and OEM-specific solutions to comprehensive ecosystems built around standards.

Standardized interfaces and metadata models also enable a fundamental shift in data recording. By interpreting measurement signals rather than simply storing data streams, intelligent recorders can perform event detection, condition-based recording, data validation, and advanced signal processing directly at the edge. This improves data quality while reducing storage and analysis effort.

The next stage of this evolution is the migration from distributed DAQ systems to cloud-connected test ecosystems. Lessons learned from automotive fleet testing show how cloud services, remote monitoring, edge intelligence, and centralized data management can significantly increase the efficiency of globally distributed validation programs. Similar concepts are expected to play an increasingly important role in aerospace flight testing, particularly for UAM platforms, and UAVs.

Although a single universal standard is unlikely to replace all existing interfaces in the foreseeable future, the industry is clearly moving toward more interoperable, metadata-driven,

and cloud-enabled architectures. Future test ecosystems will integrate standardized instrumentation interfaces, intelligent edge processing, cloud-native data platforms, and AI-assisted analytics into a seamless workflow, accelerating validation activities, improving data accessibility, and increasing engineering productivity throughout the entire test lifecycle.

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