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A RUGGED, LOW-COST, ADVANCED DATA-ACQUISITION SYSTEM FOR FIELD TEST PROJECTS

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ABSTRACT

The National Renewable Energy Laboratory (NREL) has teamed up with Zond Systems, Inc., to provide a rugged, low-cost, advanced data-acquisition system (ADAS) for use in field test projects. The ADAS simplifies the process of making accurate measurements on mechanical equipment exposed to harsh environments. It provides synchronized, time-series measurement data from multiple, independent sources. The ADAS is currently being used to acquire data from large wind turbines in operational wind-plant environments. ADAS modules are mounted on rotating blades, turbine towers, nacelles, control modules, meteorological towers, and electrical stations. The ADAS has the potential to meet the testing and monitoring needs of many other technologies as well, including vehicles, heavy equipment, piping and power transmission networks, and building energy systems.

KEY WORDS

Data Acquisition, A/D Conversion, Rugged Environment Test Measurement, Distributed Source Telemetry

INTRODUCTION

The ADAS is comprised of multiple, microprocessor-based data-acquisition modules (DAMs) designed to be located near the sources of measurement. Each DAM converts analog signals from up to eight local sensors and transducers into highly noise-tolerant digital signals. The digital signals are stored in the DAM and can be transmitted or conducted in a number of ways to a ground station. Each DAM contains sophisticated signal conditioning capabilities, built-in calibration capabilities, a computer to control operation and communication, and up to 4 Mb of random access memory (RAM) to store data. The DAMs can operate in a stand-alone mode, meaning that they can independently acquire long-term average data to internal memory for durations up to months. Short bursts of high-rate data can also be collected. The DAMs can additionally operate in a real-time mode, continuously transmitting updated data to the ground-station real-time display. The ADAS acquisition rate is user selectable over a range of 160 samples per second to 10-minute averages. Up to 14 eight-channel DAMs can be independently located on various components of the system to be measured to provide up to 112 individual measurement channels. Multiple-DAM data acquisition is synchronized at rates up to 160 Hz with all 112 channels recording data simultaneously. Susceptibility to induced noise is reduced by using instrumentation amplifiers and high-speed integrating converters, and by locating individual DAMs close to the measurement source. Signals from digital and analog sources are connected directly to the inputs of local DAMs. A standard personal computer (PC) operates as a ground station and is used to set up the DAMs, coordinate data transmission to and from the remote DAMs, display real-time values, and archive data sets.

BACKGROUND

Over the last few years, NREL has become involved in many cooperative projects with industry partners to explore new design concepts and evaluate their capabilities. Many of these projects require loads and performance testing of wind turbine systems and components. To quantify the benefits and merits of design changes and enhancements, accurate and reliable field-based data measurement systems are needed. There are many conventional commercial data-acquisition systems on the market today, but few are suitable for in-situ testing of large mechanical systems (such as wind turbines) exposed to a wide range of environmental extremes. Most conventional commercial systems are designed for use in laboratory applications. Field-based data-acquisition needs are very different from those of laboratory experiments. In a laboratory, experiments, equipment, and their environment are typically controlled to ensure that measurements are appropriately made. Few conventional data-acquisition systems are designed to operate accurately when exposed to extremes in temperature, vibration, or gravitational loading. Conventional systems also typically require signals from sensors and transducers to be conducted over cables from the measurement source to the data-acquisition system. In a field environment, cables might be difficult or impossible to use. Most of the hardware designed for field testing was developed for aerospace and military applications, and it is usually too expensive for commercial use. NREL and Zond Systems teamed up to develop the ADAS to provide a low-cost, field-based data-acquisition system that meets the needs of the commercial industry. Zond has experience in operating wind plants and has instrumented and tested electrical and mechanical systems since 1980. This system is based on an expanded version of previous systems designed, developed, and manufactured by Zond (Cousineau, 1989). The ADAS system was designed to perform the following:

- Obtain synchronized time-series data from multiple, independent sources.
- Decrease the time and effort required to instrument a field experiment, verify data validity, collect data, and perform preliminary data analysis.
- Improve the end-to-end accuracy of data collected in field experiments.
- Control all data-acquisition functions (data sample rate, anti-alias filter setpoints, channel configuration, calibrations, etc.) from the ground station.
- Provide a small and light system capable of making a wide variety of reliable measurements in rugged environments.
- Provide independent, stand-alone operation by utilizing telemetry and low power-consumption battery operation with in-situ recharge capability.
- Provide a complete integrated package using off-the-shelf components.
- Develop flexible, expandable hardware that can be integrated with common experiment control software to provide necessary quick-look data display, processing, and analysis capabilities.
- Provide a way to easily get experimental data into a standard PC data file format, thus enabling the use of inexpensive, standard PC-based software products to perform post-processing analyses and displays.

Obtaining measured values, however, is only a small part of the overall task. It is also necessary to verify measured values to ensure data accuracy and reliability, and to use those values to produce results in a quick and efficient manner. This requires data-acquisition hardware components which work in conjunction with data processing and analysis software. There are no existing systems which provide a complete package of hardware and software to meet the specific needs of the wind industry. NREL has begun to develop the ADAS to meet these needs, and this paper describes existing capabilities in detail. Further system software developments are forthcoming as outlined in the Future Plans section below.

THEORY OF OPERATION

The ADAS was designed to provide synchronized time-series data from all measurement sources. This means that data values are measured on all channels exactly at time T. At an exact time interval Δt later (e.g., if the sample rate was 40 Hz, Δt would be 0.025 seconds), data values on all channels are measured again, and so on. This measurement accuracy is necessary to minimize sample phase and skew effects. A typical application, for example, might require structural dynamic studies and load-path evaluations using data from multiple sensors mounted in various positions on a structure.

Taking the ADAS objectives into consideration, the required multiple-channels, multiple-source synchronized measurements can be performed in either the real-time or stand-alone mode. In the real-time mode, all data channels are synchronously sampled, and data are continuously streamed from many potential remote locations to a central receiving station. A computer at the central receiving station receives, combines, and stores the multiple stream data in real time. This option becomes expensive as sample rates and the number of channels increase because higher communication bandwidth and greater real-time computer processing and storage capability are required. In the stand-alone mode, all data channels are synchronously sampled and data values are recorded directly into the computer memory of microprocessor-controlled remote modules. Data sets are downloaded, combined, and stored on a central receiving station computer at a later time. This option eliminates the need for high bandwidth communication links and computing requirements, because data downloading does not have to occur in real time. NREL has traditionally operated data-acquisition experiments in the real-time mode. Higher bandwidth applications ($>$100 Hz) have been performed using pulse code modulation (PCM)-based telemetry systems designed for military and aerospace applications (Simms and Butterfield, 1990). These types of systems are not practical for the ADAS because high bandwidth telemetry equipment is not commercially available and costs are prohibitive for commercial applications. In other experiments, NREL has used typical personal computer (PC)-based data-acquisition systems to provide real-time measurement capability (Tangler, et al., 1989). These systems are extremely cost effective, but they require all analog signals to be conducted directly to the PC data-acquisition boards. Since PCs are not rugged enough to use in most field applications, they have to be located in suitable environments to which measurement signal cables have to be run. These systems do not meet the objectives of the ADAS because they are difficult to install and debug on wind turbines, especially for measurements made on the rotor. Analog signals conducted over long distances are susceptible to induced noise from ground loops, high power sources, and slip rings. This affects measurement reliability and sacrifices accuracy.

The ADAS compensates for the expense of high-rate digital systems and unreliable analog systems by combining both the real-time and stand-alone modes of operation. The real-time mode is utilized for low data rates. In this mode, the ground station continuously triggers, polls, downloads, and displays results, completing a cycle from all remote stations in less than one second. This allows real-time monitoring on a visual display of current conditions which vary at an acceptable rate compatible with a human interface. This rate is suitable for performing most required visual data checks and verifications and can be accomplished using inexpensive common communication technology. The stand-alone mode is utilized to obtain higher rate data sets by triggering all channels at all remote locations to start data acquisition at the exact same time. The real-time data values are streamed to internal memory on each microprocessor-controlled remote data-acquisition module. At the end of a given period of data acquisition, data are then downloaded. The ground station computer polls each remote site individually to initiate transmission of its data. The data from each remote site are sequentially collected at the ground station and then assembled into a single time-series data set. The advantages of stand-alone operation which contribute to the cost-effectiveness of the ADAS are as follows:

- o Low-cost radio frequency (RF) telemetry is practical since all data transmission can be done on the same RF system. The need for multiple frequencies and multiple ground station transceivers is eliminated.
- o A high rate mode of digital transmission (e.g., PCM) is not needed. Lower rate PC-compatible serial communication (e.g., RS-232 and RS-422) can be used.
- o Incoming data streams do not have to be multiplexed in real time.
- o Full duplex communication (transmission occurring simultaneously in both directions) is not required.
- o Digital data are in standard PC-compatible format and do not require special decommutation hardware.
- o A statistical summary characterizing data in remote memory can be downloaded and used to determine whether or not the entire time series is needed. This lends itself to automated test-matrix filling.

The disadvantages of stand-alone operation are as follows:

- o High rate data cannot be continuously streamed and, therefore, contiguous long-period records cannot be saved and unexpected transients may be missed.
- o Current conditions cannot be monitored while data from remote modules are being downloaded.
- o The user may have to wait long periods of time between events while data are being downloaded, which may slow down experiment tasks.

SYSTEM DESCRIPTION

The ADAS is defined as a complete signal-conditioning, data-acquisition, and data-processing package composed of both hardware and software components. Each ADAS package is made up of a single **Ground Station** and one or many **DAMs**. A variety of different types of **Sensors and Transducers** may be connected to the DAM's **Signal Conditioning Cards**. Up to eight cards may be installed in each DAM. These filter and digitize analog signals from the sensors and transducers, directly input digital signals, and provide data to the DAM's master processor. Each DAM has a single 68332 microprocessor which controls data acquisition and communication functions. DAM to ground station interface is provided via a **Communication Link**. The ground station utilizes **Control and Processing Software** to perform required functions. A sample six-DAM data-acquisition scenario is shown in Figure 1. Individual components of the ADAS system are further described and specified below.

Sensors and Transducers

The ADAS works with a wide variety of sensors and transducers and allows them to be easily connected to the DAMs. The sensors and transducers produce some form of digital or analog output signal that usually varies linearly, corresponding to changes in the measured parameter. Sensors and transducers vary widely and are extremely dependent on the nature of specific tests being conducted. Types of sensors and transducers typically used in wind turbine experiments are strain-gage bridges, strain-gage bridge-based transducers (such as pressure transducers or accelerometers), linear voltage output transducers, DC or AC pulse output sensors, other potentiometer or LVDT-based devices, and optical-type rotary encoders.

Data-Acquisition Modules

These are located near the source of the measurement to which transducer inputs are connected. They can be mounted at various locations, including on the hub of a rotating wind turbine, on the wind turbine tower or in the nacelle, on a meteorological tower, or in a turbine controller. This enables analog data signals to be digitized as close as possible to the measurement source to minimize noise induced by long signal paths. Many DAMs may be used concurrently. The DAMs may be exposed to harsh environments and are of robust design.

Environmental specifications are shown in Table 1. They are capable of being battery powered or AC/DC powered. The DAMs are able to accept, condition, and sample various types of analog and digital input signals from up to eight connected sensors and transducers.

Table 1. Data-Acquisition Module Physical and Environmental Specifications

Size	16.3 x 20.3 x 28.9 cm (7.25 x 9 x 12.8 in) diecast aluminum enclosure; easily mounted on or in another enclosure or structure
Temperature	-25° to 85°C (-13° to 185°F) operating
Environment	Sealed, rain-proof enclosure, 0% to 100% humidity including condensing atmosphere
Weight	Less than 9 Kg (20 lb.), excluding battery (with eight analog input signal conditioners and mating connectors)
Mounting	Internal and external mounting holes provided with enclosure
Connections	Easy to connect/disconnect standard connectors from input signal cables, battery packs, and communications
Channel signal conditioners	Easily interchangeable signal conditioning cards to provide for three types of signal inputs: either low- or high-level analog; digital; and high-speed pulse counting/anemometry
Battery operation	12 ampere-hour battery system; continuous operation duration can be extended using photovoltaic panels or DC power supply charging
Battery changing	Easily accessible and interchangeable batteries; battery change should take less than 5 minutes

Each DAM has eight slots which can hold any combination of analog, pulse counting, or digital signal conditioning cards. The analog card provides input signal conditioning, external device excitation voltages, anti-alias filtering, and analog-to-digital (A/D) conversion. A programmable instrumentation amplifier allows operation over a wide range of analog input voltage values. A/D conversion is completed in 3.125 ms using a high-speed, integrating converter operating at 160 samples per second and providing 12 bits of resolution (one part in 4096). A 6-pole Butterworth anti-alias, low-pass filter is also employed with programmable cutoff frequencies of 20 and 40 Hz. The analog card can be operated without the filter to provide full Nyquist 80 Hz signal bandwidth. To achieve required accuracy, the filter attenuates all input frequencies greater than the filter setpoint to a level less than one least significant bit of the A/D converter range. The analog card provides ground-station selectable input ranges of ±10, ±5, ±1, ±0.5, ±0.1, ±0.05, and ±0.025 V full scale per channel. The minimum resolution obtainable on the ±0.025 volt scale is 12.2 μV at 160 samples per second. Through digital averaging, a resolution of better than 1.0 μV is obtainable at one sample per second. The analog card also provides excitation voltage levels of 1, 2, 4, 5, 6, 7, 9 and 10 V DC with ±0.5 mV accuracy. This represents an error of less than one part in 4096 over a temperature range of -25° to +85°C. Analog card specifications are summarized in Table 2.

Table 2. Analog Signal Conditioning Cards

Analog input	Differential or single-ended; inverting and non-inverting
A/D converter	True 12-bit integrating type, integration period = 3.125 ms
Sample rate	160 Hz fixed, DAM digitally averages values to produce lower rates
Input overvoltage protection	±100 V
Bipolar voltage range	±10, ±5, ±1, ±0.5, ±0.1, ±0.05, ±0.025 V
Overall channel accuracy	±0.025% FS typical, ±0.04% FS max. at ±10, ±5 V range ±0.03% FS typical, ±0.06% FS max. at ±1, ±0.5 V range ±0.05% FS typical, ±0.12% FS max. at ±0.1 V range ±0.1% FS typical, ±0.24% FS max. at ±0.05, ±0.025 V range
Anti-alias filter	6-pole Butterworth
Cutoff frequency	20 or 40 Hz (-3db), or filter disabled
System AC bandwidth	DC to 20 Hz or DC to 40 Hz (-3db)
Excitation driver	100 mA current limited, sense and force leads separate

Pulse-counting cards are typically used with AC-output and photo-chopper type anemometers. Other types of pulse-emitting devices, such as standard single-channel incremental encoders and tachometers, can also be used with this card. The digital input cards accept digital status signals (on-off) or up to 12 bits of digital data, such as from a binary or gray-code absolute position encoder or other digital encoders. Specifications for the pulse-counting and digital cards are shown in Table 3 and Table 4.

Table 3. Pulse-Counting Signal Conditioning Cards

Type of Pulse	AC (zero crossing wave form) or pulse output (square waves)
AC input frequency range	0 to 10,000 Hz
Pulse input frequency range	0 to 32,000 Hz
LED excitation	2.5, 5, 10, and 12 V
LED current limit	40 mA max.(short-circuit-proof)
Transient and over-voltage	Included
Signal filtering for AC input	Provided
Pulse input logic	HTL

Table 4. Digital Input Signal Conditioning Cards

Input voltage range	10 to 40 VDC
Number of optically isolated channels per board	12
Number of accumulators available	12
Maximum accumulation in counts	65,536
Maximum count frequency	8 Hz
Running sample rate (to master processor)	160 Hz
Isolation voltage	2500 VDC

Each DAM can be controlled from the ground station. Control means selecting various options which affect the operational characteristics of the DAMs, and the interfacing between the DAMs and the ground station. DAM operations which can be ground-station controlled include the following:

- Type of operation: stand-alone or real-time
- Channel type (analog, digital, or pulse) and number of channels used
- Sample rate and low-pass filter setpoint
- Amplification level and excitation voltage level
- Synchronize and initiate data acquisition, initiate data download
- Calibrate.

Each DAM samples data from up to eight incoming channels simultaneously. The number of operational channels which send data is selected and controlled from the ground station. A common system-wide sample rate can be selected from the ground station to provide synchronized data acquisition from all measurement transducers up to a maximum of 160 Hz. The DAM microprocessor provides slower rate acquisition by digitally averaging the higher rate data samples in real time to produce lower rate averaged data over periods up to 10 minutes. By using separate A/D converters on each channel, all channels on each DAM are sampled simultaneously to eliminate skew or inter-channel phase-shift effects. With multiple DAMs, all are simultaneously triggered to start acquisition from the ground station.

Each DAM has space for up to 4 Mb of low-power static RAM. This memory is provided in 1 Mb modules. Recording space available with this memory is dependent on the sample rate, but not on the number of channels used. Since each DAM has up to 4 Mb, a total of 56 Mb of memory is available for 14 DAMs. The recording time for various sample rates is shown in Table 5. The memory can be used to hold a single contiguous time series or any number of shorter duration segments. Acquisition duration for DAMs operating at 1 Hz or less is limited only by the amount of available hard disk space, since real-time acquisition direct to PC data file can be used at these rates.

Table 5. Data Acquisition Duration

Rate (Hz)	1	5	10	20	40	80	160
Duration for 1 Mb RAM	18.2 hr	3.64 hr	1.82 hr	54.6 min	27.3 min	13.7 min	6.83 min
Duration for 4 Mb RAM	3.03 day	14.6 hr	7.28 hr	3.64 hr	1.82 hr	54.6 min	27.3 min

Each DAM can be operated with either AC line power (120, 240, or 480 V AC), a DC power supply, or a DC battery pack. Each battery pack can be recharged with the same AC line power supply or by using standard photovoltaic panels. At an ambient temperature of 25°C, each DAM can operate continuously for 20 hours if configured for eight full strain-gage bridges with 350 ohm gages excited at 5 V DC, and communications via the RS-232 port. At 0°C, this will drop to less than 12 hours. Recharge time is 6 to 8 hours for a fully discharged battery pack.

Communication Links

Communication links are used to provide two-way communication between DAMs and a ground station. Asynchronous serial communication is used throughout. The DAMs are able to download their digital-format data by transmitting it using RF telemetry or conducting it through an interconnecting cable to the ground station. They are also be capable of being controlled and configured by ground station commands uploaded over the same cable or RF link. Both RS-232C and RS-422 are available. RS-232C can be used for short communication distances up to 30 m (100 feet) from a single DAM through a direct-connect cable. RS-422 is used for multiple direct-connected DAMs at greater distances, up to 1000 meters (3281 ft) at 19,200 baud. Of more importance is the optical isolation provided by the RS-422 converters. Such isolation solves any ground loop problems that may come about when using AC power.

RS-232C interfaced radio links are also available for DAM communication. These eliminate the need to run a cable from the DAM to the ground station. Multiple RF links can be used, one at the ground station and one at each DAM. Each is capable of both transmitting and receiving. The RF links provide communication at 19,200 baud up to 4570 m (2.8 miles). They utilize spread spectrum technology (which uses several frequencies across a broad band from 902 to 920 MHz), are inexpensive, are authorized by the FCC, and require no license. Download rate depends on the distance from the DAMs to the ground station and the type of communication link. Data download duration options are shown in Table 6. Data cannot be downloaded from more than 1 DAM at a time; therefore, rates are cumulative for multiple DAMs.

Table 6. Data-Acquisition Module Download Rates

Communication Type	Data Rate (Baud)	Distance (m)	Duration for 100 Kb RAM	Duration for 1 Mb RAM	Duration for 4 Mb RAM
RS-232C Hard wire	115200	<3	15 s	2.5 min	10 min
RS-232C Hard wire	19200	<30	53 s	9 min	36 min
RS-232C RF-link	19200	<4570	2 min	18 min	72 min
RS-422 Hard wire	19200	<1000	53 s	9 min	36 min

Ground Station

The ground station receives and stores incoming data, and it originates DAM control commands. It also runs software to present a user-friendly interface to control the DAMs and produce data in a format easily used by standard PC DOS-based system software. The ground station is typically located at a convenient central site, such as a test shed or trailer. It can be any PC-compatible computer and does not require custom hardware or modifications. The ground station can communicate with up to 16 DAMs using a standard internal RS-232 to RS-422 converter board. It can be configured with typical memory and hard disk capacities to suit anticipated data volumes and analysis software requirements. Standard DOS-compatible devices such as tape backup units or optical disk drives can be used to provide permanent data archive.

Three basic software functions are provided with the ADAS system to run on the ground station. The first function enables the operator to configure channels on each DAM as described above. The second allows data to be downloaded from each DAM and stored to PC hard disk or RAM (in binary format). This software also provides the ability to convert the stored data to engineering units by applying linear conversion factors, combine data from multiple DAMs into a single contiguous time series, and output binary or ASCII data files. A compatible header file is also produced along with the data sets to save operator field notes, data conversion factors, and other information. The third software function allows real-time alphanumeric monitoring and a display of current conditions in engineering units. The display refreshes at least the 1 Hz real-time rate reflecting the current status of all channels on all DAMs. Actual real-time display refresh rate capability varies widely, depending on the number of DAMs which compose a system. If a system consists of a single DAM with eight channels, real-time rates of 20 Hz are attainable. A maximum of 10 Hz is available with two DAMs operating a total of 16 channels, and a maximum of 1 Hz is available for eight DAMs operating 64 channels. A typical data path from transducer to ground station is depicted in Figure 2.

FUTURE PLANS

The hardware described is extremely flexible and capable of evolving to meet future anticipated data-acquisition, display, and processing needs. Two areas of development are planned for the immediate future. First, work will continue on improving the download capabilities utilizing new technology communication links in an effort to decrease download time and increase real-time rates in a cost-effective way. We will provide the capability to operate the system so that high rate acquisition data are transmitted to the DAM memory while low rate (1 Hz) data are simultaneously downloaded in real time, so that real-time monitoring of current acquisition status can be accomplished. Second, we plan to specify and develop software tools needed to facilitate the collection, display, calibration, and analysis of multiple-source wind turbine test data. This will most likely involve interfacing the ADAS hardware with an existing third-party software package which can meet all required needs. Some desired options include the following:

- Real-time, quick-look alphanumeric and graphical display of current measured and calculated parameters.
- Digital filtering, de-spiking, interpolation, fast fourier transform (FFT) for power spectra, rainflow counting, and other time-series and frequency-domain signal processing capabilities.
- Test matrix parameter definition and automated test matrix filling.
- Statistical data processing, including standard deviation and higher order moments, curve fitting, linear and higher-order regression, for the purpose of calculating transducer calibration coefficients.
- Parameter binning to provide blade azimuth averaging, wind roses, power curves, etc.
- Data-base capabilities for defining and maintaining information associated with all measured data channels, keeping track of channel configurations, parameters, and histories, especially for organizing transducer calibration records and calculating measurement uncertainties.
- File maintenance system to organize experiment-associated data files and channel data-base records.
- Test event control and log to define a sequence of experiment events, initiate appropriate actions, and record results.
- Graphical utilities to provide comprehensive post-processing data display and presentation.
- Provide all capabilities through a common, easy-to-use, graphical user interface (e.g., Windows).

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REFERENCES

Cousineau, K. L., "Recording Turbine Blade Strain Data from Rotating Wind Turbines," Windpower '89 Conference Proceedings, September 24-28, 1989, San Francisco, CA.

Simms, D. A. and Butterfield, C. P., "PC-Based PCM Telemetry Data Reduction System Hardware," TP-257-3662, NREL, Golden, CO., 1990

Tangler, J., Smith, B., Jager, D., McKenna, E., Allread, J., "Atmospheric Testing of the Special-Purpose SERI Thin Airfoil Family: Preliminary Results," Windpower '89 Conference Proceedings, September 24-27, 1989, San Francisco, CA.

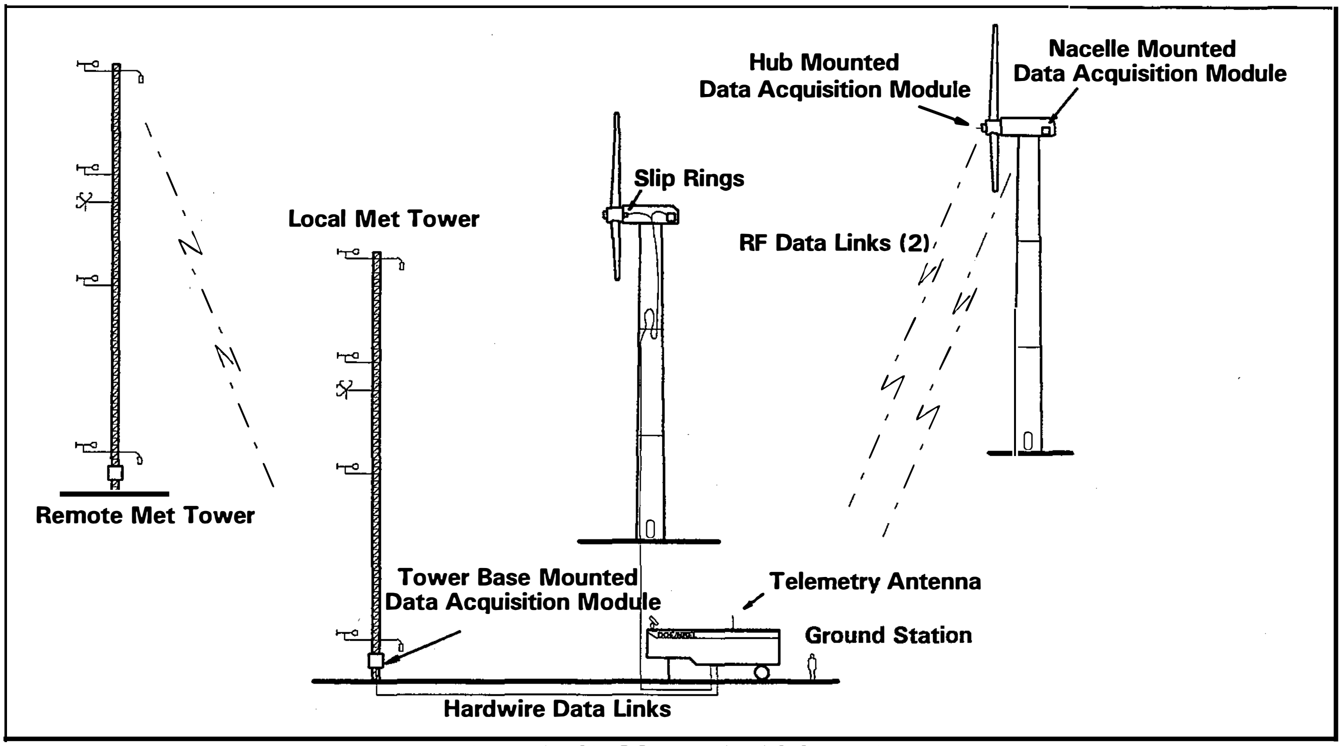

Figure 1. Six-Module ADAS Scenario

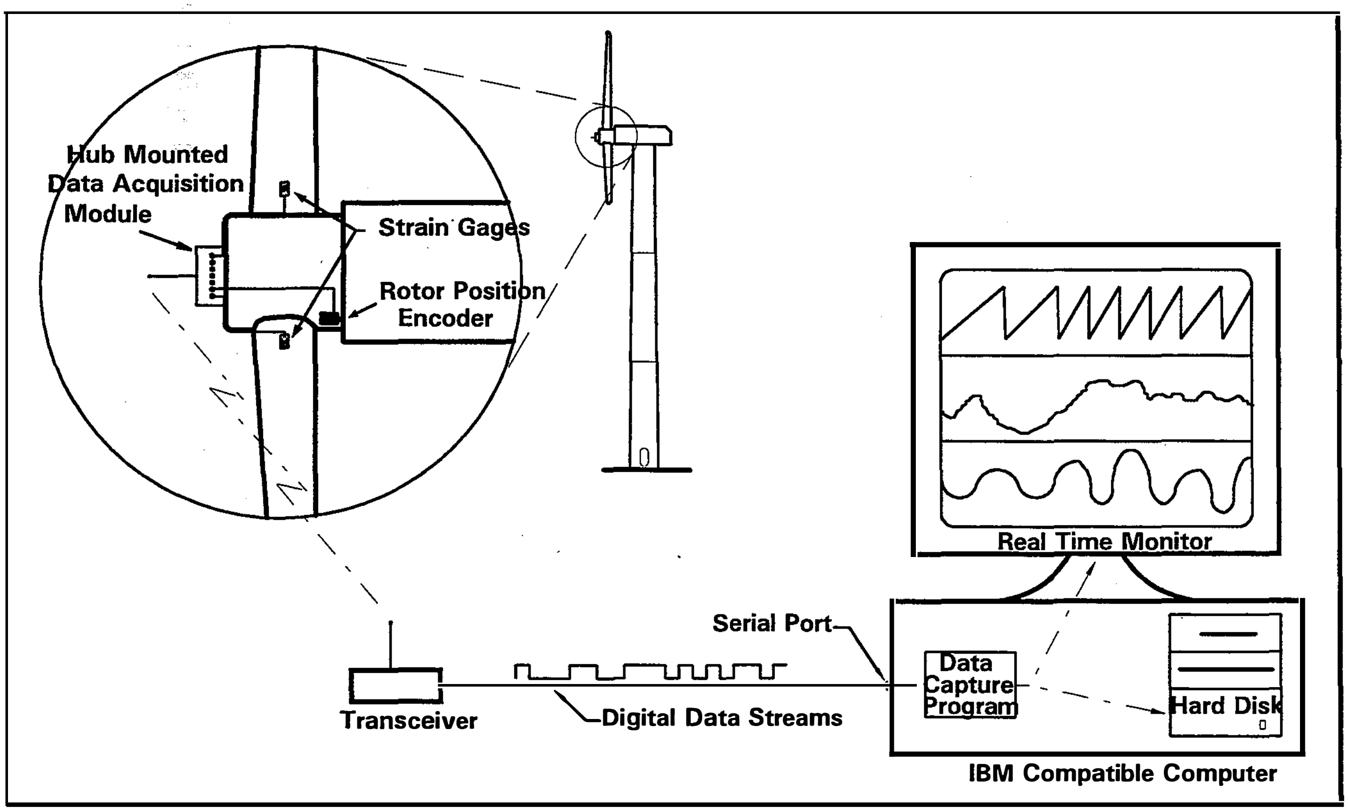

Figure 2. Typical ADAS Data Path from Transducer to Ground Station