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ATLAS: A Small, Light Weight, Time-Synchronized Wind-Turbine Data Acquisition System*†

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ABSTRACT

Wind energy researchers at Sandia National Laboratories have developed a small, light weight, time-synchronized, robust data acquisition system to acquire long-term time-series data on a wind turbine rotor. A commercial data acquisition module is utilized to acquire data simultaneously from multiple strain-gauge, analog, and digital channels. Acquisition of rotor data at precisely the same times as acquisition of ground data is ensured by slaving the acquisition clocks on the rotor-based data unit and ground-based units to the Global Positioning Satellite (GPS) system with commercial GPS receiver units and custom-built and programmed programmable logic devices. The acquisition clocks will remain synchronized within two microseconds indefinitely. Field tests have confirmed that synchronization can be maintained at rotation rates in excess of 350 rpm. Commercial spread-spectrum radio modems are used to transfer the rotor data to a ground-based computer concurrently with data acquisition, permitting continuous acquisition of data over a period of several hours, days or even weeks.

KEY WORDS

Time synchronization, data acquisition, light weight, GPS application, spread-spectrum modem

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INTRODUCTION

Wind-energy researchers at the National Wind Technology Center (NWTC), representing Sandia National Laboratories (SNL) and the National Renewable Energy Laboratory (NREL), are developing a better understanding of the environment in which a wind turbine operates. Until quite recently, like other wind-energy researchers around the world, they have been content to record long-term summary data (averages, minimums, maximums, cycle counting, etc.) from wind turbines, supplemented with representative ten-minute duration time-series data. The assumption underlying this mode of data acquisition is that this information is sufficient to define the wind-generated turbine loads and the turbine response. Continuing problems with premature turbine failures and measurements of loads far in excess of predictions have forced reexamination of that assumption. Obviously, some of the significant but infrequent events that drive turbine fatigue lifetimes have been and continue to be missed with traditional data acquisition techniques. We need to gather continuous long-term time-series data so we can capture and analyze those very infrequent events. How long should these time series be? We don't know, but researchers in Europe[1] have found that ten minutes is not long enough. In addition, numerous new turbines require the use of small, lightweight data acquisition systems to obtain truly accurate data. Recent advances in electronics enable us to now assemble a cost-effective, real-time, small, lightweight data acquisition system, capable of acquiring continuous time-series data over periods of days or weeks, something that would have been extremely expensive, if not impossible, just a few years ago.

We in the wind-energy program at SNL have been tasked to develop such a system as the next evolutionary step in the ongoing NWTC effort to provide a consistent set of hardware using common software that is specifically designed for use in a wind turbine environment. The primary objective continues to be the development of a data system that is easy to use, accurate, and operates reliably in this environment, thereby decreasing the time and effort required to instrument a field experiment, collect data, validate that data, and do preliminary data analysis. An important secondary objective is the development of a more cost-effective data system by decreasing the overall life-cycle costs (including the initial purchase costs, user training costs, and the on-going maintenance/modification costs) and by making it more versatile so it can be used in more applications.

WIND TURBINE DATA ACQUISITION SYSTEM

A complete wind-turbine data acquisition configuration typically contains several data acquisition subsystems (DAS), as shown in Figure 1. A normal configuration utilizes at least one rotor-based DAS unit (RBU), at least one ground-based DAS unit (GBU) and one ground-based computer unit (GBCU). The RBU is mounted on the rotor, rotating with and in close proximity to the blade- and main shaft-mounted strain gauges and other sensors and indicators. A GBU is any data acquisition unit that doesn't mount on the rotor--it could be mounted in the nacelle, on the turbine tower, or on the meteorological tower. All units are located close to the sensors and indicators from which they are acquiring data in order to minimize contamination of the data by electrical noise picked up by long signal wires. The GBCU controls the operation of the data acquisition systems and displays, stores, and post-processes the data.

Since the RBU is mounted on the turbine rotor and thus must meet the toughest operating requirements in terms of small size, light weight, robustness, immunity to vibration and rotation, etc., we have concentrated on developing a system that meets those requirements. Four distinct subsystems have been combined to perform the function of the RBU: a data acquisition subsystem (DAS), a data communication subsystem (DCS), a time synchronization subsystem (TSS), and a programmable logic device subsystem (PLDS). Although the requirements for the GBUs are less stringent, developing a different hardware/software for that application would require a significant investment. For this initial application, we have utilized the same subsystems for both the RBU and GBUs.

The complete data acquisition system, including the RBU, GBUs, and the GBCU, has been dubbed the Accurate Time-Linked data Acquisition System or ATLAS.

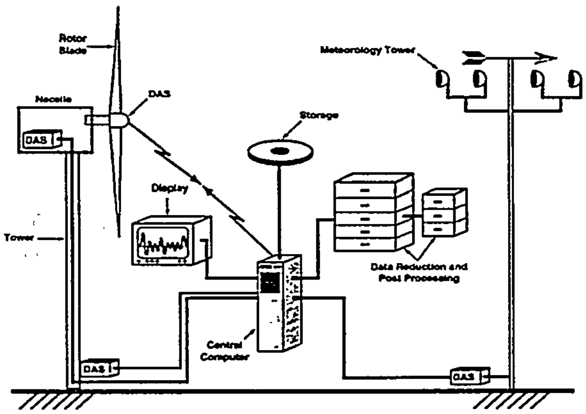

Figure 1. Schematic of Typical Wind Turbine Data Acquisition System

Additional information on the system components, including system requirements, hardware components, and early integration work, may be found in the papers by Berg, Robertson, Rumsey, Kelley, McKenna, and Gass;[2] Berg, Robertson, and Ortiz;[3] and Berg and Robertson.[4]

Our recent efforts have focussed on developments in the time synchronization, data communication, and programmable logic device hardware and system software. These developments are the subject of this paper. The data acquisition subsystems are Nicolet MicroPros‡, built by ACRA Control of Dublin, Ireland,[5] and they are described in some detail in the earlier papers listed above.

COMPONENT DEVELOPMENTS

Data Acquisition Time Synchronization

In order to obtain the precise time sequence and phase information needed to understand the turbine load and response phasing, the loading sequences, and the load paths of the turbine, data must be acquired by the RBU and the GBUs simultaneously. The length of the long-duration time-series tests may well run into several days, and over that entire time we need to maintain very accurate time synchronization between the RBU and GBUs.

The MicroPros that we are using to perform the DAS function feature simultaneous acquisition on all channels. The data acquisition operation may be

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initiated by an external clock, so the time synchronization problem becomes one of maintaining synchronous clocks on the various DAS units. If all units are connected by hard wire, this is not a problem, for we can slave all units to the same clock. If, however, the RBU communications are via telemetry, as they are for the ATLAS, it becomes a problem, due to the time delay inherent in that operation. Independent clocks are clearly inadequate, because the drift of even a highly accurate, temperature-stabilized clock is on the order of one part per million. This corresponds to a drift of as much as 86 milliseconds (ms) per day per clock, for a drift of up to 172 ms per day between two clocks. This is nearly one-fifth of a second! At sample rates of 10 Hz or higher, two independent systems could be out of synchronization by more than one sample interval at the end of a single day. This is unacceptable for most applications.

This cumulative clock drift can be eliminated if the data acquisition clocks in the units are continually resynchronized. The Global Positioning Satellite (GPS) system facilitates an elegant, but cost-effective, solution to this problem. GPS receivers not only determine their location very accurately; they also track the time very precisely, re-synchronizing their internal clock to the Universal Time Coordinated (UTC) time every second. Typical variation from UTC time for commercial GPS units is ±1 microseconds (μs) or less, over any time period, so the clocks of two GPS receivers will vary with respect to each other by a maximum of 2 μs over any time period. GPS technology is relatively mature, and small, inexpensive receivers are readily available. For this particular application, we need a device that will generate two GPS-aligned pulse trains at user-specified rates and that is small, rugged, and capable of running on battery power. The smallest commercial unit we have found that can perform this function is approximately 4 by 4 by 15 cm, weighs a kg, and costs about $4000. We have developed our own timing system utilizing the small, single-card Jupiter GPS receiver from Rockwell International.[6] This receiver maintains synchronization with UTC time to within ±1 μs as long as it can acquire signals from at least three GPS satellites, and it generates a one-pulse-per-second (1 PPS) clock signal, with the rising edge of the pulse occurring precisely on the UTC second.

In actual use, the user must be sure that the GPS units are receiving messages from at least three satellites, for only under that condition is the internal clock synchronized or "locked" to the UTC time. This satellite linkage may require up to five minutes after the system power is turned on. The ability of the GPS units to retain satellite communications and time lock is dependent on the rotation speed and antenna configuration. The half-wavelength antenna configuration that we are using (see Figure 2) is adequate for maintaining time lock at rotation speeds as high as 350 rpm. The stationary system will usually lock onto six or more satellites, while the system rotating at 350 rpm will only receive communication from three or four satellites at any one time, and those satellites will change frequently. Momentary satellite communication drop outs, such as might occur during brief periods of higher rotation speed, are not a problem, as the on-board clock will continue to run and produce the 1 PPS clock, although it will slowly drift with respect to UTC time. Once the rpm drops to 350 or less, communications are re-established with three or more satellites, and the on-board clock is quickly re-locked to UTC time.

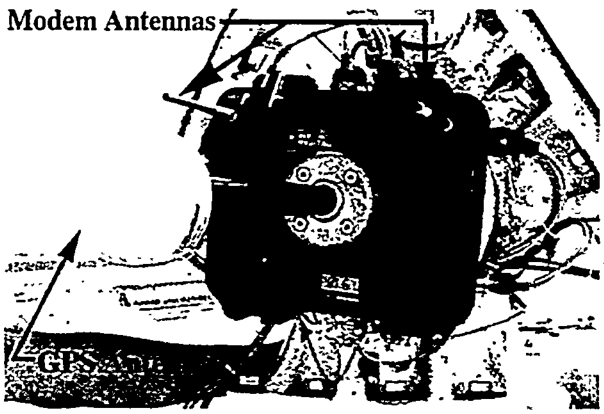

Figure 2. Closeup of ATLAS Mounted on AOC Turbine

Telemetry System

Data must be transferred from the RBU to the GBCU (ground based computer unit) concurrent with data acquisition to enable us to acquire data continuously over a period of hours, days, or weeks. Although we may be able to utilize wires and slip rings to effect this transfer on some turbines, many of the turbines on which the ATLAS will be used will not be equipped with slip rings, and telemetry will be required. Rather than attempt to add the telemetry capability at a later date, we have included it as an integral element of the system

The rotating turbine blades of a wind turbine create a severe multi-path environment for a telemetry system. We have utilized conventional single-frequency telemetry systems for a previous wind-turbine application, but we had to resort to a diversity combiner/receiver arrangement to avoid data loss. That was a very expensive, complicated system, and we do not wish to utilize it for this application. In this case, we need to transmit the data only a few hundred yards, so a low-power system will be adequate. In addition, we want to avoid the need to license the system through the FCC, so using a low-powered radio system that operates in the ISM (industry, science, and medical) frequency band is quite attractive. The radio we've selected for this application is a low-cost, commercially available, frequency-hopping, spread-spectrum radio modem. These units operate in the 2.4 Ghz band, incorporate a transparent error-correction feature that automatically requests re-transmission of any data that is not received properly, and achieve data rates up to 115 kbps (thousands of bits per second), in either asynchronous or synchronous mode. At this time, we utilize the asynchronous transfer mode to program the RBU DAS and the PLDS, and to monitor the Global Positioning Satellite (GPS) receiver status, while we utilize the synchronous transfer mode to send the digitized data to the GBCU.

Highly robust transfer of the data to the ground computer is essential for our application--the long-duration data records are required for detailed analysis, and loss of data during transmission will invalidate those analyses. Recent tests of this system have shown that we can maintain an error-free link for data transfer speeds of up to 100 kbps between an RBU mounted on a wind turbine and a GBCU located inside a cinder-block building about 100 meters away. Tests on a HAWT simulator show that the data link does not degrade with rotation speed, at least for rotation speeds less than 350 rpm.

System Integration

We have designed and built a programmable logic device subsystem (PLDS) to perform most of the system integration tasks. The subsystem utilizes an ALTERA® 10K70 programmable logic device from Altera Corporation,[7] programmed using a combination of AHDL (Altera Hardware Design Language) and traditional schematic-based digital design to perform these functions. An eight-layer application-specific integrated circuit board was designed and built to supply the power and provide the necessary input and output connections for the PLD. The board size is approximately 7 cm by 7 cm., and it fits within the MicroPro mainframe. Additional hardware details and general information on the PLDS may be found in an earlier paper by Berg and Robertson.[4]

One of the major tasks of the PLDS is the generation of the synchronization (sync) clock and bit-rate clock timing signals, locked to the GPS receiver 1 PPS signal. The sync clock triggers the DAS data acquisition cycle, and the bit-rate clock transfers the data from the DAS to the GBCU. The GPS-generated 1 PPS signal initializes the sync clock at the user-specified rate, precisely aligned with the 1 PPS signal. The sync clock then starts the bit-rate clock at the user-specified rate. The bit-rate clock is re-initialized by every sync clock pulse, and the sync clock, in turn, is re-initialized by the occurrence of the 1 PPS signal. Since the 1 PPS signal is aligned with the UTC second, the sync clock, and thus the data acquisition time, is kept synchronized to the UTC time.

The PLDS card also reads and decodes the UTC time that is output as a serial stream by the GPS card every second. A two-digit centi-second counter and a four-digit tens-of-milliseconds counter are re-initialized on the occurrence of the 1 PPS signal, to yield a very accurate internal PLDS clock. The PLDS latches the time from this internal clock, accurate to one microsecond, into internal registers when the sync clock is issued. Those registers are then read by the DAS as part of the normal data acquisition process, and the time is included in each data frame as a time-stamp identifier for that frame.

In the near future the PLD software will be enhanced to enable the PLDS to perform the following additional functions:

1. Transfer user-generated programming commands to the DAS.
2. Transfer GPS receiver card status messages to the ground and user-generated commands to the GPS card.
3. Monitor the status of the GPS receiver (including satellite lock and UTC lock status bits), input power voltage, and the current sync and bit-rate clock settings, and returns these to the user in response to the appropriate inquiry.
4. Switch between functions 1,2, and 3, above, in response to user command, enabling the system to operate with a single asynchronous modem.
5. Place the system into a "sleep" mode in which all components are either shut off or placed into a low power state to draw a minimum current and thus conserve battery life. The PLDS checks the modem input line once every 10 seconds. If the appropriate message has been received, the PLDS will power up the entire system and it will be ready to start full-power data acquisition within 2 seconds.

We intend to develop an enclosure to supply power and provide RS-232 communications to the PLDS so it can be used as a stand-alone unit for other applications. We also plan to transfer the GPS/PLDS technology to industry so that it will be readily available for alternative timing applications in the future. We feel that the small size, low power consumption (~200 mw), flexibility, and low cost (~$1000) will make it attractive for numerous data acquisition applications such as missile flights, remote sensing, and general aerospace testing. Also, having it available as a commercial product may free us of the need to provide ongoing hardware and software support for it.

System Software

The MicroPro hardware was supplied with ACRA-developed 16-bit DOS-based control and acquisition software. A major focus of our recent development effort has been the development of a windows-based data acquisition package for the MicroPro hardware utilizing the National Instruments LabVIEW® software environment. Our goal is to adapt the LabVIEW-based ADAS II software, developed by NREL for use with the Advanced Data Acquisition System (ADAS) hardware[8], to work with the MicroPro hardware. The ADAS-II software was developed specifically to facilitate acquisition of wind-turbine data and contains many useful features, in addition to the basic ability to store, display, and analyze the data. These useful features include storing time-series data, setting triggering conditions, displaying multiple channels on the screen in near real time, and maintaining a log file listing all significant events and failures that may happen during a test. By modifying the ADAS-II software and developing a MicroPro-specific Virtual Instrument (VI) for it, we are creating a single window-based software package that works with both ADAS and ATLAS hardware.

ACRA has been developing Windows '95 system-level software in the past few months, and we have worked closely with them in that effort, serving as a beta test site and developing LabVIEW software to utilize and test that software. We have developed a LabVIEW Virtual Instrument (VI) to decode the incoming data stream and place the data in computer memory, retrieve that data from memory, display it, and store it to disk. We have also developed a LabVIEW program to monitor the GPS card status so we can monitor the number of satellites in view, the number of satellites from which data is received, and whether the GPS receiver has a valid solution and thus is locked to UTC time. Still another LabVIEW program permits the user to specify the sync and bit-rate clock rates for the PLDS card. These separate programs enable us to perform basic data acquisition tasks. Although we are currently utilizing the standard ACRA-supplied software to actually program the MicroPro to specify the channels to be sampled, to set the channel gains, filter cut-off frequencies, and excitation voltages, to set the data acquisition rates, etc., we are working on a LabVIEW VI to perform this programming. We are now integrating these capabilities into the ADAS-II software, so all configuration and acquisition will be accomplished in a single seamless application, tailored for wind-turbine data acquisition.

Our long-term goal is to migrate our software to the Windows NT operating system, in order to take advantage of the better real-time data acquisition capabilities and overall robustness of that software platform. We are currently working with ACRA and a contractor to develop the necessary Windows NT system-level software to allow us to accomplish all of these tasks under the NT operating system.

System Costs

While cost-competitive, the MicroPro and other hardware required for the ATLAS are not cheap. The list price for a basic six-slot mainframe MicroPro with power supply, encoder, decoder, and software, is $14,000; for a three-slot unit, $12,500. List price for an eight-channel strain-gauge module is $4,900; for an eight-channel high-level analog module, $3,900. Thus, for a six-slot MicroPro that will measure 16 channels of strain gauge data and 8 channels of high-level analog data data, the list price is $27,700. The list price of the Digital Wireless radio/modems is $600 per unit or $2400 for the two pair that we are now utilizing for communication. The cost of the GPS receiver and the other components for the PLDS card is about $600, so a reasonable figure for the completed card is $1000. The power supply, enclosure, and connectors add another $250 or so, for a total list price of about $32,350 for a 24-channel RBU. This gives a per-channel cost of $1348. The prices for the MicroPros, in particular, will drop somewhat as we purchase more units. For comparison, the 1992 cost of the NREL/Zond ADAS system was approximately $1,000 per analog channel.

SYSTEM FIELD DEPLOYMENT

In August 1998 we installed the ATLAS system on the AOC (Atlantic Orient Corporation) 50-kW wind turbine at the USDA Agricultural Research Service location in Bushland, Texas. This turbine is a three-bladed, downwind, free-yaw machine, rotating at 60 rpm. To perform the function of the RBU, we placed a 6-slot MicroPro, a power supply, and two modems (one for RS-232 asynchronous communications and one for synchronous data transmission) in a waterproof plastic container as shown in Figure 3. The main components of the RBU are labeled in the figure. The external dimensions of the unit are approximately 10" by 10" by 4" (25 by 25 by 10 cm), with a weight of about 11 pounds (5 kg). For this application, the MicroPro is configured with three 8-channel strain-gauge modules to acquire 15 channels of strain-gauge data from the rotor. The GPS/PLD combination occupies two additional module slots, so one MicroPro slot remains open. Waterproof connectors on the sides of the box are used to connect the blade and rotor shaft strain gauges to the RBU. The antennas for the modems and the GPS receiver are mounted on the outside of the container, and the entire RBU is attached to the downwind side of the rotor hub, at the centerline of rotation. The system is shown mounted on the rotor hub in Figure 2--the GPS antenna (placed on a 12-inch mast extending along the axis of rotation) and the four-inch stub modem antennas are labeled for clarity.

Figure 4 shows the very small size of the ATLAS relative to the turbine rotor. The only part that is clearly visible is the GPS antenna.

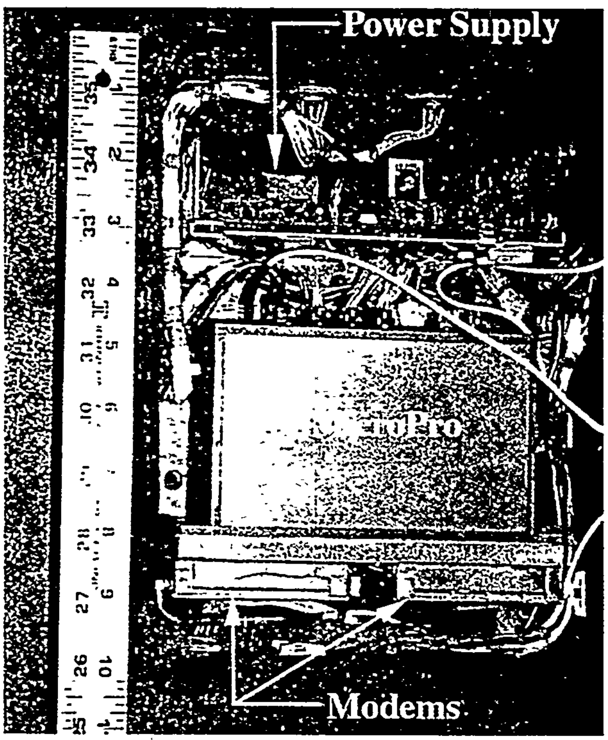

Figure 3. Interior View of ATLAS Rotor-Based Unit

A second MicroPro is located at the base of the tower and acquires tower load and turbine drive-train data. A third MicroPro is located in the wind lab building (approximately 100 meters away) to record meteorological data. A GPS/PLD unit in the second MicroPro is used to drive the data acquisition for both GBUs at precisely the same times as the data acquisition on the rotor. This acquisition time is recorded by both the RBU and one GBU and serves as a timestamp for the data. The telemetry data from the RBU is received by a modem inside the wind lab. That data, together with data transferred via wire from the turbine base MicroPro, is merged into the data stream from the wind-lab MicroPro. The composite data stream is then sent to a computer where it is decoded by the PCMCIA decoder and placed into computer memory. Our LabVIEW program retrieves the data from computer memory and, if necessary, rearranges it by time of acquisition to place the RBU data with the appropriate data from the two GBUs. At this point, the data looks just like the data acquired from other hardware systems and we can use the existing ADAS-II software routines to write the data to disk, view it, and post process it. Although we are utilizing prototype rather than fully integrated software at this time, the system is fully operational.

Power draw for the RBU is approximately 30 watts. Although this does not correspond to a large amount of heat generation within the unit, we quickly discovered that the RBU container material is an excellent insulator, and the internal temperature inside the closed box rises fairly rapidly. We modified the means for mounting the RBU to the rotor hub to ensure a conduction heat path to the hub and the temperature inside the RBU is now kept to no more than 25°F (14°C) above ambient.

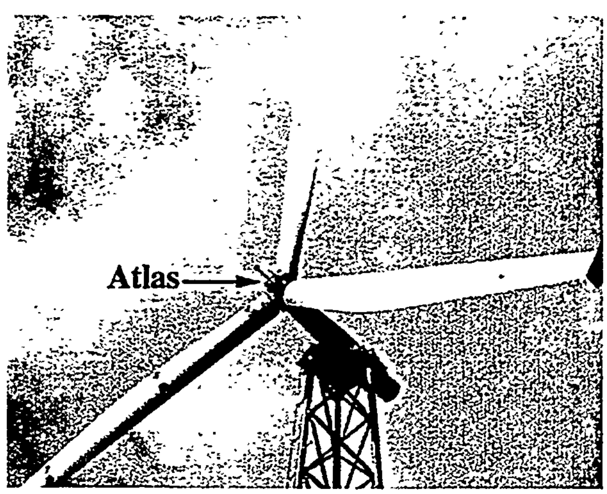

Figure 4. ATLAS Mounted on AOC Turbine

In our initial check-out of the system, the data timestamps revealed that the RBU data is normally delayed with respect to the GBU data by one acquisition period, that is, the RBU data present in a particular data frame actually corresponds to the GBU data from the previous data frame. Including the timestamps in both data streams is thus essential for establishing the desired time correlations.

SUMMARY

The need to gather detailed, long-term time-series data on the rotors of highly dynamic and/or small wind turbines has led to the development of new-generation, lightweight, robust, time-synchronized data acquisition units that are suitable for mounting on the rotor or base of the turbine. These units comprise four distinct subsystems. The data acquisition subsystem (DAS) consists of a small, rugged, lightweight commercially available data acquisition system. This device simultaneously acquires data on all input channels in response to a GPS-aligned clock pulse, and transmits the resultant digital data to a control computer.

Commercial spread-spectrum radio/modems are utilized as the data communication subsystem (DCS) to transmit control information, programming information, and data between the turbine rotor and the ground. The error-correcting, spread-spectrum technology makes the radio link much less susceptible to interference than conventional, single-frequency radio technology.

Data acquisition times and rates are synchronized between the rotor unit and one or more ground-based units through the use of a time synchronization subsystem (TSS). The TSS utilizes the one-pulse-per-second signal generated by a GPS receiver to generate pulse trains that are precisely synchronized to UTC time. These pulse trains are used to drive the data acquisition of both the rotor and the ground units, enabling them to consistently acquire data within two microseconds of each other over indefinite time periods.

Finally, a custom-built programmable logic device subsystem (PLDS) has been developed to fit inside the DAS, to handle all communications with the user and all communications and data interchange between the system components, and to coordinate the operation of those components.

A full data acquisition system utilizing these data units, referred to as ATLAS (Accurate Time-Linked data Acquisition System), has been deployed on a wind turbine at Bushland, Texas, and we are now acquiring data with it.

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