Unmanned Rotorcraft Flight Testing Using Wireless Sensor Networks for Data Collection and Cloud-Based Computing

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Background

Aircraft flight test has traditionally been expensive and time consuming to accomplish, requiring complex hardware design and integration and extensive operational test teams to address aircraft downtime for instrumentation maintenance and calibration, flight operations, and post-flight data handling and evaluation.

Recently, elements of Boeing Military Aircraft flight test and LORD MicroStrain worked jointly to conduct a flight load, vibration, and thermal survey of a Boeing S-100 autonomous rotorcraft using a suite of LORD MicroStrain wireless sensors and inertial devices. This program represents a technology breakthrough wherein an autonomous rotorcraft flight test program utilized only wireless sensors within synchronized networks to collect flight data of interest.

In addition to the successful collection of high quality data, the Boeing team was able to accelerate the flight test program with significantly reduced expense by leveraging off-the-shelf wireless technology. The wireless nature of the comparatively affordable technology allowed a minimally-invasive integration onto the flight vehicle, and LORD SensorCloud™ analytics enabled a single team of limited personnel to make go/no-go decisions based on nearly real-time data evaluation. This approach provided augmented decision efficiency, which accelerated flight test execution by allowing multiple daily sorties and concurrent data analysis.

Introduction

The S-100 Camcopter platform is an unmanned Vertical Takeoff and Landing (VTOL) aircraft produced by Schiebel of Austria (Figure 1). This autonomous rotorcraft is capable of flying with a 50 kg payload for up to a six-hour loiter time with a service ceiling of 5400m. Operators can control the aircraft in real-time via a ground-located control station, or the aircraft can fly a preprogrammed mission completely independent of operator intervention. Boeing Mesa is the current US-based distributor, and it conducted a flight test program for the S-100 to better understand and characterize effects on flight critical dynamic and structural sub-systems.

Figure 1: Boeing S-100 Flight Test Vehicle

The test team at Boeing Mesa set the objective to execute a flight strain, vibration, and thermal characterization program using a centralized test and analysis scheme. Boeing expected one internal team to manage all aspects of the flight test, from initial planning and scheduling to conducting flights and follow-on data analysis. Part of the challenge in designing the test equipment for the flight vehicle lay in the very limited amount of space and weight restrictions of the platform. Inherently, heavy instrumentation systems added to the aft section of the aircraft would move the vehicle center of gravity (CG) further aft. Weight added to the forward payload creates a similar CG issue. The best case for instrumentation is a distributed modular system without requiring added ballast to the airframe for CG correction. To minimize intrusiveness of the installation, reduce aircraft downtime, provide ready access, and analyze data on-site directly after landing, Boeing Mesa approached LORD MicroStrain Sensing Systems about using its array of 2.4GHz wireless sensors, data aggregators, and SensorCloud analytics for flight test support.

Flight Test Results

At the time of this paper, a total of 25 ground and flight tests have been conducted by the Boeing test team, each representing a specific flight envelope test point. Between tests, engineers utilized the visualization and analytics tools available in SensorCloud to view the flight test data at the completion of each test point, while at the test site. This powerful tool enabled engineers to make decisions to move forward with the test program using data less than 20 minutes old or to repeat test points if more data was needed. Data was viewed in calibrated engineering units, thus enabling the capability to authorize follow on sorties. More importantly, it allowed engineers to evaluate flight anomolies and adjust safety controls as they moved forward.

This flight test program is revolutionary in that a small centralized team of personnel completed the program without larger organization support. In addition, all flight test data channels were taken using wireless sensors, data was available for evaluation within minutes of aircraft landing, and flight data was used almost real-time to make determinations on safety and airworthiness for multiple flight tests conducted on the same day.

Throughout the test program, the team did not repeat a single test or have any lost time due to wireless instrumentation failure. The period of performance for the flight test program was reduced by 50% due to the on-board data conversion and evaluation tools that are part of the

SensorCloud suite. This specific aircraft continues to fly and collect flight test data while leveraging the cost and time saving advantages of wireless technology. Specifically, this flight test program provided Boeing with a deeper understanding of the load and vibratory environment of this platform, which allowed justification of resource allocation for product improvements, payload integration criteria, and, in the longer term, a basis of comparison for development of health and usage monitoring improvements.

Immediate Benefits of Using the Wireless System

Hardware Cost

The cost of all wireless instrumentation including custom hardware changes, blade pass counter custom design, tail rotor drive shaft (TRDS) custom design and balancing, on site engineering support, and SensorCloud/MathEngine® access was less than $70K. Alternately, if one considered a conventional measurement installation with two aerospace-grade slip ring assemblies, the cost of the assemblies alone is of a simliar order of magnitude, not including recorder equipment, instrumentation time (hardwires), airframe modification, and time and support personnel added for data analysis.

The cost of modifying aircraft components to utilize known strain gage technology is equivalent to typical methods used, regardless of the wireless nature of the LORD system.

Schedule Compression

Originally the program scheduled 15 flight card plans to accomplish, each allotted one day to fly, with one day following for data analysis. This pattern, which did not include emergent problems such as weather or aircraft maintenance, allocated 30 continuous days of flying and data analysis. Using LORD MicroStrain's technology and analysis platform, flight testing was accomplished, including required time for aircraft maintenance and other emergent issues, in 14 days. This represents slightly more than a **50%** improvement in flight test schedule.

Air Vehicle Integration Benefits

The small form factor of the individual pieces comprising the larger network system allowed a data collection suite this robust to actually be installed within the aircraft. Typical recorders are too large to be installed within aircraft itself and would necessitate airframe modification to utilize external mounting provisions.

Because the sensor suite is modular, the total weight of individual components was distributed throughout the aircraft, preventing the typical aft CG problem that inevitably arises as a result of aircraft load modification. The unitized, self-contained node and WSDA® components did not require specialized packaging.

The need for two complex, noisy, and maintenance intensive slip rings was negated by the wireless nature of data transmission. A simple main rotor head support for two wireless LORD MicroStrain V-Link®-LXRS® nodes in the rotating reference frame replaced the need for a specially designed 32-channel slip ring. From a technical standpoint, not having to consider the complexity of slip ring integration within the minimal space afforded by the aircraft was priceless. Quick replacement of suspect or defective components of the larger networked system prevented delays in testing. Failure of any one channel within a singularly unitized datalogging system would have resulted in delays for the entire testing program.

All wiring runs were minimized as compared to traditional means due to the ability to locate node transmitters very near the instrumented components. The design of LORD wireless components allowed use of known strain gauge technology with lab calibration, which afforded a high degree of comfort with regard to reliability and data integrity.

Data retrieval and analysis

The ability to monitor all channels in engineering units while the aircraft was nearby allowed real-time go-forward authorizations by flight test engineers. Because the primary node signals were being monitored, additional signal transmission equipment was not required to allow stand-off monitoring. Also, downloading recorded data directly in engineering units allowed near real-time analysis and judgment to continue testing without the time consuming task of secondary bits-to-engineering unit conversion.

SensorCloud analytic tools allowed quick cross-comparative visualization of all data channels and intuitive recognition of sympathetic interdependencies. Coupled with that ability is effortless correlation between data channels and aircraft inertial data collected throughout the flight by on-board GPS capabilities within the ruggedized wireless sensor data aggregator (WSDA-RGD) (Figure 2). Immediate correlation of any data channel response to aircraft maneuver was possible with this powerful capability.

Figure 2: Flight Test SensorCloud™ Interface from www.SensorCloud.com

Ground and Flight Test

Operational testing started with ground run-ups to observe aircraft and sensor performance. Sensor data was logged by the WSDA networks and monitored real time via a wireless link to a ground station during the engine start, and step-up in engine speed from ground idle to full power. Ground runs showed excellent sensor performance, increased loading on landing gear and system mechanicals as inflicted by operation within ground effect, and proved necessary for incremental flight test vehicle risk reduction. Figure 3 shows a typical ground run data set collected during vehicle checkout. It should be noted that any modification to the onboard sensor suite was verified via a ground run prior to any flight operations.

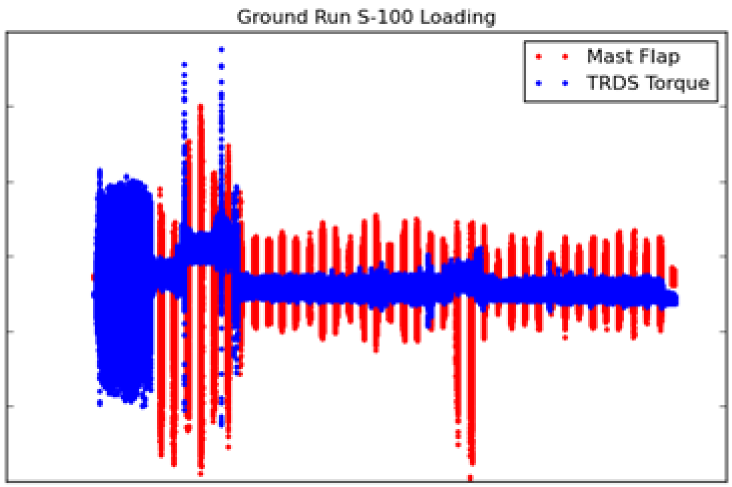

Figure 3: Normalized Ground Run Mast Flap and TRDS Torque

Following a safety review by the engineering team and safety experts, the test vehicle was cleared for flight test operations. Often more than one flight test was flown in one day after on-site engineers viewed and approved data collected for specific test points. This method also facilitated small safety reviews at the test site following the completion of a test card. The previous flight data was easily reviewed by engineers prior to continuation of the test program.

Typical normalized flight test data is shown below in Figure 4. Where conventional flight tests monitoring loads in a rotating frame would mandate the use of an electromechanical slip ring, this flight test simply used a balanced rotating wireless payload capable of transmitting the data of interest to the fixed frame. Eliminating the requirement for a slip ring allowed for a lighter flight-worthy airframe and reduced the complexity of the measurement system.

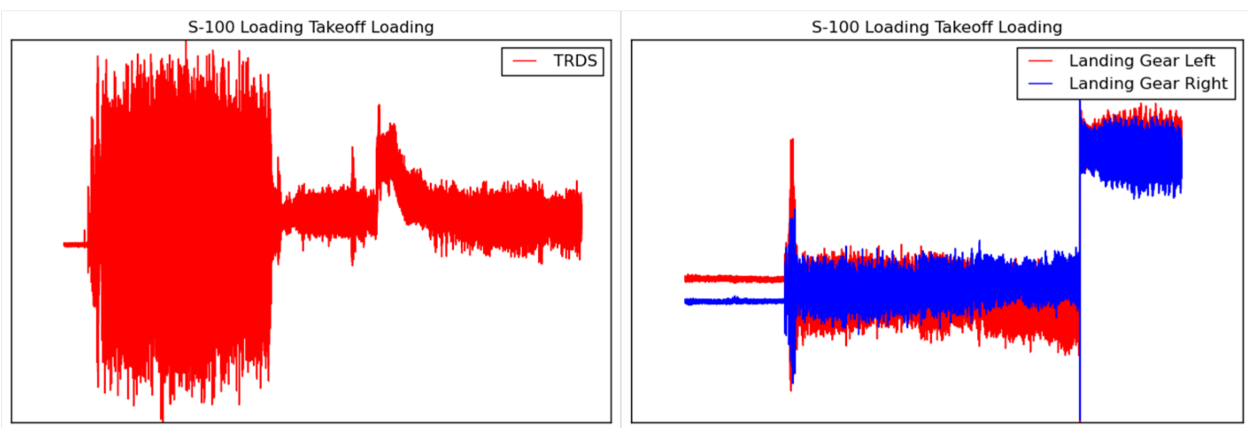

Figure 4: Normalized S-100 Takeoff Data

During the flight test, only one instrumentation engineer was required to design, install, configure, and operate the onboard sensor suite. This was facilitated by (A) the ease of removing the modular sensor nodes and replacing them if problems were detected, and (B) the minimal wiring leads between sensor and strain gauges. Test flights and initial no-go data evaluation were conducted by five personnel, including pilots and maintenance technicians.

Aircraft bus power-on with rotors turning provided electrical power to the WSDA units, which were configured to immediately wake up associated nodes and kick off the synchronized sensor networks. In this way, aircraft bus power-on equaled the start of data collection. The instrumentation engineer could then use a LORD MicroStrain base station to "listen" to the sensor nodes turning on and transmitting data on the ground. Once all nodes were awake and accounted for and the flight test commenced, the instrumentation engineer could continue to monitor the sensor networks for several hundred feet before the nodes dropped out due to the extended range from node to basestation. However, nodes continued to transmit time synchronized data to the WSDA units on board the aircraft during the flight. Later in the flight test program, WSDA power was transferred to a separate dedicated battery to further simplify sensor network power on/off.

Flight testing was primarily accomplished at the Florence Military Reservation rangespace in Arizona. The aircraft was staged and flown from an austere control facility preplaced at Florence Range.

Utilized Wireless Networks and Data Channels

It is well known that the cost to retrofit existing airframes with wired sensors and instrumentation is very high. Because of limited payload space, associated costs, risk of damage to wired systems, and additional weight inherent in running wires between systems, wireless sensors offer many advantages over wired systems [1]. These considerations prompted an all-wireless sensor data collection system for the S-100 flight test program.

Several different wireless configurations have been flown on this platform, however the most complex involved three separate WSDA networks that managed 37 individual wireless channels and ten onboard inertial channels. The data collection was broken up between three separate networks, each operating on its own frequency within the 2.4GHz open band. The WSDA platform enabled lossless communications architecture via data packet buffering, retransmissions, and acknowledgements. Along with providing continuous monitoring of ten inertial channels, the WSDA-RGD also provided a GPS synchronized timing beacon, and in turn collected time stamped data synchronized to within +/- 30 microseconds [2]. At the time of this paper's writing, the WSDA-1000 has been replaced by the WSDA-1500.

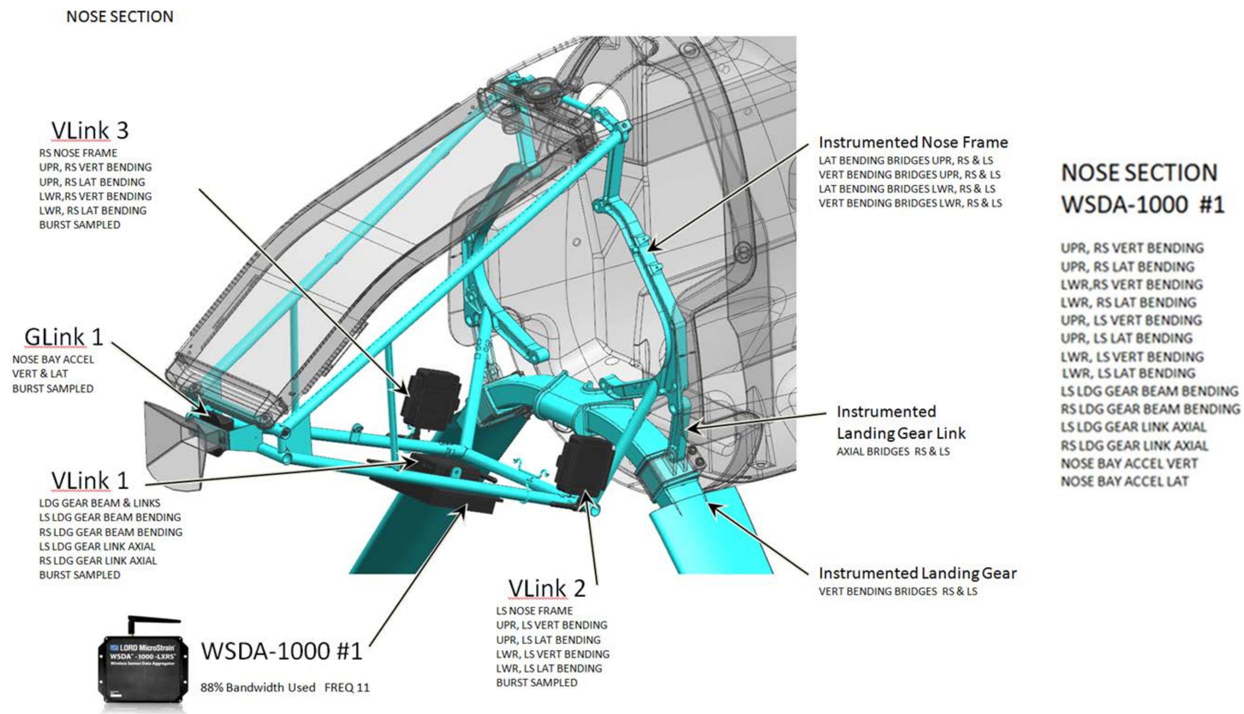

Figure 5: Nose Section WSDA®-1000

Regarding sensor location on the test vehicle, networks were broken down into respective sections. The nose section housed a WSDA-1000 and recorded nose frame and landing gear bending moments, landing gear link axial loads, and vibration data on the aircraft (Figure 5). The center section mounted a WSDA-RGD externally and recorded main rotor bending and torsion, main rotor blade pass counts, main rotor mast bending and torsion, vibration, and thermal data (Figure 6). The tail boom section housed a WSDA-1000 and recorded tail boom bending, TRDS torsion, and vibrations and temperature at two locations (Figure 7).

Structural member measurements used standard off the shelf wireless nodes from LORD MicroStrain (Figure 8). The array of sensors consisted of six V-Link, one SG-Link®, and four G-Link™ units for monitoring strain bridge differentials (multiple or single channel), on-board thermocouples (temp), and acceleration respectively. Two custom wireless electronics packages were developed using SG-Link OEM nodes for the test regime: a blade pass sensor and a TRDS torque sensor.

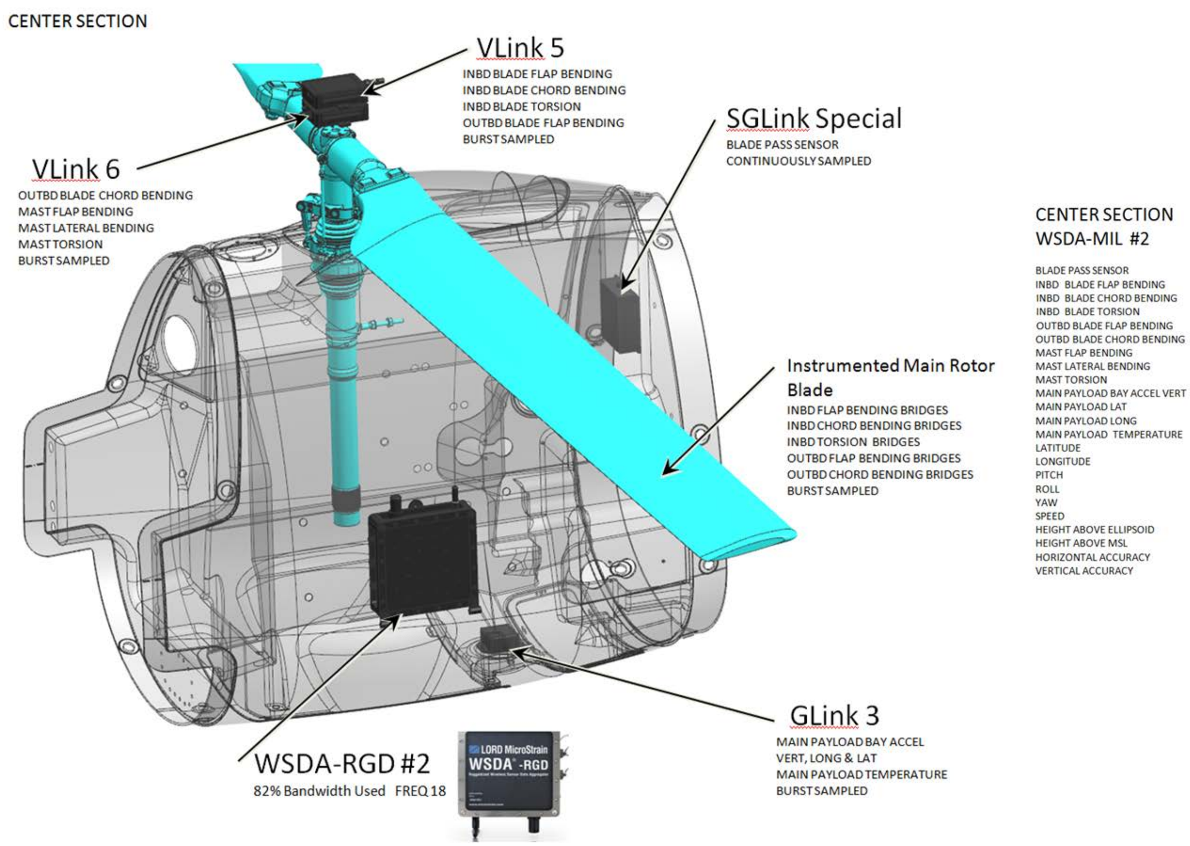

Figure 6: Center Section WSDA®-RGD

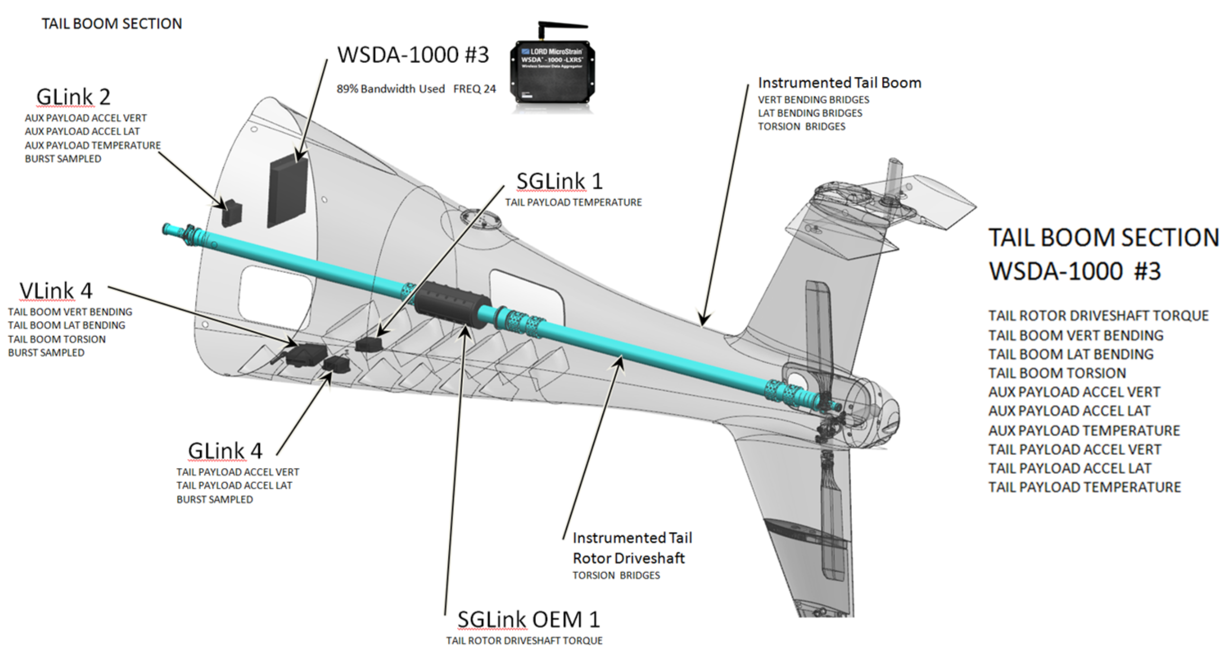

Figure 7: Tail Boom WSDA®-1000

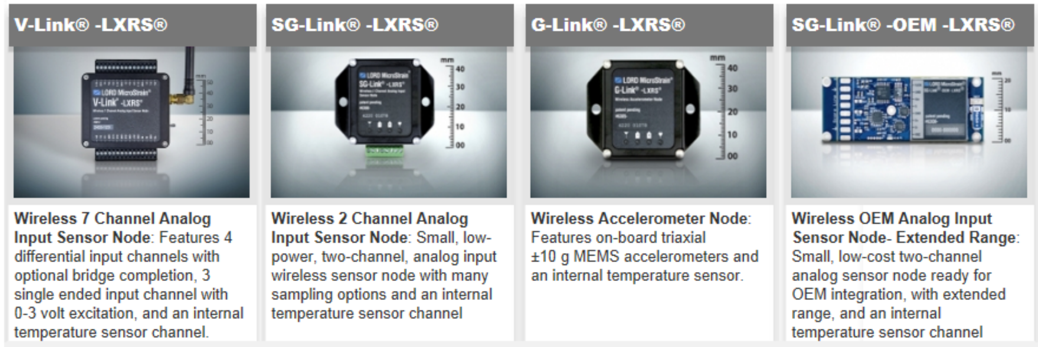

Figure 8: Wireles Nodes Used in Flight Vehicle Networks

Instrumented parts utilized conventional strain bridges applied in traditional fashion. Laboratory calibration of the instrumented parts yielded slope and offset values for each bridge that related sensitivity to engineering units. The resultant mV/V sensitivity calibration coefficient values were then entered into the configuration of each node selected for the respective measurement location, enabling the instrumentation engineer to have “eyes on” wirelessly transmitted engineering units when doing pre-flight checkout. Slope and offset values were conversely input into the WSDA-1000 and RGD modules to apply engineering unit conversions to the bulk data downloaded at the conclusion of each flight.

Blade Pass Sensor

The blade pass sensor simply detected a rotating magnet attached to the rotor mast (Hall Effect Sensor). Sensor electronics recorded a peak value when the magnet passed in front of the sensing element, thereby indicating one complete rotation of the mast and two blade pass events (Figure 9). Like other sensors in the network, these events were passed wirelessly to the WSDA-RGD.

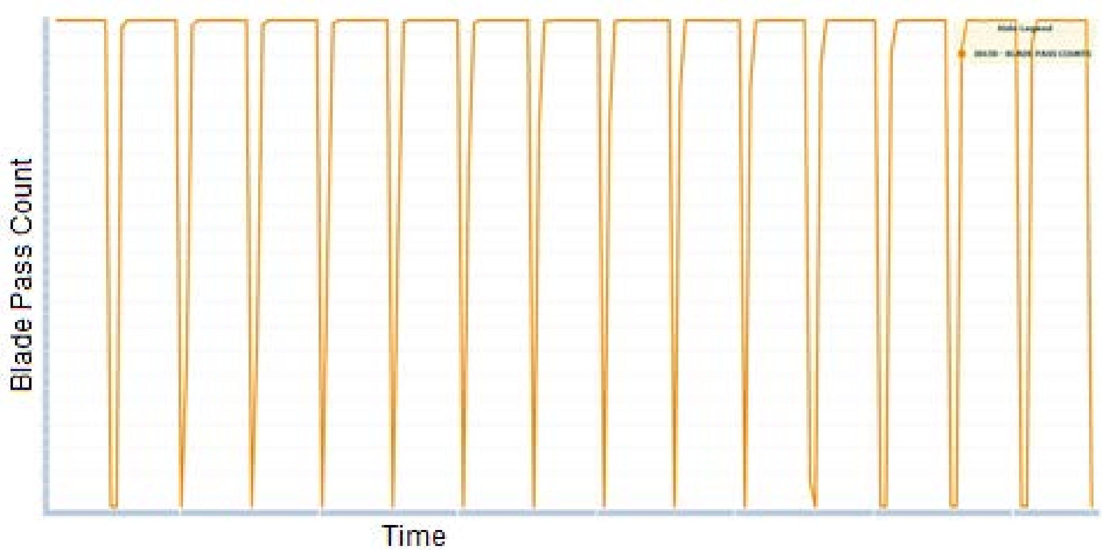

Figure 9: Blade Pass Data

Tail Rotor Driveshaft

LORD engineers supplied a purpose designed and built node that was applied to a standard S-100 drive shaft for the purpose of measuring torsion strain. Measured strain values were correlated to torque via a static radial loading lab calibration. The addition of the TRDS instrumentation package to the existing drive shaft introduced a dynamic unbalance in the system that was unacceptable for safe flight operations. To mitigate these effects, the package was initially designed as a statically balanced system with the center of gravity aligned with the axis of rotation.

For dynamic balance, adjustment collars were manufactured and installed on both ends and at the center location of the shaft, which were the necessary nodal locations to achieve three planes of unbalance correction on a flexible rotor and balance through its first critical speed. When installed on aircraft, the TRDS passes through a center bumper bearing that provides centering support on the drive shaft and reduces excessive deflection during operation.

The dynamic balancing effort used no center support, which provided an extra level of conservatism, since an unsupported driveshaft of this length will undergo its critical speeds at lower frequencies, thereby enabling balancing through a worst-case scenario. This effort balanced the driveshaft supported only on its ends through the first critical speed and up to approximately 60% of its expected operational speed. Residual imbalance caused by the sensor instrumentation was minimized to approximately 30% of the factory-specified limit with two evolutions of dynamic balancing using three balance correction planes. The TRDS instrumentation package is shown in a balancing fixture and a typical trace of data collected during one ground-air-ground (GAG) cycle in Figure 10.

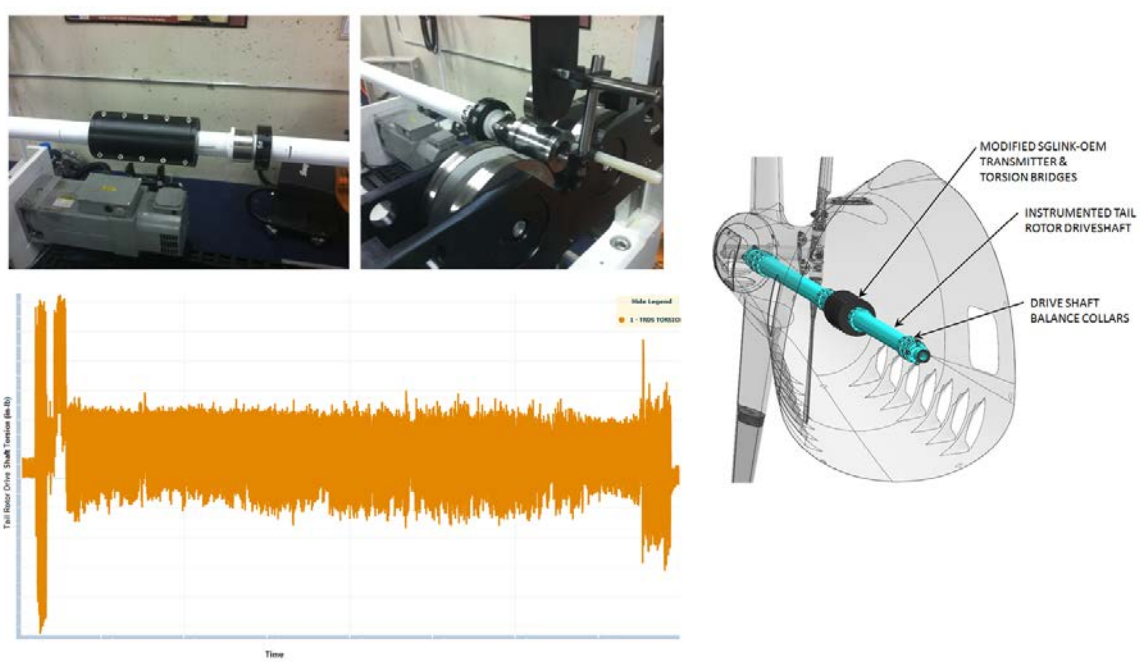

Figure 10: TRDS Balancing Setup, Integration, Data

Main Rotor Head

The main rotor head was instrumented to provide operational bending moments in flap and lateral axes and main rotor torque. The main rotor head also was used to attach the structure that supported two V-Link nodes that provided eight differential channels for the rotor head and main rotor blade measurements (Figure 11). At full speed, the main rotor head achieved 1178 RPM. Traditional requirements would dictate a 32-channel slip ring for signal transfer. Mounting the wireless nodes to the rotor head negated any need for a traditional slip-ring assembly.

The signals from the V-Link transmitters were received by the WSDA-RGD mounted externally on the left side of the ship. High frequency burst sampling was employed.

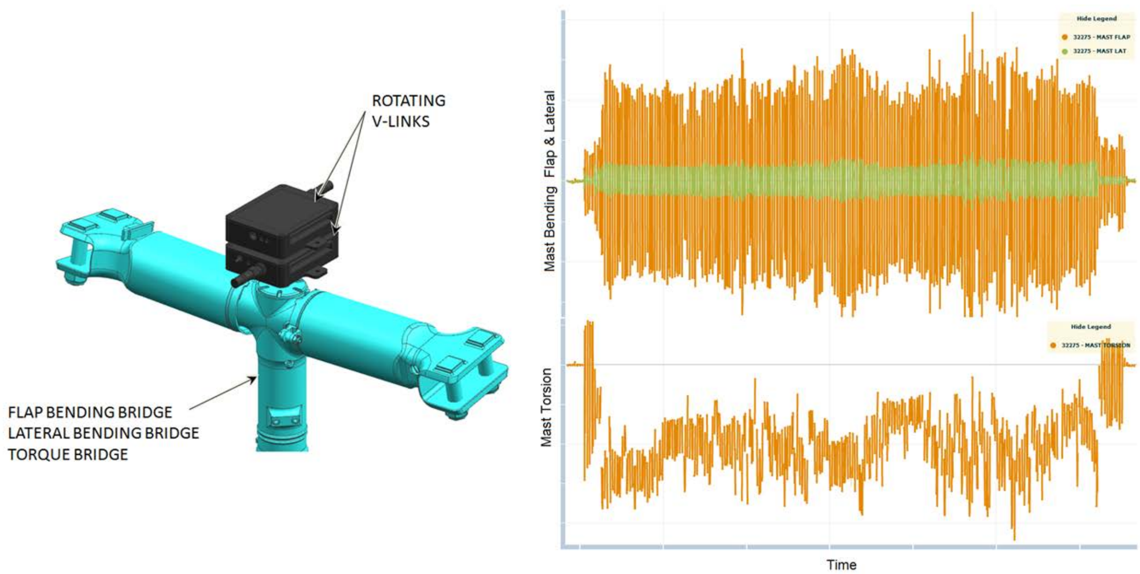

Figure 11: Main Rotor Head Integration, Data

Main Rotor Blade

The main rotor blade was instrumented with strain bridges for flap, chord bending, and root end blade torsion (Figure 12). High frequency burst sampling was employed. Signals were received and aggregated by WSDA-RGD mounted on the left side external payload.

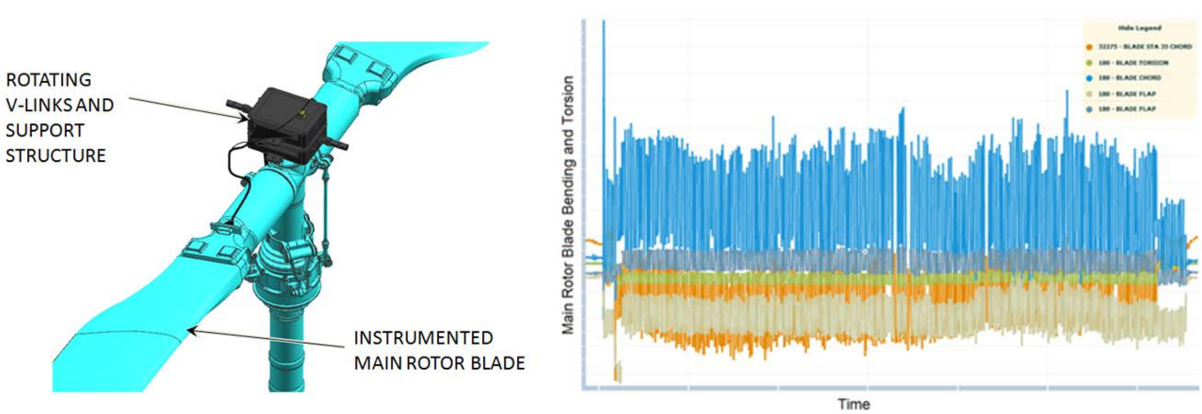

Figure 12: Main Rotor Blade Integration, Data

Nose Frame Instrumentation

Lateral and vertical bending moments were measured with strain gages applied to the upper and lower nose frame joints on both sides of the aircraft. High frequency burst sampling was employed. Signals were received and aggregated by WSDA 1 mounted in the nose bay (Figure 13).

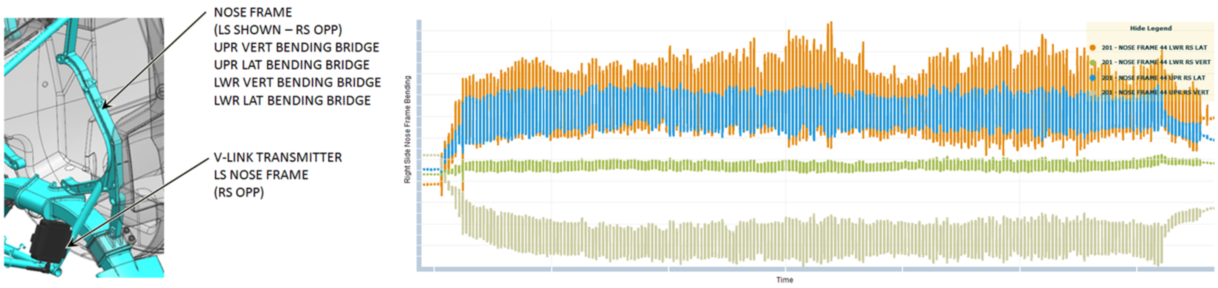

Figure 13: Nose Frame Integration, Data

Landing Gear Instrumentation

The main landing gear beam and landing gear links were instrumented with bending bridges and axial bridges. Medium frequency continuous sampling was employed. Signals were received and aggregated by WSDA 1 in the nose section (Figure 14).

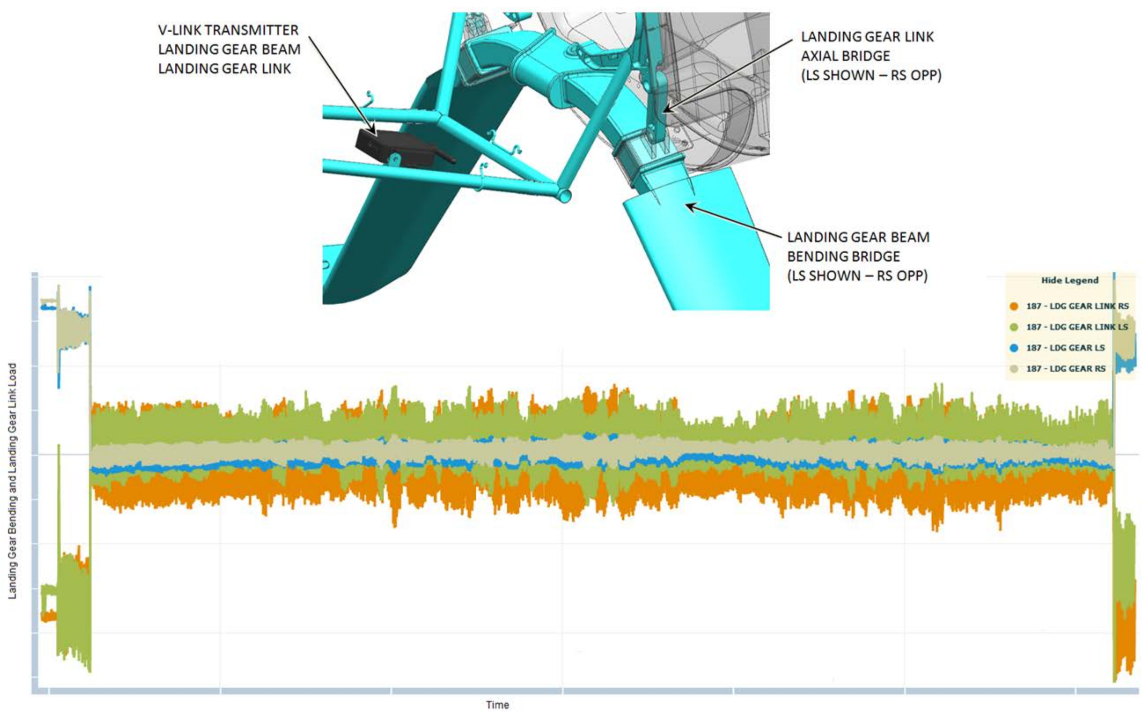

Figure 14: Landing Gear and Landing Gear Link Integration, Data

Tail Boom Instrumentation

Lateral and vertical bending moments and torsion were measured with strain gages applied to the outer surface of the tail boom. High frequency burst sampling was employed. Signals were received and aggregated by WSDA 3 mounted in the auxiliary payload bay (Figure 15).

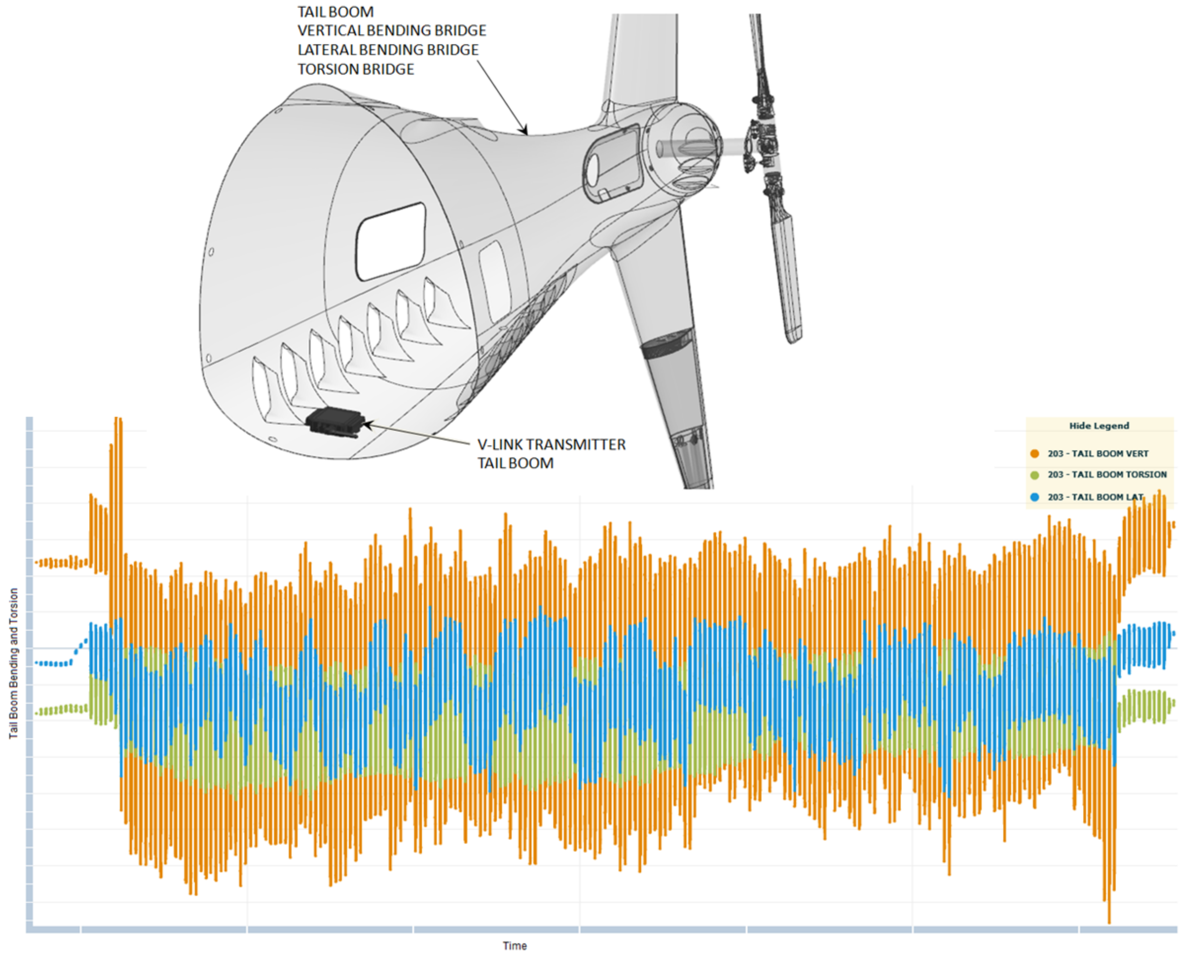

Figure 15: Tail Boom Instrumentation, Data

Accelerometer Integration

Four G-Links (10 G model) were used to accumulate vibration data in the nose, auxiliary payload bay, main payload bay, and tail section. High frequency burst sampling was employed. Signals from the nose were received and aggregated by WSDA 1 in the nose section. Signals from the main payload bay were received and aggregated by the WSDA-RGD. Signals from the auxiliary payload bay and tail boom section were received and aggregated by the WSDA 3 (Figure 16).

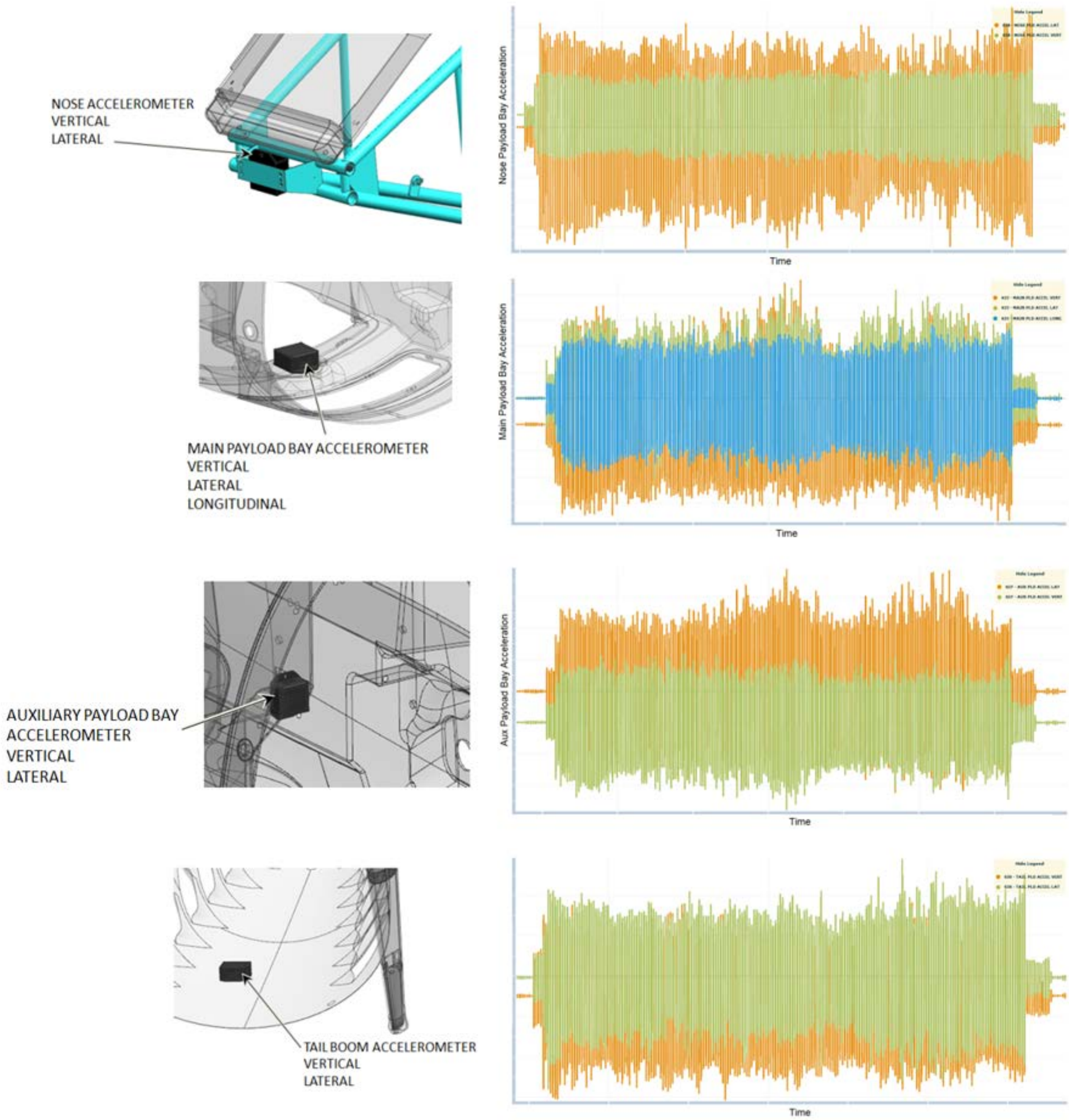

Figure 16: Accelerometer Integration, Data

Temperature Survey

On-board capability of the G-Link nodes was used to record temperatures in the main payload bay, auxiliary payload bay, and tail boom. High frequency burst sampling was employed due to the established sample rate used for acceleration channels. Temperature signals from the tail boom were low rate continuous and provided by a dedicated G-Link programmed to only transmit one channel from the on-board thermocouple (Figure 17).

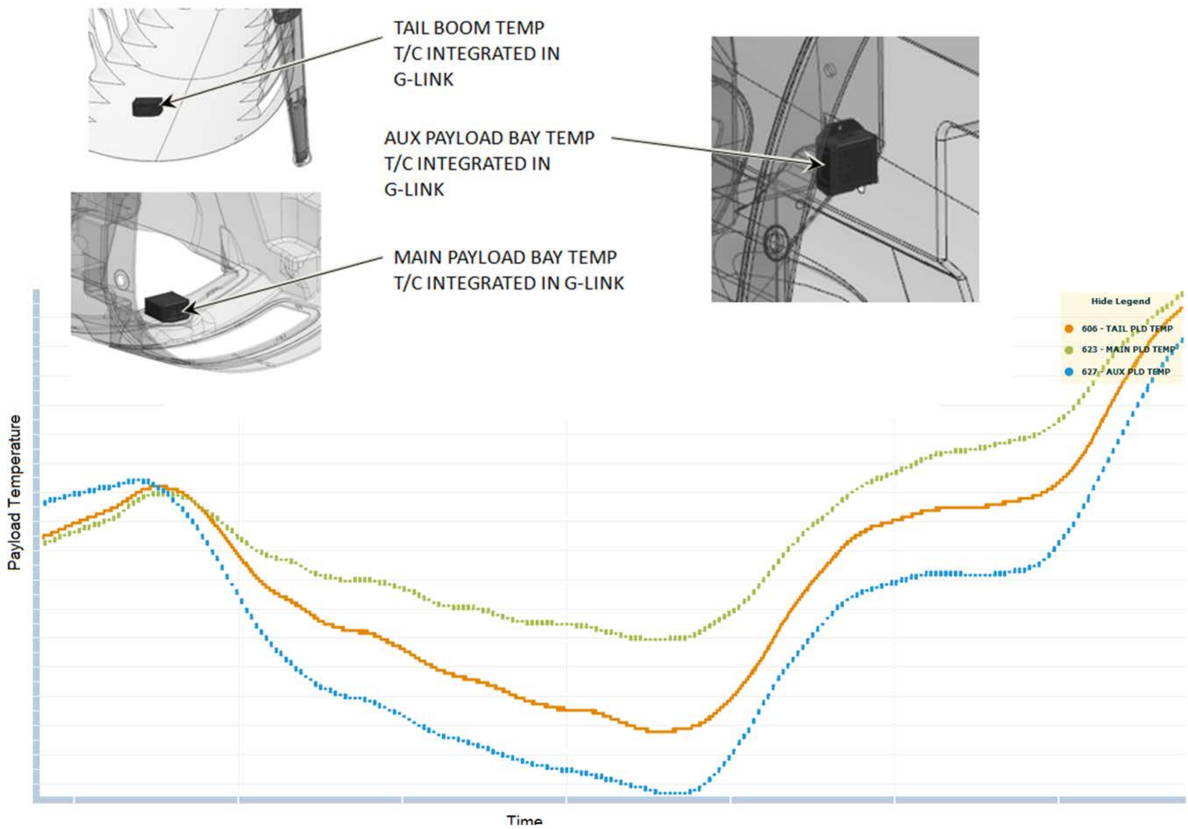

Figure 17: Thermocouple Integration, Data

Conclusion

Flight test efforts for the S-100 program were a complete success, and were facilitated by COTS wireless products from LORD MicroStrain. The program experienced a condensed flight schedule, which not only saved time and money, but also resulted in good data readily available to test engineers in a timely manner. Boeing engineers have leveraged the data collected from flight test points to provide aircraft operational performance feedback to their customer, and also to evaluate flight safety envelope and aircraft configuration that directly affects safety of flight. The flight test vehicle used for this program is still flying today and routinely carries several different wireless sensor configurations.

References

[1] Wilson, W., Atkinson, G. *Wireless Sensing Opportunities for Aerospace Applications.* NASA Langley Research Center, 2009.

[2] DiStasi et al. *Scalable, synchronized network of lossless wireless sensors for rotorcraft monitoring*. AIAC Forum 15, Melbourne, Australia, 2013.