Wireless Instrumentation System for Aircraft Testing

Test Instrumentation Workshop (TIW)
Instrumentation in a Constrained Environment

22-25 May 2023

Las Vegas, NV

- Shiv Joshi, Kurt Rasmussen (presenters)
- Robert DeMott, Mike Juneau, Gerardo Cervantes, Adam Goldman (NextGen)
- Grecia Roman, Robert Neufeld (812 AITS/ENIE, Edwards Air Force Base)

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Company Background

- **Started in Late 2002**
- **Highly Qualified Team**
  - 23 Employees
  - >500 Person-years of Aerospace Engineering Experience on Major Airframe Development Programs
  - Conceptual Design to Full-Scale Development
  - Rapid Design and Fabrication and Prototype Development Capabilities
- **R&D, Fabrication and Prototype Development Contracts**
  - DARPA, Air Force, Navy, Army, NASA
  - System Integrators Including NGC, Boeing, LM, Raytheon, BAE Systems, AeroVironment
- **Strong Partnering Network with Universities, Small Companies, System Integrators**

NEXTGEN RESEARCH & DEVELOPMENT
Torrance, CA

- Wireless Sensors
- Flexible Hybrid Electronics
- Software/Process Development
- CLB Antenna Systems
- Structural Science
- Smart Materials
- Novel Actuation
- Biomimetic Propulsion

NEXTGEN DESIGN & ANALYSIS
Danville, VA

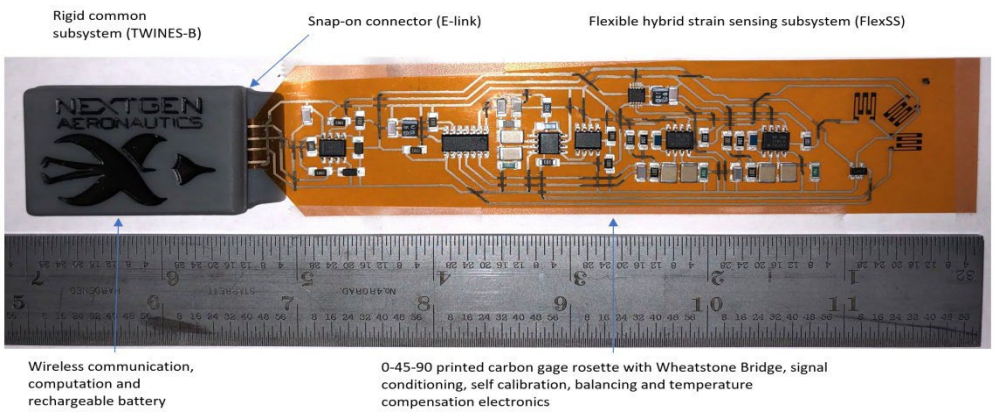
- WT Model Design
- Aircraft/Vehicle Design
- Structural Design and Analysis
- Electrical Design
- Simulation and Controls
- Stress and Fatigue
- Aerodynamics
- Test Design, Planning, Execution

NEXTGEN FABRICATION & TESTING
St. George, UT

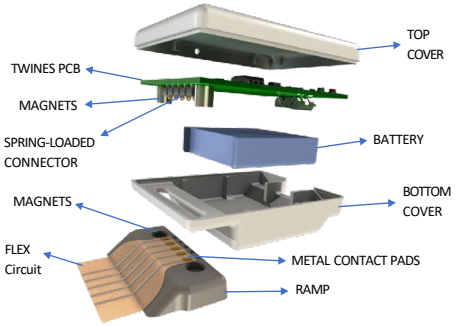
- Composite Fabrication
- CNC Machining
- Assembly and Finishing
- Electrical Integration
- WT Testing
- Flight Testing
- Ground Testing
- Material Testing

Wireless Sensors – Past Projects

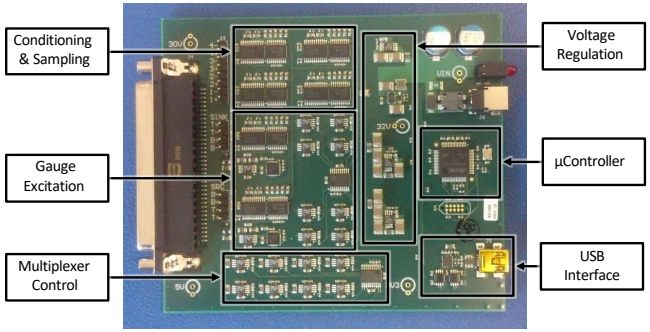
All-Printable Real-Time Airframe Monitoring System (ARAMS)

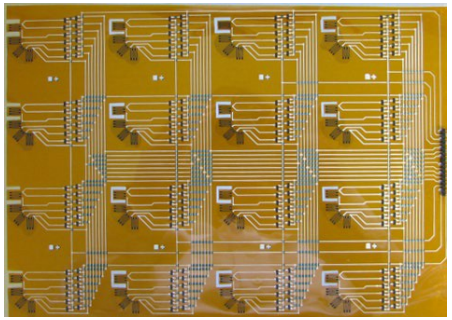


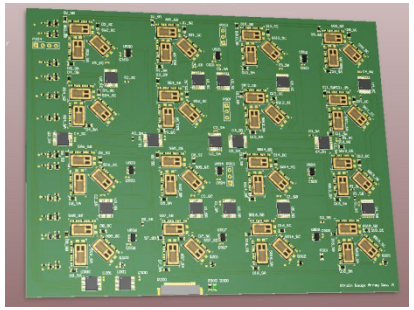
FlexSS with Carbon Strain Gauge Sensors



Tiny Wireless Networking Module for Strain, Pressure, Temperature Sensing





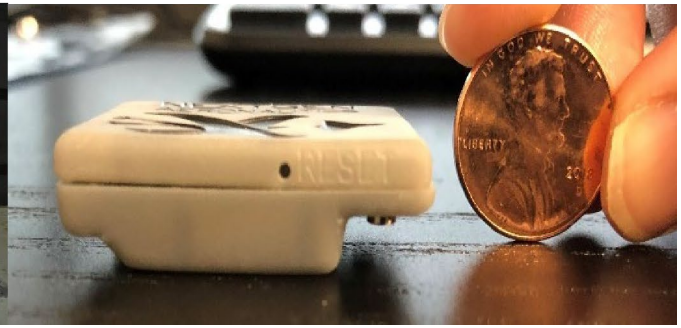


4×4 Strain Gage Array Developed using a Hybrid Approach of Printed Strain Gages and Discrete COTS Transistors Bonded to the Substrate to Perform Multiplexing

Wireless Sensors – Past Projects

Tiny Wireless Networked MEMS Sensors (TWINES)

- Swappable modular sensor units with a Bluetooth radio module, a lithium polymer battery, and a hot-swappable sensor unit
- Achieved combined 10 KHz bandwidth from up to 12 sensors of different types sampling simultaneously
- Tested accelerometers, strain sensors, pressure, and temperature sensors
- Designed and built software to save and analyze data
- Sensors can be put to sleep remotely
- Design resulted in Patent No. US20090058663



Wireless Sensors – Past Projects

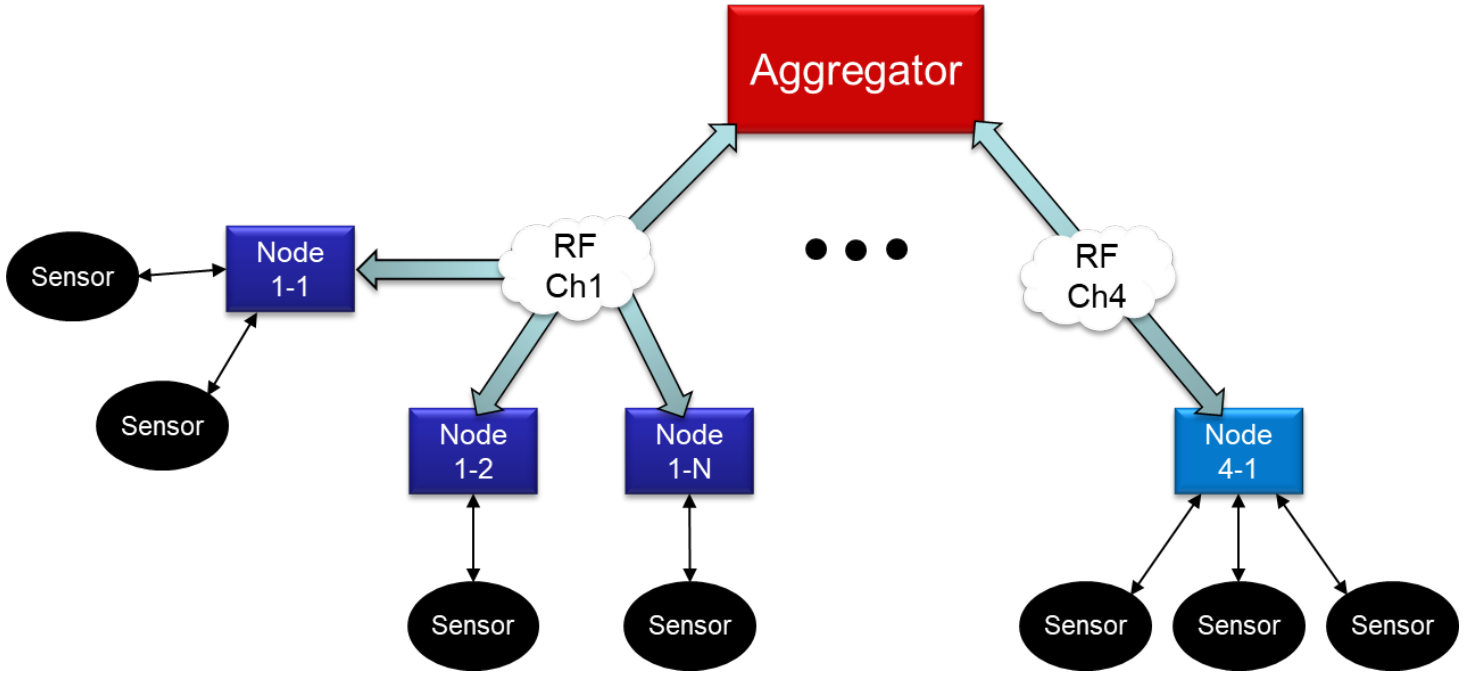
BodyKinetix – Body Worn Wireless IMUs (SWIFT)

- Multi-sensor system using an IMU, microcontroller, 900 MHz radio, and lithium polymer battery
- Achieved frame rate of 100 Hz while utilizing 16 sensors simultaneously
- Master clock synchronizes with each node to maintain a system timing accuracy of 10ms
- Tested the quaternion output of IMUs to verify that they accurately represent body movements
- Designed and built software to capture the data and display it in real-time using a 3D avatar
- Sensors can sample continuously for 4 hours on a single charge

WIS Overview

The Wireless Instrumentation System (WIS)

- Provides a means of reliably capturing and wirelessly transmitting timestamped sample data from sensors spread across numerous remote locations within an aircraft
- Consists of a central aggregator unit and multiple wireless sensor nodes; each sensor node can handle one or more sensors



WIS Overview (cont'd)

The Wireless Instrumentation System (WIS)

- Supports individual sensor sample rates of up to 1 kHz
- Supports handling more than 100 sensors simultaneously
  - Combined wireless sensor data throughput can be up to 40,000 samples/sec when fully utilizing all RF channels
  - Maintains precise end-to-end timestamp accuracy to better than **one microsecond (< 1µs)**
    - **Time correlation per IEEE 1588 Version 2**
    - Can utilize the precision time protocol for real-world (GPS) time synchronization
  - Provides timestamped sensor data to the end user via a 100Mbps Ethernet interface
    - The IRIG 106 message format and communication protocols are used
  - Supports direct operation from 28V DC aircraft power as well as lower voltage options (12V, battery)

WIS Figures of Merit

Desired System Capabilities	NextGen Solutions
Sample Rate of 1 kHz	Select a COTS wireless transceiver that maintains a raw data rate of 1Mbps to support sample throughput of at least 1 kHz
Time correlation per IEEE 1588 Version 2	Observing the propagation time of the message exchange between the master and slave determines the offset between both clocks and synchronizes both subsystems.
Bit Error Rate (BER) $<10^{-6}$	Establish high signal-to-noise ratio (SNR) and use error detection and correction (EDAC)
Time tagged to an accuracy of 1 μsec	Sensor nodes use precision clock sources and are continuously resynchronized to master clock using a specialized TDMA communications and timing protocol
1-Sensor/Signal	Wireless sensor nodes individually timestamp each sensor sample and communicate per-sensor metadata and parameter identifiers for real-time status reporting

WIS Development Objectives

- **Develop Wireless Instrumentation System (WIS)**
  - **Define WIS Architecture**
    Define fundamental organization of WIS system. System architecture shall follow communication principles, provide concept template, and be traceable to system requirements
  - **Design, Build, and Assemble System Components**
    Design and fabricate prototype subsystems and functional components; after clearing CDR, NextGen shall fabricate and assemble modular components of the designed WIS
  - **Develop Embedded Software for System Components**
    For active components in tandem with hardware under the last objective
  - **Perform Screening Tests and Validation Demonstration**
    Provide/perform test plans for all WIS module, subsystems, and system-level electrical, mechanical and environmental evaluations

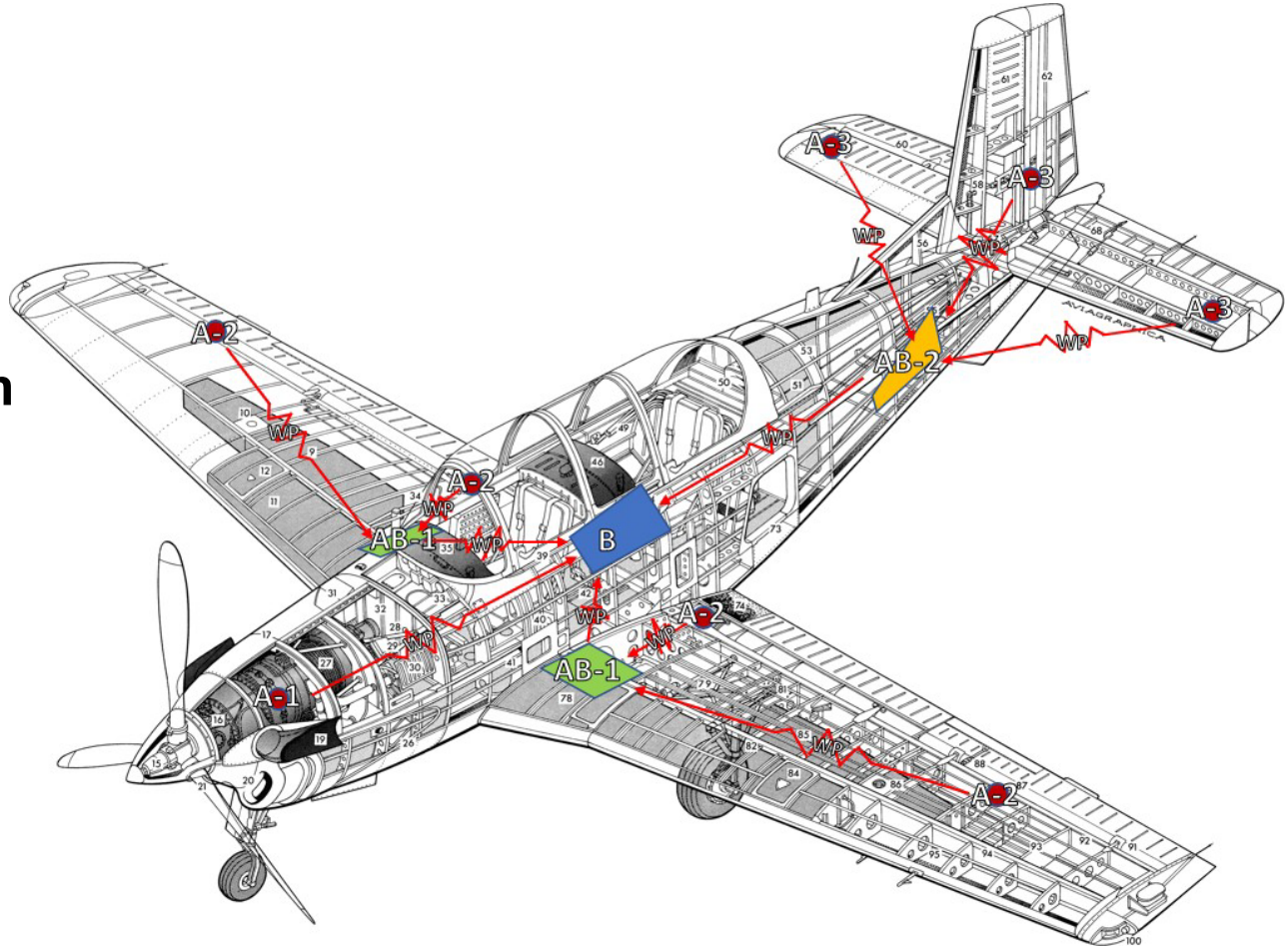
WIS Architecture

Main Subsystems

- Sensor Block (S)
- Repeater (RP or RA)
- Transceiver Block (TR)
- Aggregator Block (Ag)

Auxiliary Subsystem

- Interrogator (I)

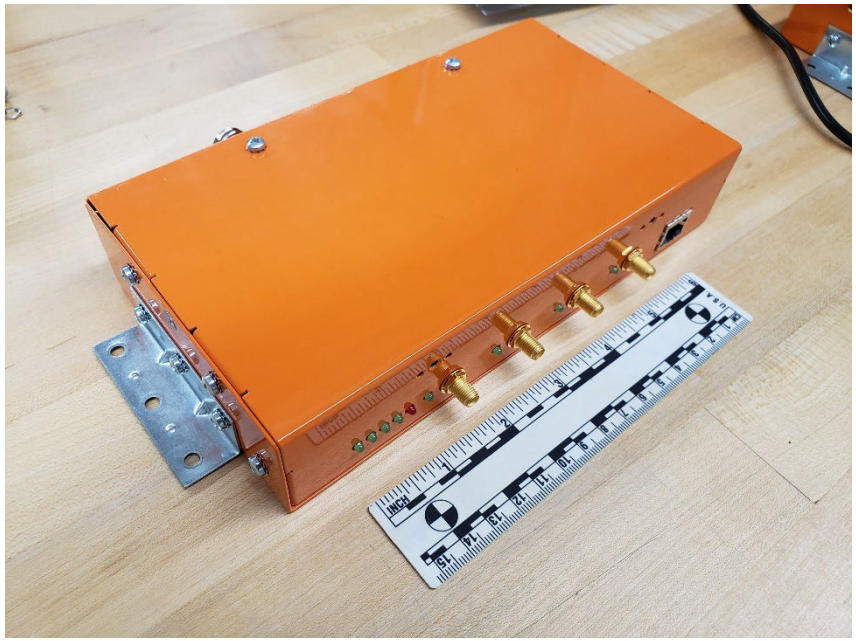


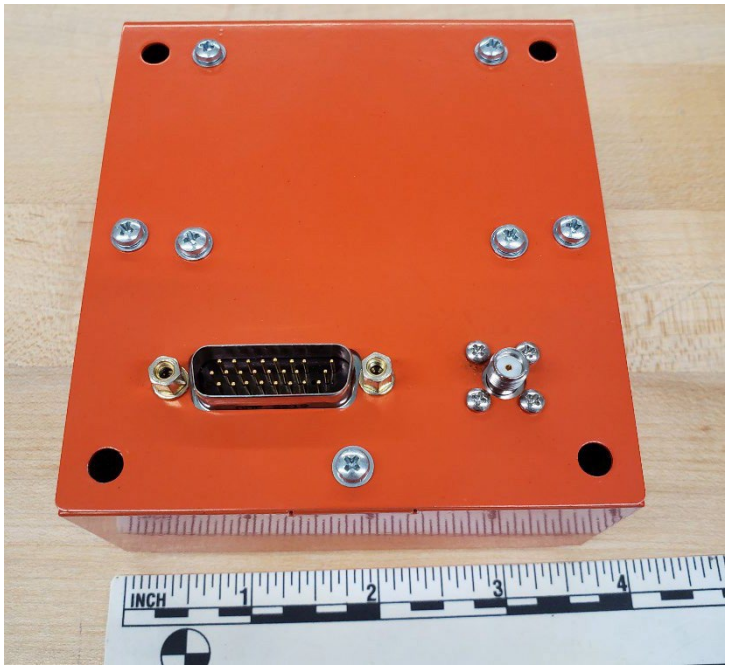
A-1: Direct LoS to the aggregator block (Ag antenna) which is near position (B)

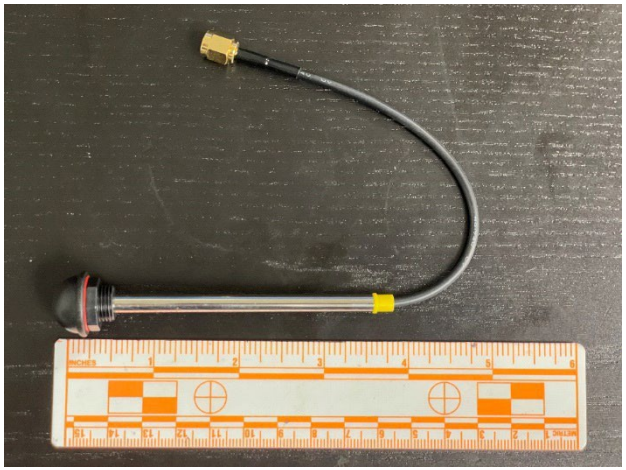
A-2: No direct LoS to the aggregator block antenna; thus, a passive repeater is used in position AB-1

A-3: No direct LoS to the aggregator block positioned in B, In this case, an active repeater in position AB-2 is used to multiplex each sensor node, A-3

WIS System Elements



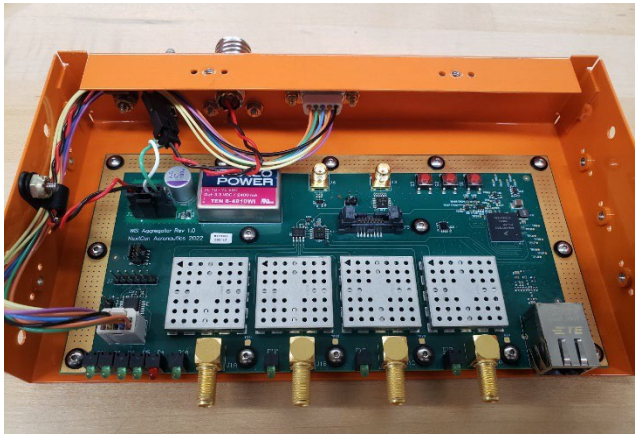




WIS Aggregator

- **Aggregator Overview**
  - **Coordinates all WIS sensor node communications**
    - Communicates within the 902-928MHz ISM band
  - **Can support over 100 connected sensors**
  - **Features 4 integrated RF transceiver blocks**
    - Supports up to 4 antennas and 4 frequencies simultaneously
    - Allows for both frequency and spatial separation of sensor nodes
  - **Interfaces with customer hardware via ethernet interface**
    - Utilizes IRIG 106 communications protocol and IEEE 1588
    - Timestamps all sensor data to within 1 microsecond
    - Will support both static and dynamic IP assignment
  - **Configuration and programming via RS-232 serial interface**
    - Used to upload firmware and change network settings

WIS Aggregator (cont'd)



- **Aggregator Hardware**
  - **Front panel LEDs for status and error indication**
    - Includes sensor communication activity and time synchronization status
  - **Powered from 28VDC aircraft power (isolated)**
    - Designed based on MIL-STD-704 specifications
    - Expected worst case power consumption: 3W
    - Cooling approach: passive no fans or vents

WIS Aggregator Details

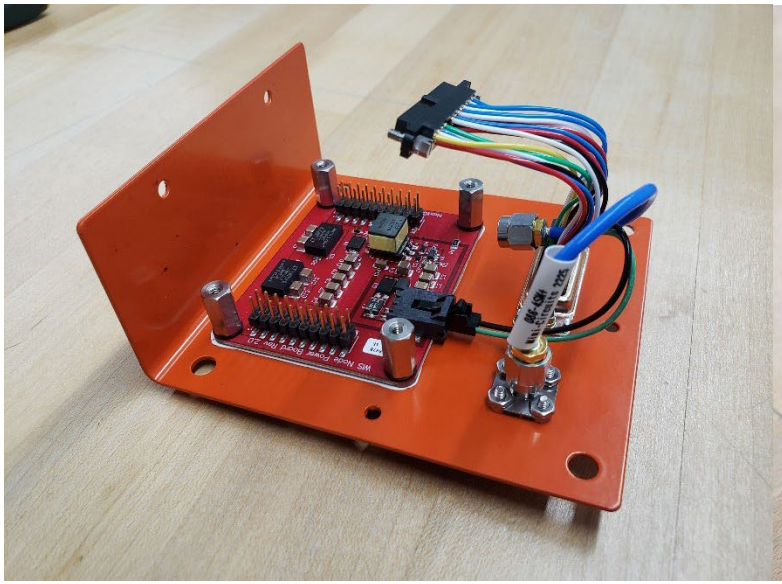
- One aggregator serving one or more transceiver blocks
- Aggregator is the master for everything
- Single communication point to the platform's main processing/communication hub
- Aggregator collects the data from all transceivers, then formats and applies the proper time stamp information to the data before sending it to the main processing/communication hub
- Transmission between the aggregator and the main processing hub is via an Ethernet interface that uses TCP/IP protocol
- Aggregator also provides the physical clock (reference frequency) used by the transceiver blocks (TR) and aligns time across the TR blocks
- Therefore, TR blocks are also phase and frequency coherent
- Frequency/time drift between the aggregator and remote sensors is periodically corrected
- Responsible for framing and TDMA control as well as multiplexing all sensor data
- Framing and TDMA control include control segment, time sync, sensor node time slot assignment, frequency assignment, and coordination of co-located TR blocks which transmits at the same time and then listens at the same time

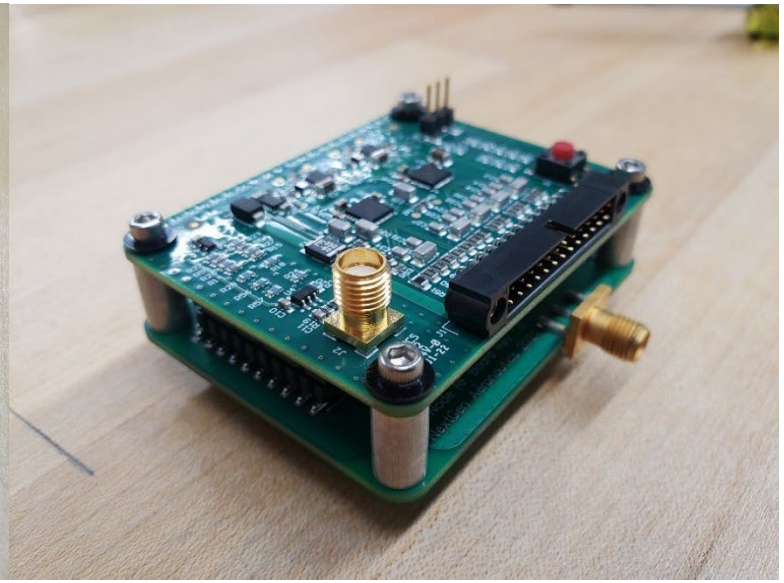
WIS Wireless Protocol

- **Time-division Multiple Access (TDMA) Approach**
  - Periodic (100Hz) beacon from aggregator controls channel access
  - Fixed-size timeslots for sensor node responses
- **Wireless Time Synchronization Occurs Every Update (100Hz)**
  - Two-way synchronization with automatic delay compensation corrects offset and drift between nodes and aggregator
- **Sensor Data Packetization and Transmission**
  - Number of sensor readings per packet limited by timeslot size
  - Efficient transfer of 8, 16, 24, and 32-bit sample types supported
  - Every sensor reading includes sensor identifier, timestamp and health status information (over/under-range, reference fault, etc.)
  - Supports up to 32 distinct sensors per node
- **Can Utilize Optional Acknowledgement and Retry System**
  - Allows for retransmission of sensor data to mitigate packet loss
  - Buffering is limited based on strict maximum latency parameter

WIS Sensor Node

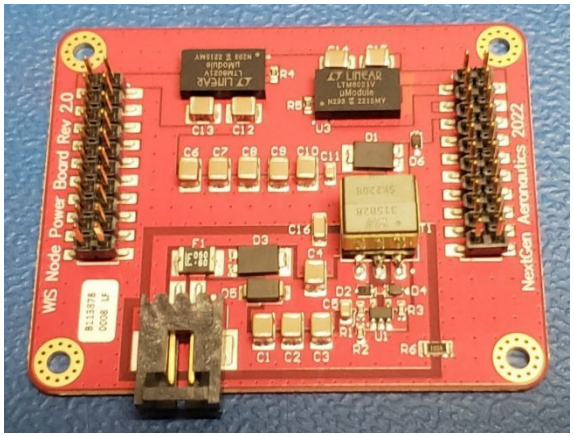
- **Electronics Consist of a Modular Stack of Three PCBs**
  - Power Board: Voltage regulation and input protection
  - RF Board: Wireless communications and data processing
  - Sensor Board: Signal conditioning and data conversion (ADC)
  - Board Dimensions: 2.5" x 2"
  - **Individual boards selected based on target requirements**
    - ex: Specific signal conditioning board dependent on sensors used





WIS Sensor Node Boards

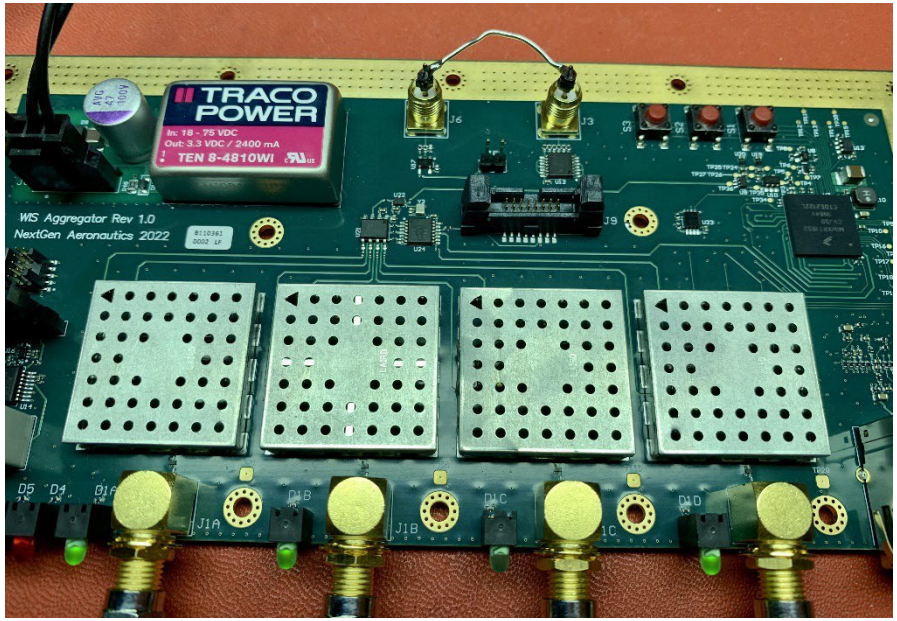
- **Power Board Details**
  - Provides regulation of all internal supply voltages
  - Fully isolated switching regulator with input fault protection
    - Over-voltage, reverse voltage, over-current, and transient protection
  - Designed to requirements of MIL-STD-704F for 28VDC operation
  - Input voltage range:
    - Minimum: 9.5V, Maximum: 40V (continuous), 60V (surge)
  - High efficiency: Full node consumes 6.8mA @ 28V DC (190mW)

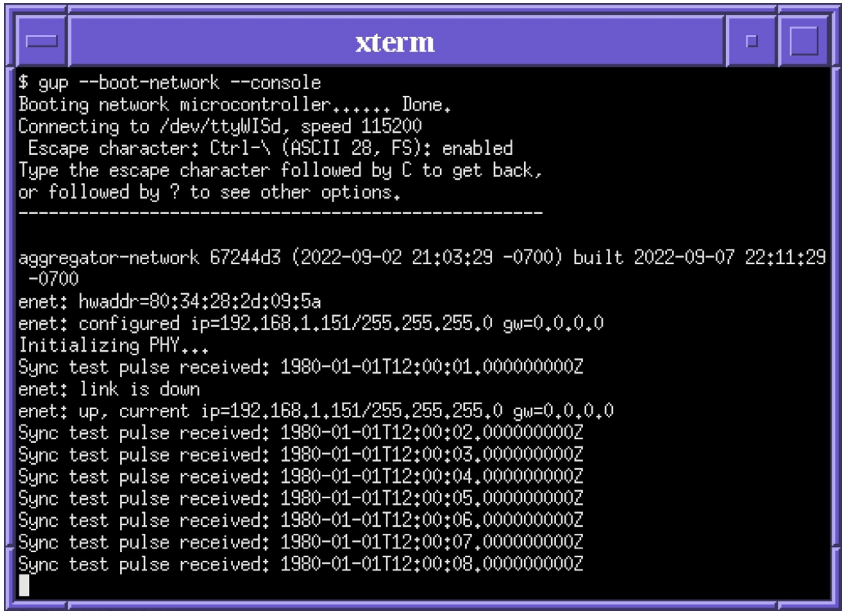


WIS Sensor Node Boards (cont'd)

- **Signal Conditioning Board Details**
  - Two Delta-Sigma Analog to Digital Converters (16-bit)
    - Programmable gain 1-128x, and input buffering
    - Configurable filtering
    - Adjustable sample rate from 1Hz to 4kHz
    - Synchronized with clock generated from RF board
    - 24-bit version available
  - Five fully differential analog inputs
    - Supports both ratiometric and non-ratiometric analog sensors
    - Examples: string potentiometers, load cells, pressure transducers, temperature sensors (3 or 4 wire config)
    - Dedicated excitation voltage pins for each input available
  - Byte erasable chips (EEPROM) for automatic board detection/identification
    - Stores configuration and calibration information

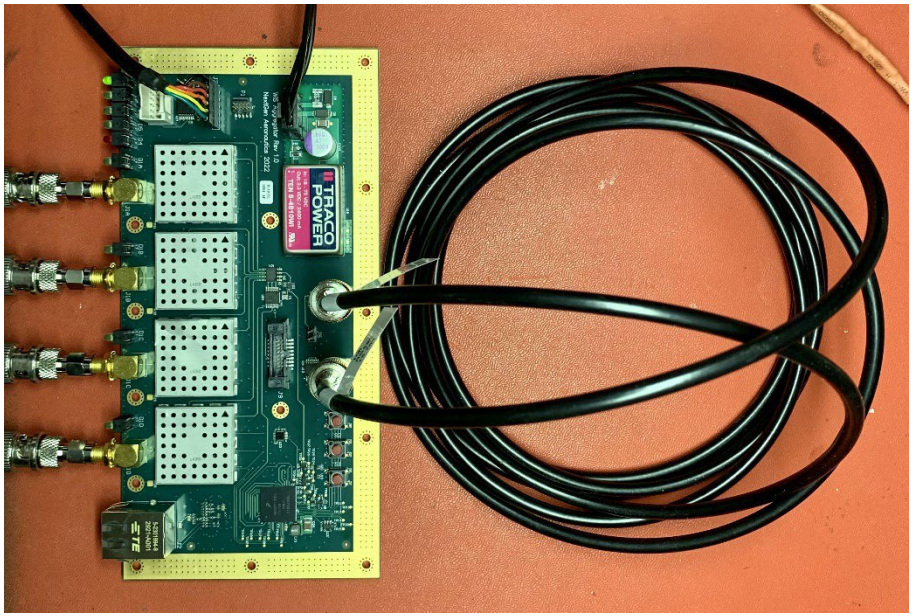
Time Sync Verification Testing

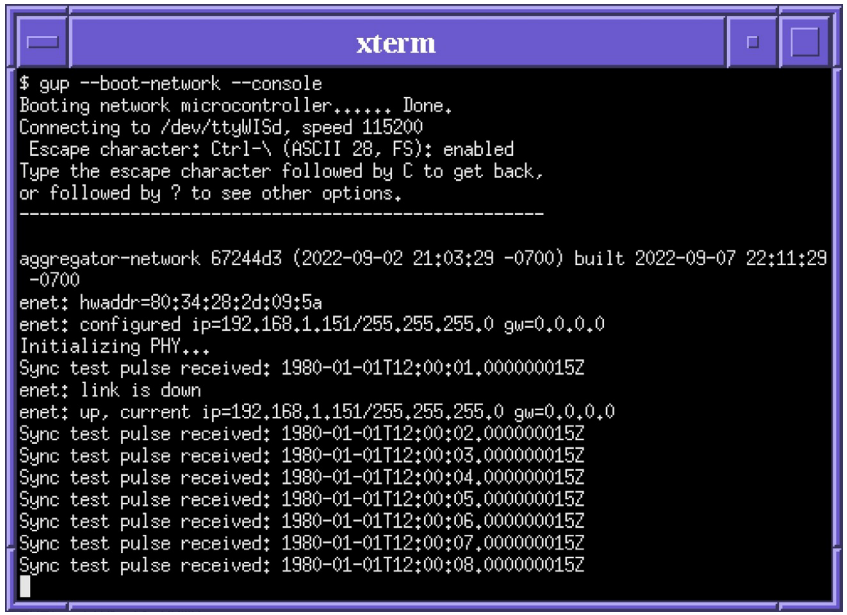




- 1.5" Wire from Sync Test Out to Sync Test In
- 1 PPS signal from Sync Test Out
- Timestamped by Sync Test In
- Captured timestamp values: hh:mm:ss.000000000

Time Sync Verification Test

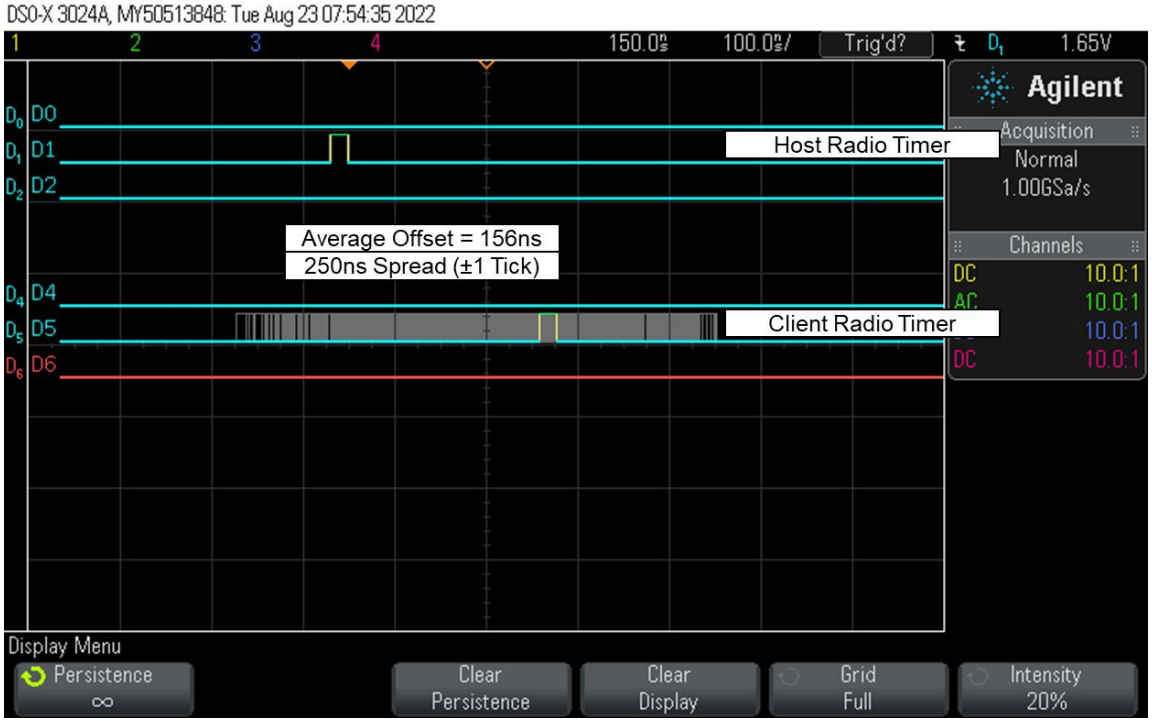




- 10ft RG58C from Sync Test Out to Sync Test In
- Captured timestamp values: hh:mm:ss.000000015
- Actual cable delay 15.7ns (measured by time interval counter)

Conclusion: Sync test ports will allow for accurate assessment of time synchronization

Time Sync Verification Test



- Wireless Time Synchronization Validation Between Host and Client using TDMA Protocol
  - Host = Aggregator Radio, Client = Sensor Node Radio
- Logic Analyzer Shows Synchronized Radio Timer Pulses of Both End-points
  - Average offset is 156ns
  - Worst-case deviation is 250ns

Testing and System Validation

WIS Subsystems Screening Tests

- Communication
  - Bench/LoS tests ensured system feasibility within lab environment
- Preliminary Mechanical/Environmental
  - Testing ensured robust system enclosures and connectors can withstand harsh airborne and ground handling conditions

```
2023-02-15T12:43:54.867255102-08:00 Radio_3_Node_4_Param_02 -3290 uV@5Vex
2023-02-15T12:43:54.877495102-08:00 Radio_3_Node_4_Param_00 1.28 %FS
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2023-02-15T12:43:54.887735102-08:00 Radio_3_Node_4_Param_00 1.28 %FS
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2023-02-15T12:43:54.908215102-08:00 Radio_3_Node_4_Param_00 1.28 %FS
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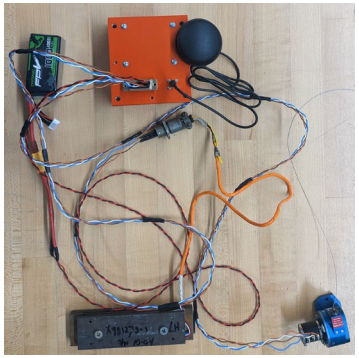

Summary

- The NextGen WIS will **minimizing labor hours and airframe downtime** when needing to install sensors on test aircraft.
- **1 microsecond time synchronization:** One of the challenges with other wireless systems currently on the market is time synchronization between multiple sensors. The WIS system solves this with **accuracy of better than 1 microsecond**. Timestamps are provided with nanosecond resolution.
- The system consists of a **central Aggregator** and **multiple wireless Sensor Nodes**, with each node capable of handling multiple sensors. Can accommodate over **100 total sensors** with sample rates ranging from **1Hz to 1000Hz.** Aggregates **4 independent radios across 10 independent frequencies.**
- Sensor Node power is **approximately 0.5 watt** at Input voltage between **12 and 40 volts**. A **battery-operated version** of the sensor node is also available.
- The aggregator uses **IEEE1588 precision time protocol** via an **Ethernet** connection and propagates better than **1 microsecond time accuracy to Sensor Nodes**, data collected by the sensor nodes and **tags each sensor reading**. This data is made available to the aircraft LAN in **IRIG Chapter 26 format**.

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