Energy Harvesting, Synchronized, Wireless Sensor Networks

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MicroStrain's Smart Sensors

Displacement

DVRT®

Robotic systems

Orientation

3DM-GX320®

Unmanned systems

Wireless

G-Link®, V-Link®, SG-Link®, TC-Link®

Machine Monitoring

The Economist
April 28th – May 4th 2007

"We're wearing out…plan to replace us soon"

Sensing the Future

Wireless sensors, in the billions, will become deeply embedded within structures & machines.

Sensed information will be automatically compressed & forwarded for condition based maintenance.

Problem:

But who will replace all those dead batteries?

Solution:

- Harvest & store energy from strain, vibration, light, thermal gradients, motion
- Use power management to balance the energy "checkbook"
- Use embedded processors to compress data, compute fatigue life

Loads Tracking on Helicopters

Direct loads monitoring of rotating structures enables damage tracking based on actual usage for improved condition based maintenance.

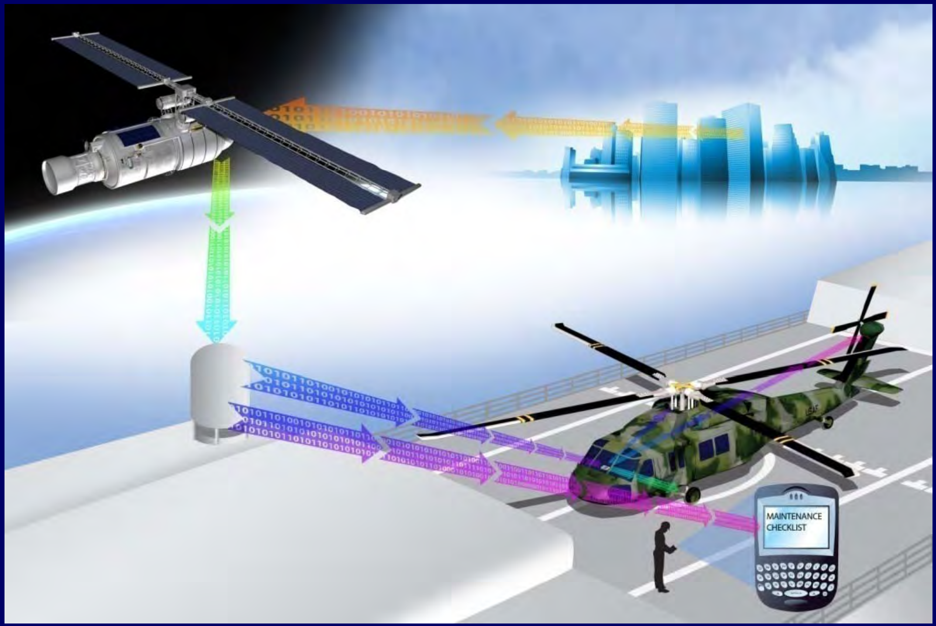
S. Maley et al, “US Navy Roadmap to Structural Health and Usage Monitoring – The Present and Future”, 63rd AHS, Virginia Beach, 2007

Overall Program Objectives

- Design, develop, and demonstrate an energy harvesting, wireless structural health monitoring (SHM) system for military helicopters.

- These systems shall be designed for long term operation, without the need for battery maintenance.

MicroStrain's helicopter structural health monitoring system (patents issued & pending)



Patents pending

Methods:

Communicating wirelessly,
collecting sensor data,
harvesting & consuming energy,
synchronizing wireless networks

Communicating Wirelessly

MicroStrain’s Scalable Wireless Networks

- Time Division Multiple Access (TDMA)
- Carrier Sense Multiple Access (CSMA)
- Frequency Division Multiple Access (FDMA)

How many strain gauges?

Over the air:

TDMA/CSMA: 500 nodes*4 strain ch= **2000** strain gauges, all @ 5Hz
w/ FDMA: 2000 strain gauges*16 radio channels= **32,000** strain gauges

Data logging:

65,536 multi-channel nodes

What frequencies for 802.15.4 and will it work around WiFi?

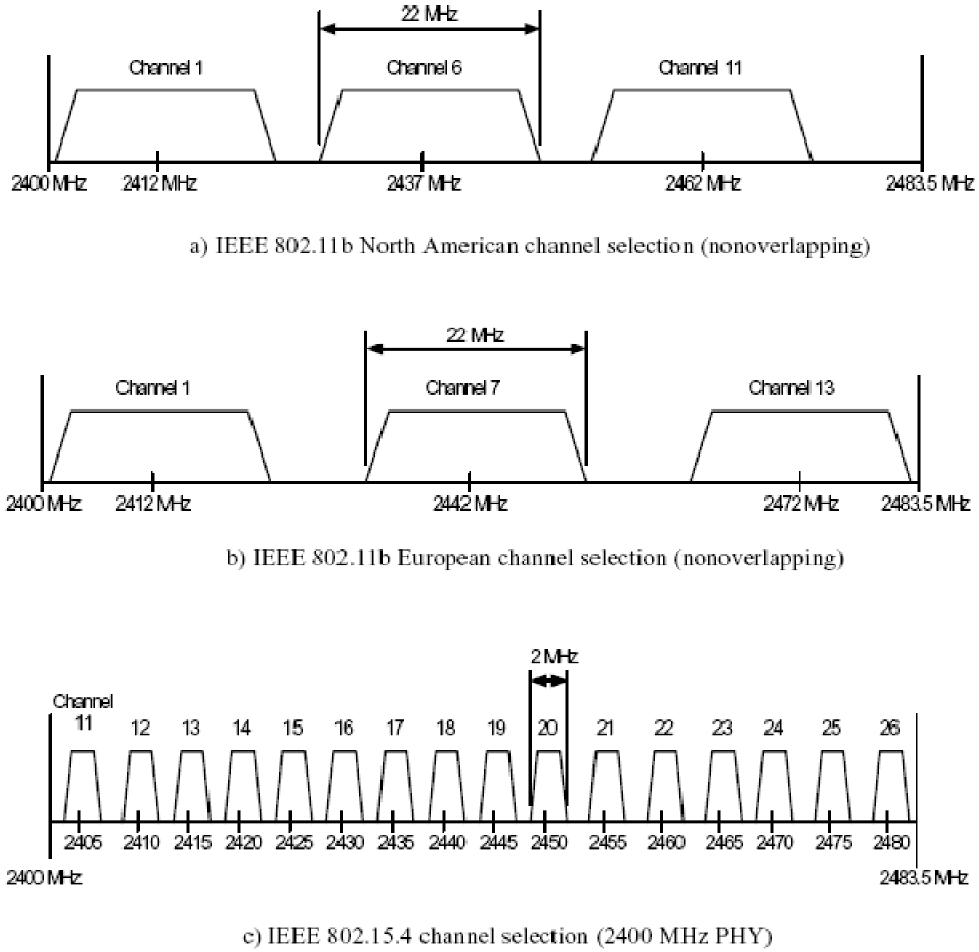


Figure E.1—IEEE 802.15.4 (2400 MHz PHY) and IEEE 802.11b channel selection

802.15.4 Chs 15, 20, 25, & 26 non-overlapping with 802.11b

802.15.4 Chs 15, 16, 21, & 22 non-overlapping with 802.11.b

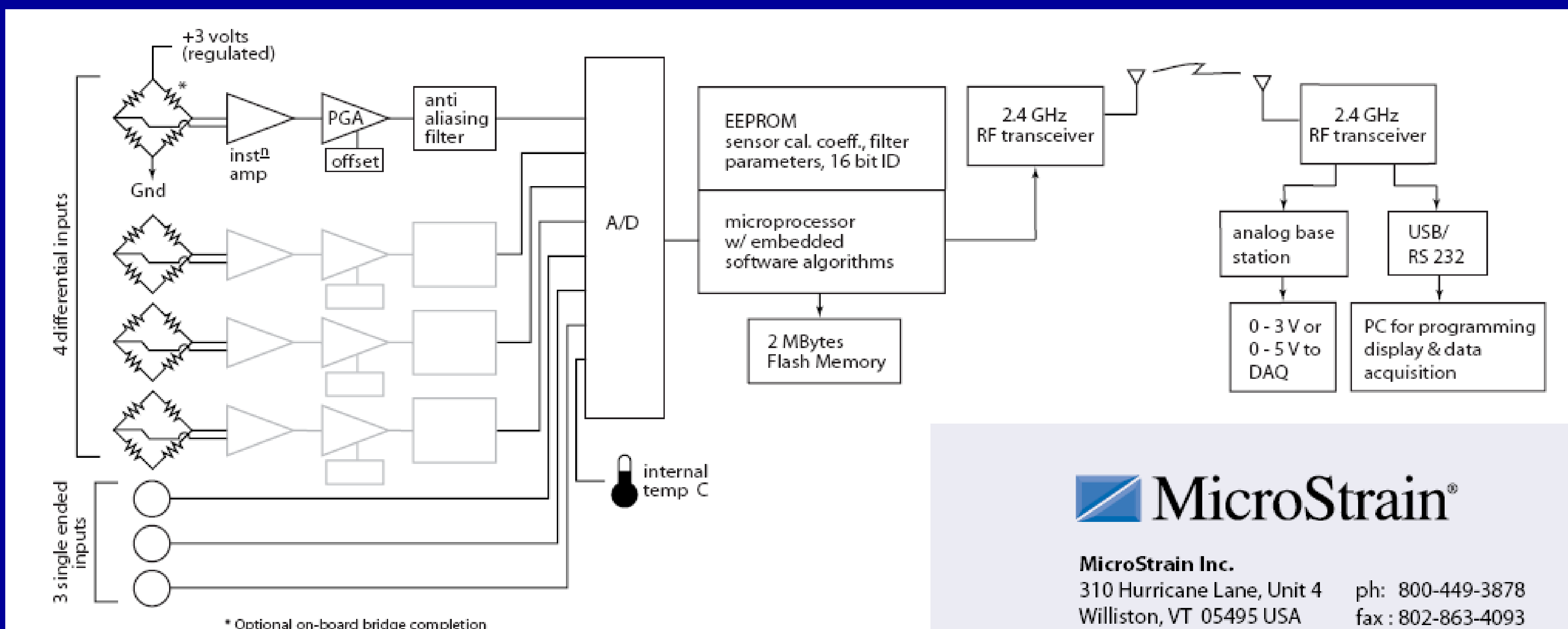
Time Initialization & Synchronization (patents pending)

- Wireless nodes each have an independent precision nano-power real time clock (RTC) with +/- 3 ppm (-40 to +85 deg C) time reference.

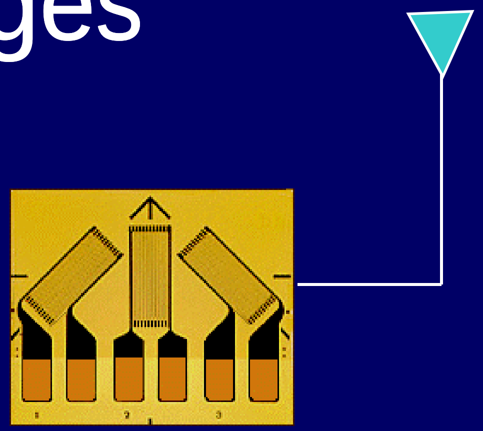
- RTC time on reference node (Data Aggregator) uses Global Positioning System (GPS) as time reference.

Measuring strain, force, pressure, torque, vibration…

Wireless Strain System Diagram (patents pending)



MicroStrain’s embedded firmware optimized for strain gauges



- Wireless offset adjust
- Wireless gain adjust
- Wireless control of sample rates
- Wireless shunt cal – bits to microstrain
- Low tempco’s:
  offset: -.007%/C , span: .015%/C
- Mux’d, pulsed & regulated bridge excitation

Patents pending

Pitch Link w/ Energy Harvesting, Sensing, Data Storage, & Wireless Communications

MicroStrain, Inc. patents pending

RF antenna

Circuit board module, microprocessor, and electrochemical battery

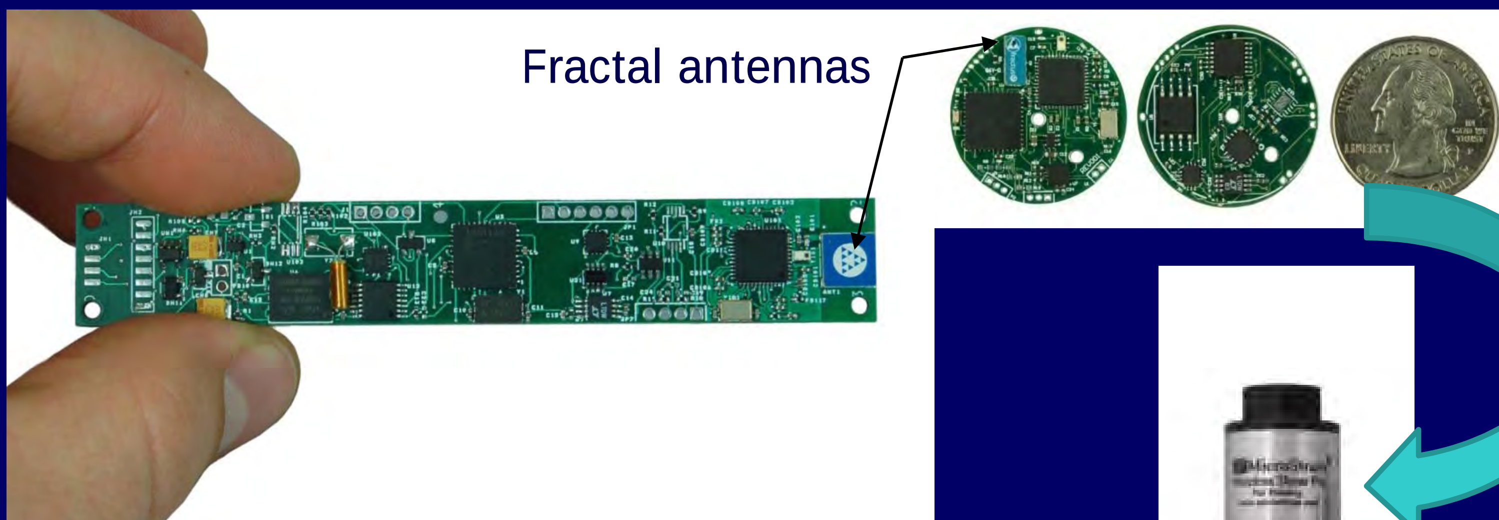
Piezoresistive strain gauge

Electrical insulation, EMI shielding, & protective covering (shown transparent for illustration purposes)

Piezoelectric energy harvesting elements

Sikorsky H-60 Blackhawk

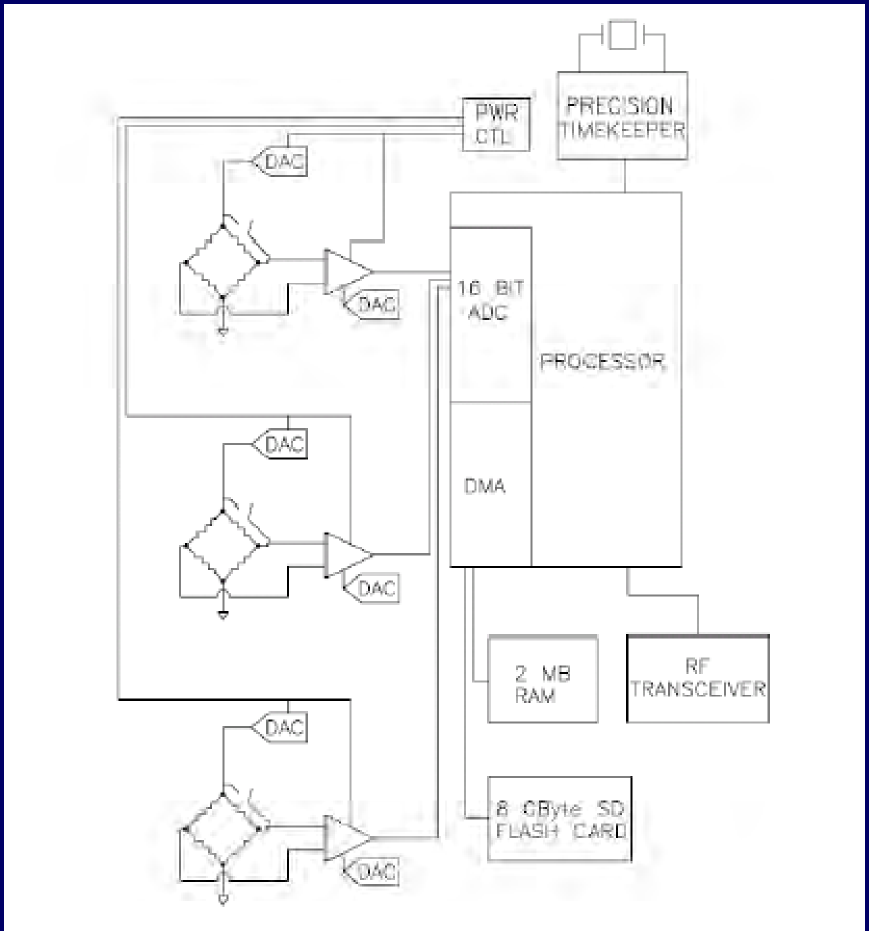
Wireless Strain
& Load Sensing Nodes



Shear-Link ™

High Speed Wireless Node

- Digitally programmable offsets, gains, & anti-aliasing filters
- Offset & gain errors within +/- 1 bit after calibration
- A/D resolution: 16 bits
- Maximum A/D sampling rate: 100 KHz sweep of 3 chs
- 8 Gigabyte secure digital (micro SD) flash memory card



Patents Pending

Measuring Strain:

Wireless vs. Hard Wired

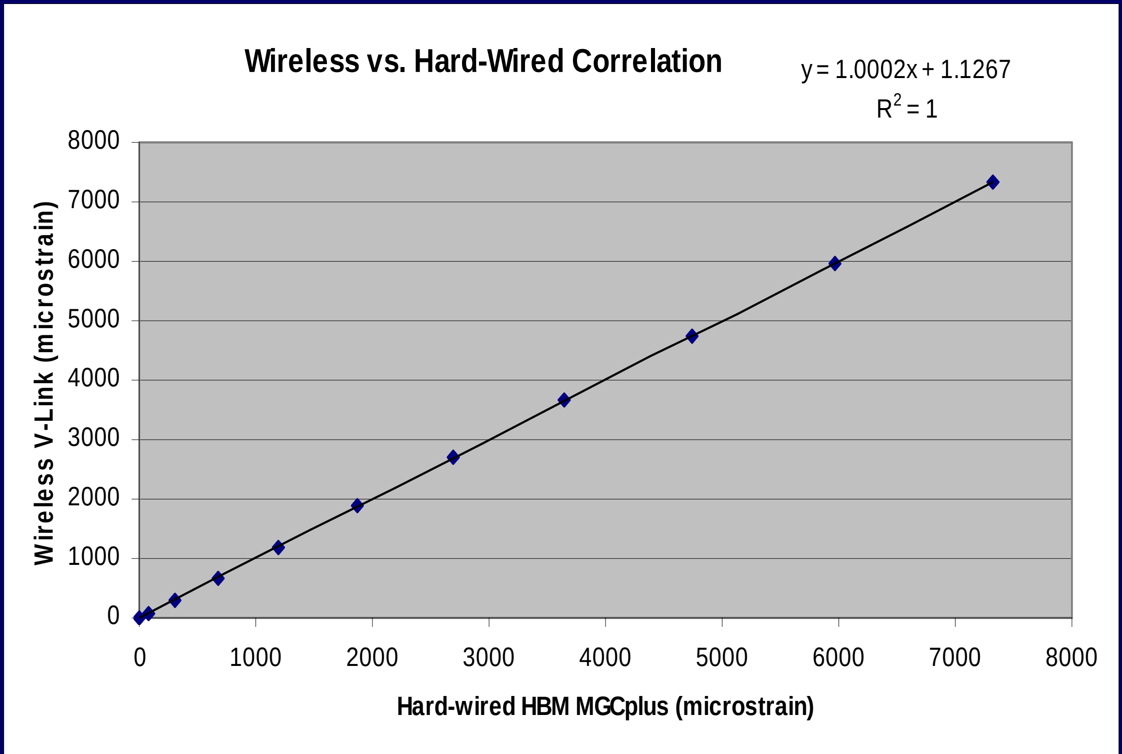
Lockheed Martin Aerospace (LMA) Fatigue Testing Environment

A05-14210 - PDC7216-3

Lockheed Martin Aerospace Accuracy Tests: Hard Wired vs. Wireless Strain

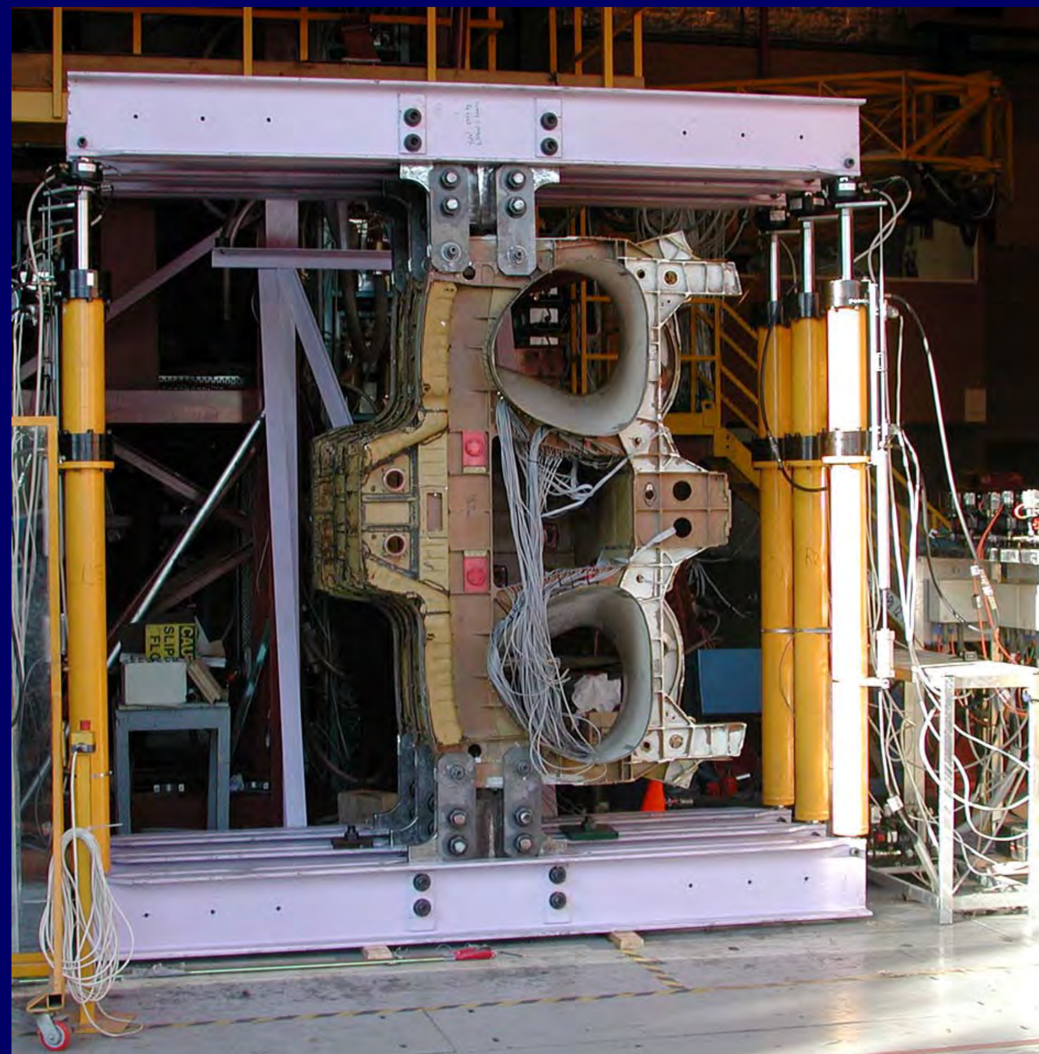
(Baldwin Precision Calibrator used for strain input)

- HBM MGCplus ® vs. MicroStrain V-Link ®
- Each system provided bridge excitation
- R^2=1
- Max wireless error: 2.5 ustrain

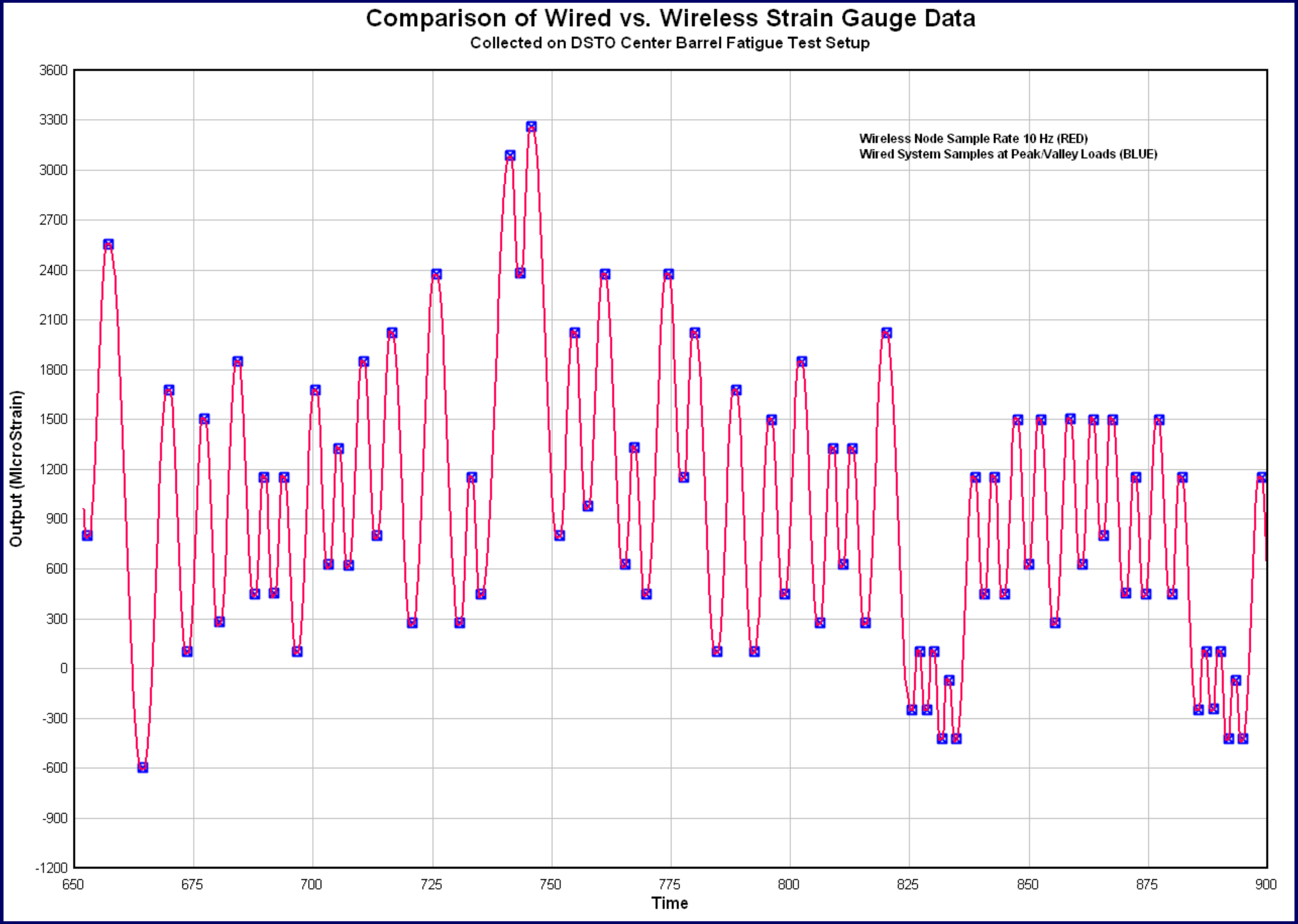


Wired vs. Wireless Gauge Comparison on DSTO F-18 Center Barrel Test Bed

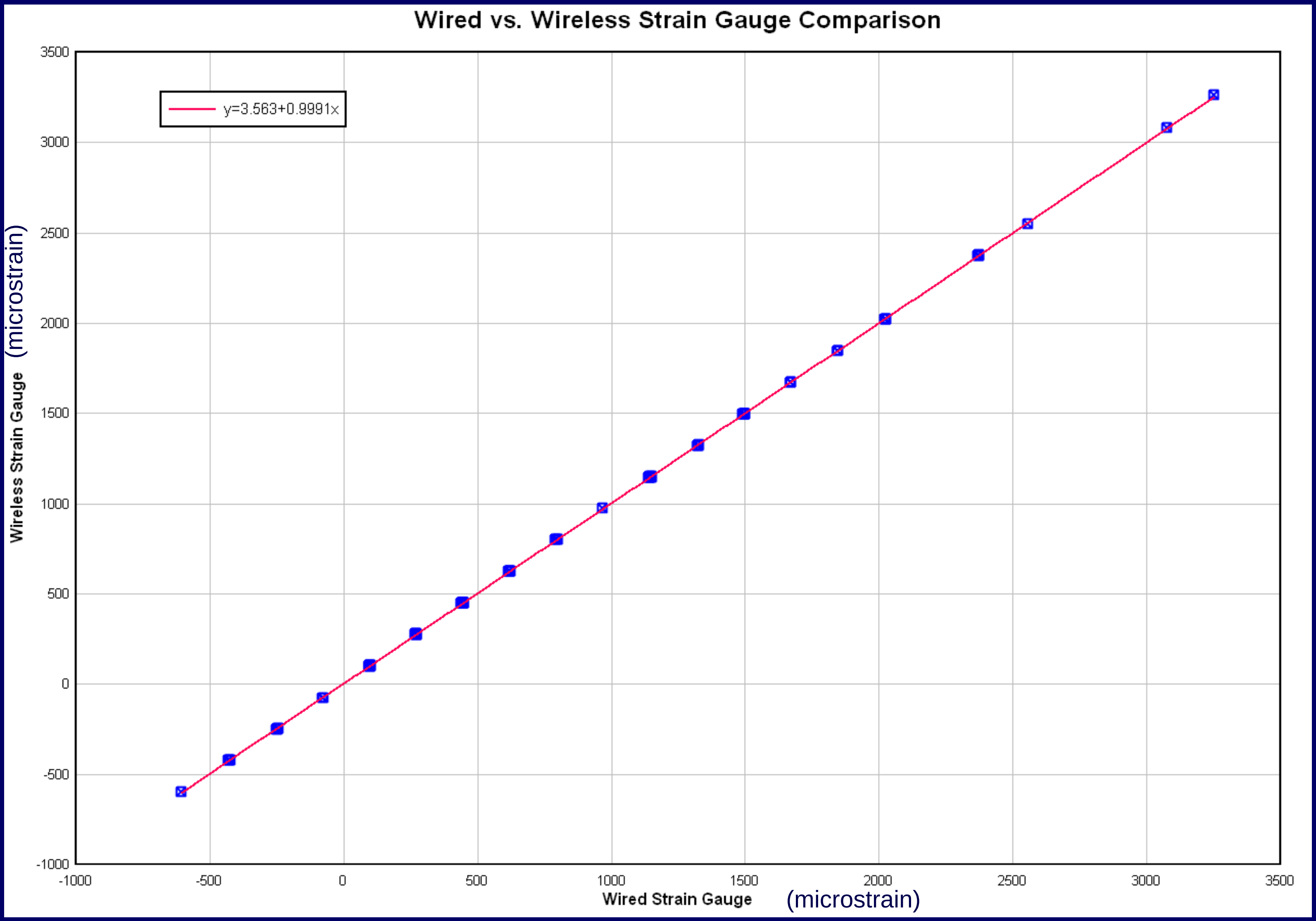
- Two wireless SG-Links sampled at 10 Hz
- DSTO wired system collected data at peaks
- Time synchronized at beginning and end of test



DSTO F-18 Center Barrel Test Bed



DSTO F-18 Center Barrel Test Bed



Harvesting Energy

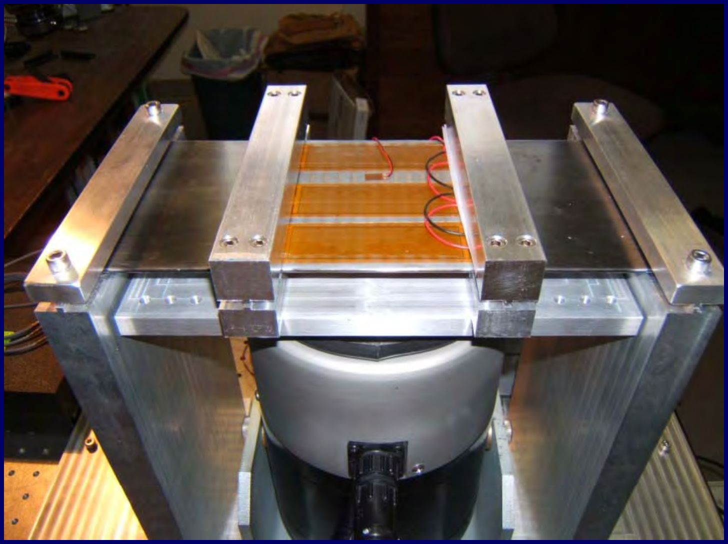
Harvesting Strain Energy

- Macro Fiber Composite, P2 type (Smart Material Corp., Sarasota, FL)

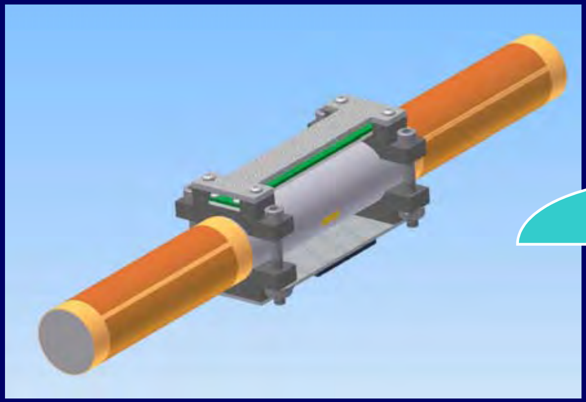
- Ongoing PZT fatigue testing: OK after 10 billion cycles

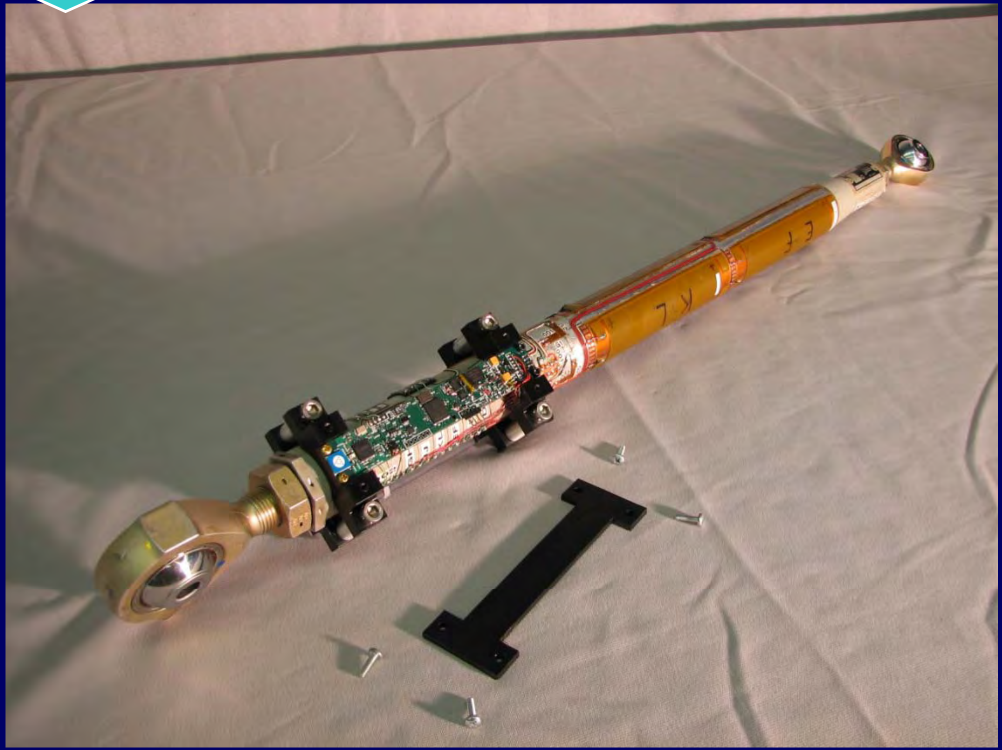
  (>9 years at 30 Hz)

- 4 point bending fixture delivers uniform strain field to PZT



MicroStrain's wireless pitch link for Bell M412 (patents pending)





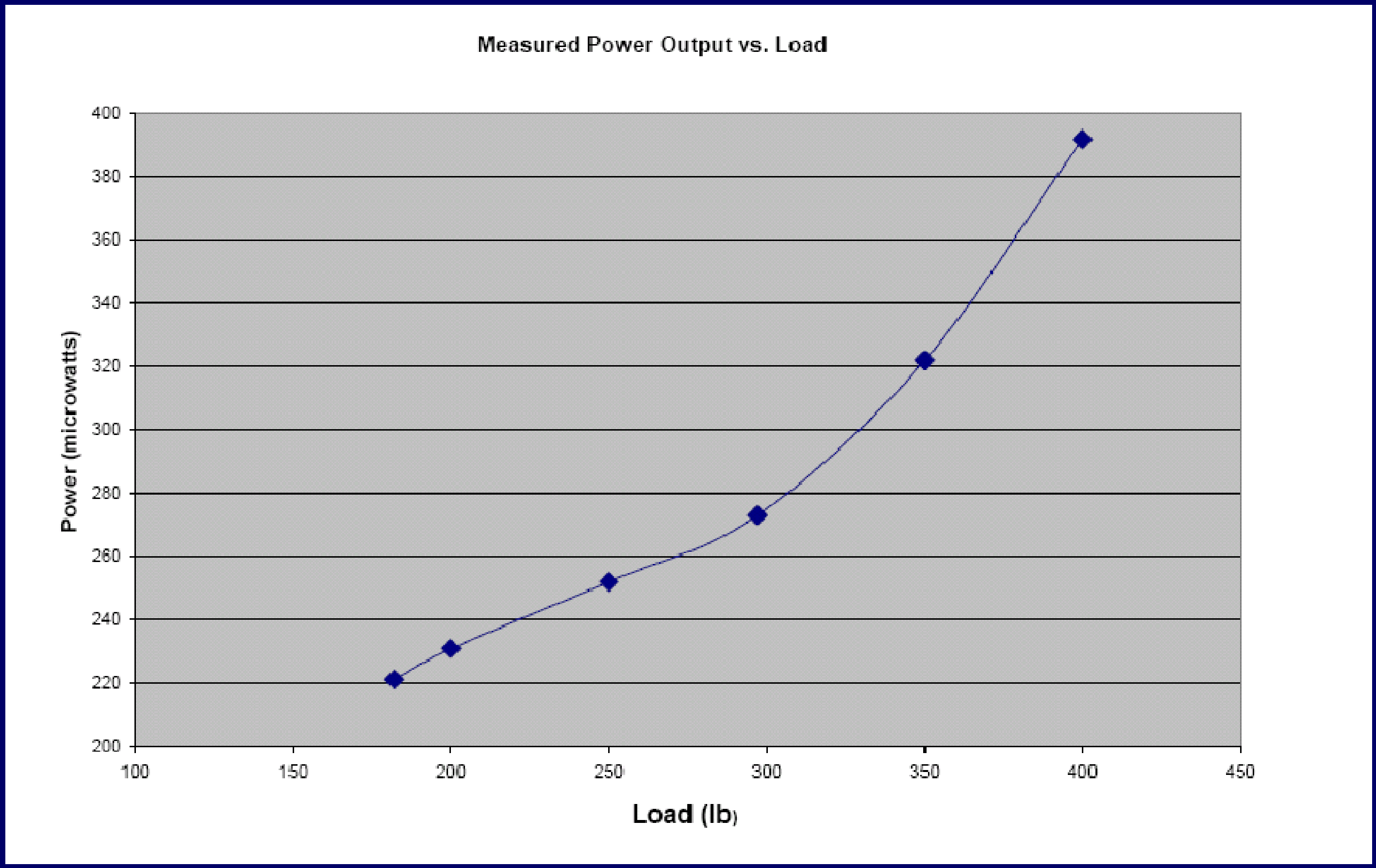
Electronics module: 8.2 g

PZT total weight: 4.3 g/patch x 12 patches = 52 g

Protective covering weight:
7 g/inch x 8 inches = 56 g
(Bell chose clamps w/ counter-balance rather than covering)

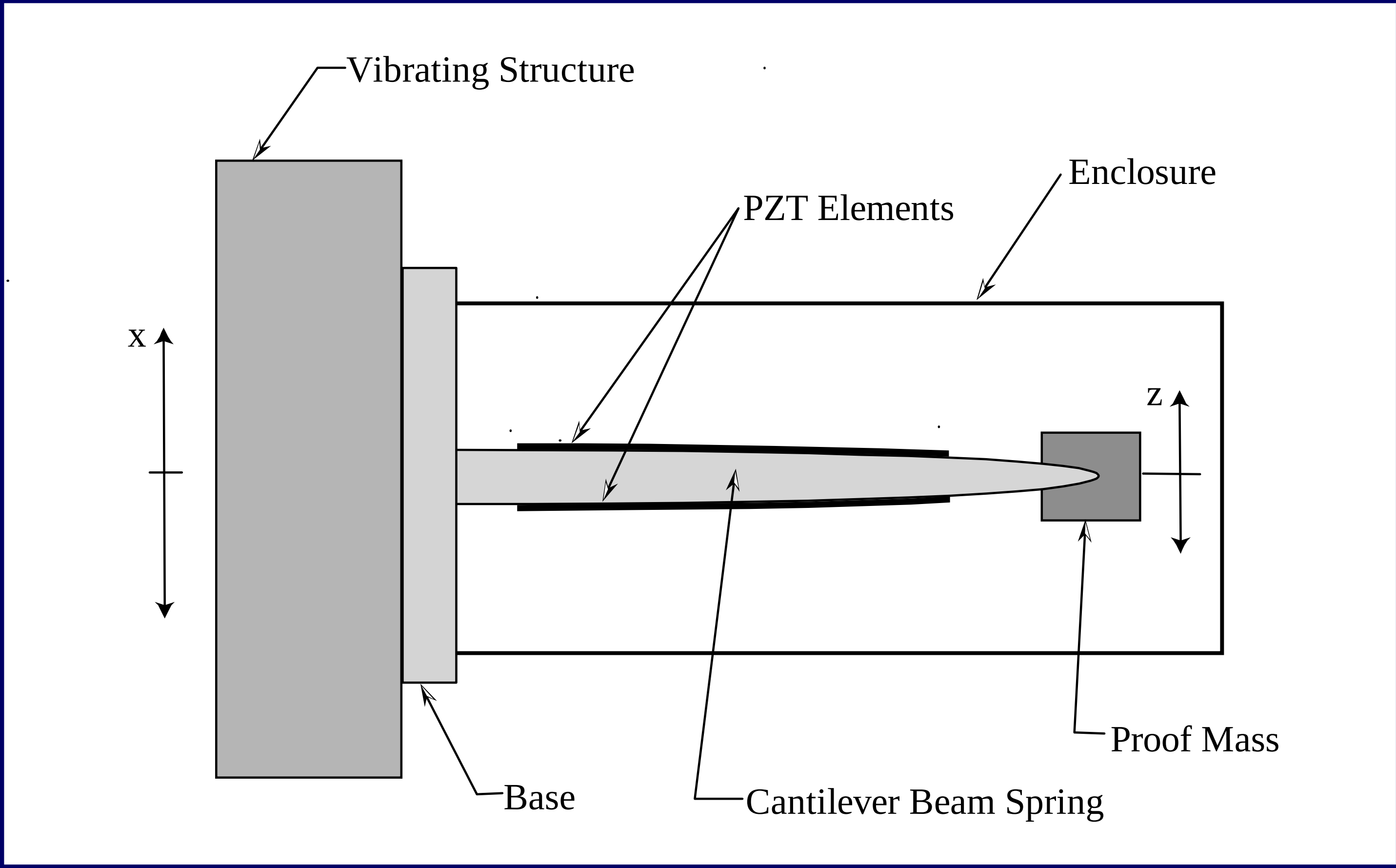
M412 Pitch Link, 5 Hz sine input

PZT power output vs. load
(measured at output storage cap)



Tuned vibration harvester

produces from 3-70 milliwatts, depending on operating conditions



Consuming Energy:

work to balance the "energy checkbook"

Powering down between samples greatly reduces power consumption

Embedded routines allow microelectronics to adapt to the amount of available energy

Patents pending

Pitch Link operating modes & consumption levels:

- Mode 1: Real Time Transmission: Data logged at specified rate, system transmits 100 samples Consumption @ 32 samples/sec: ~250 uwatts.

- Mode 2: Real Time Transmission w/ Energy Awareness: Data logged at specified rate, system checks stored energy, transmits 100 samples if possible. Consumption @ 32 samples/sec: ~250 uW, drops as conditions dictate.

Patents pending

Pitch Link Operating Modes (con't):

- Mode 3: Real Time Data Logging: Data logged for wireless download at the end of test. Consumption @ 32 samples/sec: ~100 uwatts

- Mode 4: Data Transmission When Stored Energy Sufficient: When output capacitor voltage crosses threshold, nano-amp comparator turns circuit on & a predetermined amount of data are transmitted. System consumes no power until sufficient energy is available. Consumption varies with available energy, timekeeper draws 9 microwatts.

Patents pending

Flight Testing

Bell M412

- MicroStrain piggy-backed on Bell's planned flight tests
- Wired (via slip rings) data could be collected simultaneously with wireless data

Detailed Objectives

- Demonstrate reliable operation of energy harvesting, wireless load sensor on Bell M412 pitch link
- Enable timed load sampling w/ precision micro-power timekeeper
- Conduct flight tests on Bell M412 for proof of concept

Bell M412 Installation

- Wired (slip rings) data collected simultaneously w/ wireless data

Flight Test Results

Flight Test Results

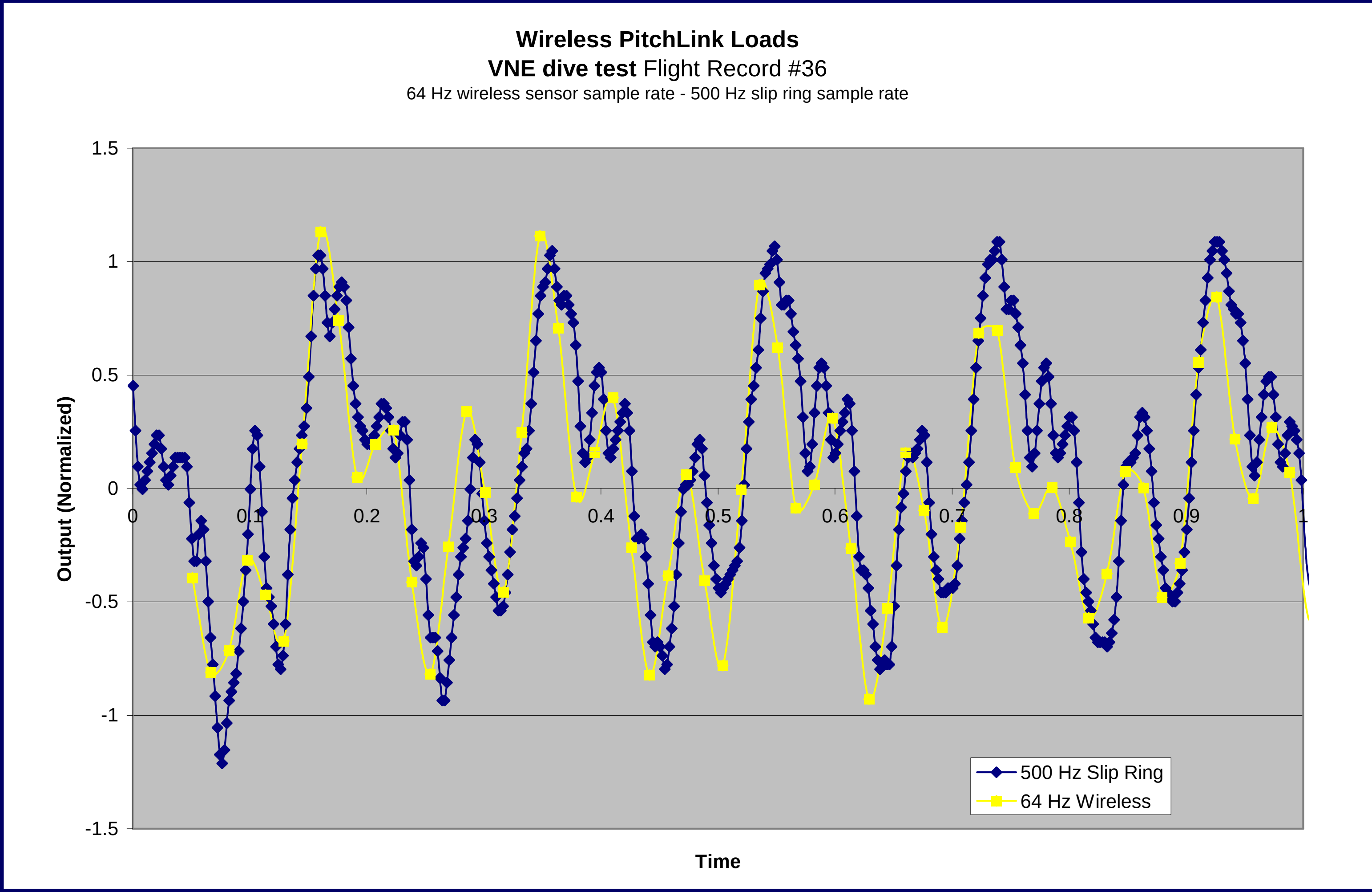
- Energy harvesting wireless pitch link installed on Bell M412 Feb 2007 (1st time ever)
- Passed
  - in-flight EMI evaluations
  - rotor track & balance verification

Patents pending

Bell M412 Flight Test Results (con't):

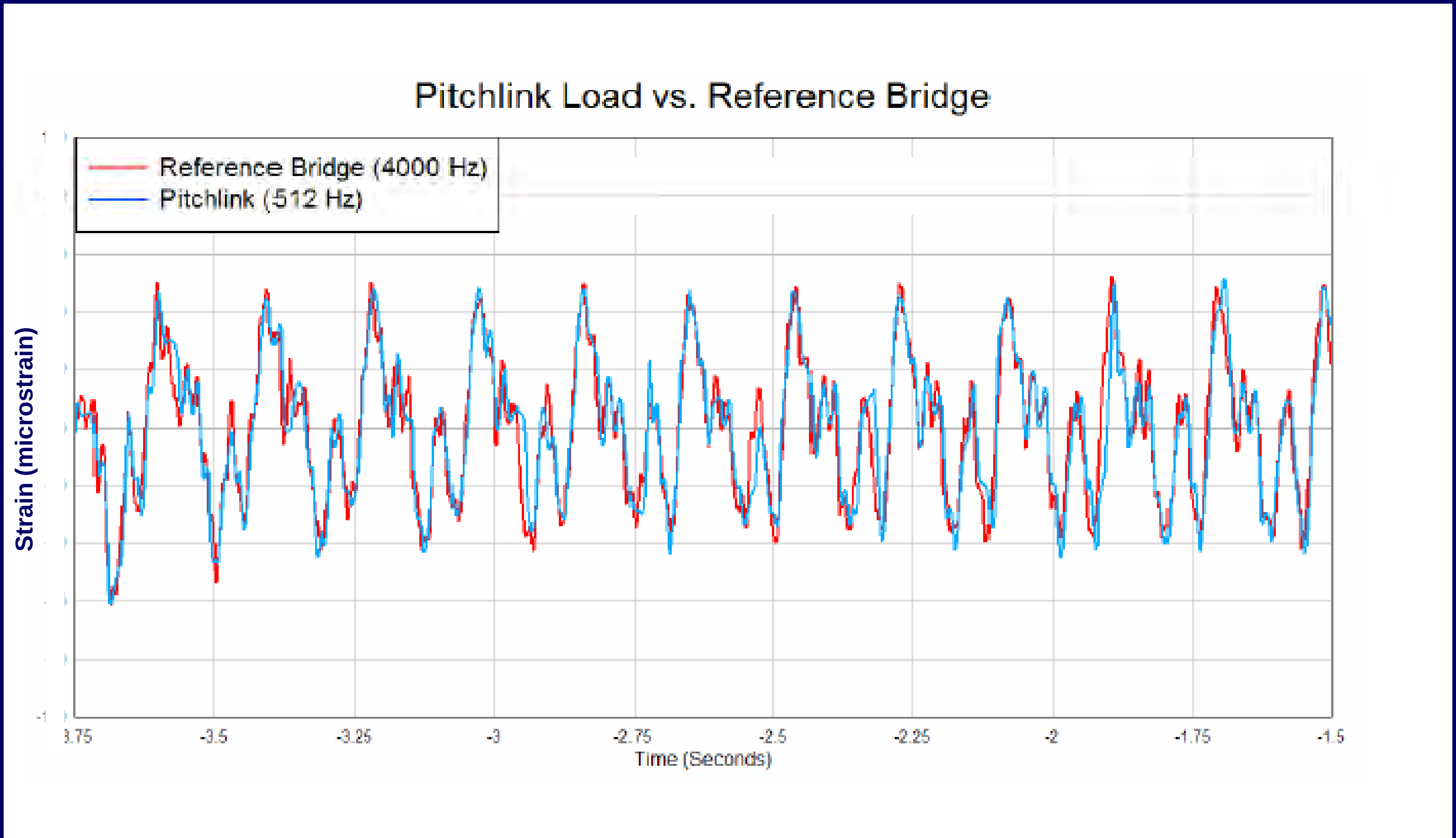
- Data were collected wirelessly on board the aircraft with no indication of data loss
- Data were also collected external to the aircraft during ground operations at various locations around the aircraft (50 ft)

Bell M412 Wired vs. Wireless Pitch Link Flight Test Data



MicroStrain, Inc. High Sample Rate Bench Test:
hard-wired reference bridge vs. wireless pitch link

(two separate & distinct strain gauge bridges bonded to a single steel plate in 4-pt bending)



Infrastructure to support scaleable wireless & wired sensor networks

Detailed Objectives

- Design, develop and test a **Data Aggregator** to support data recording & remote data access from *wireless & hard-wired* networked SHM sensors
- Develop the timing & communications protocols required to support flight tests using a scalable network architecture

Previous Work

- Le Cam, V., “Synchronization of Wireless Sensors: Review of Methodologies, Experience Feedback of the Very Precise GPS Solution”, Third European Workshop on Structural Health Monitoring, July 5-7, Granada, Spain, July 5-7, 2006

Placed GPS receivers at each wireless node to achieve absolute precision of 1 microsecond

Methods:

Wireless Sensor Data Aggregator (WSDA™)

Wireless/Wired Sensor Data Aggregator (WSDA™) collects time synchronized data

Multiple remote wireless sensors are equipped with precision (3 ppm) time keepers

Wired inertial sensor uses same time reference as Aggregator

Data Aggregator sends beacons to update time sensing node's time keepers

Patents pending

Results:

Wireless Network Timing -

How quickly are broadcast commands processed?

Objective & Methodology

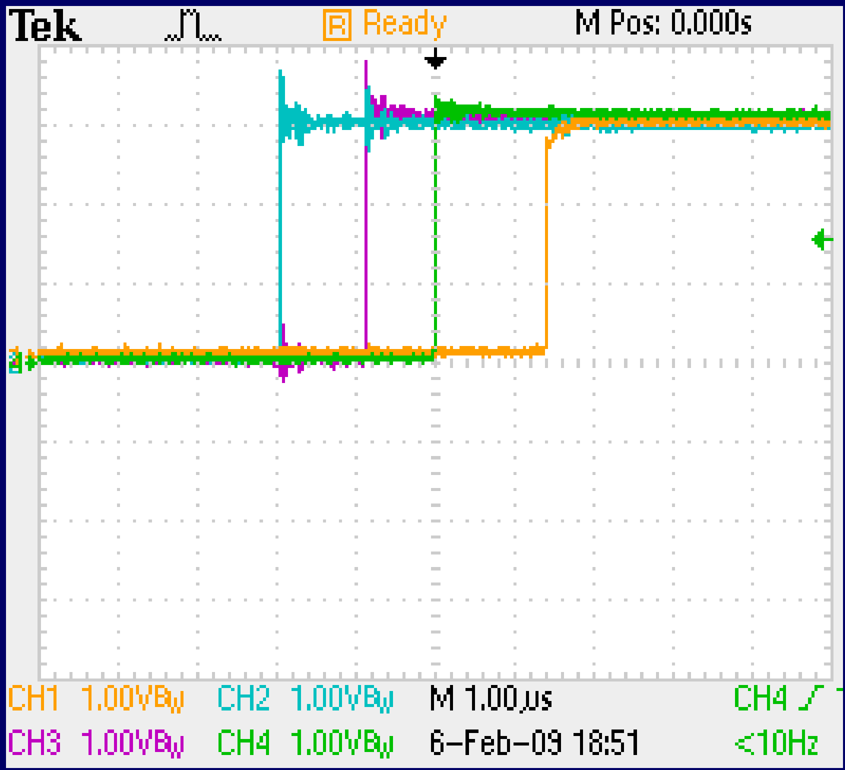
- *Objective:* determine timing uncertainty (jitter) associated with receiving & responding to a broadcast-datalog command packet.
- *Materials:* MicroStrain's USB base station, four (4) SG-Link wireless strain nodes, Tektronix 100 MHz 4-ch oscilloscope
- *Methods:* directly measure relative sync of 4 nodes triggered by a wireless broadcast-datalog command packet. Scope probes connected to digital I/O line corresponding to start of sampling for each node's A/D converter.

Broadcast Synchronization Results

- Waveform at right shows 4 captured waveforms representing the start of sampling for each of the 4 nodes.

- Note that each node starts sampling at slightly different times. In this specific case, the **last node** starts sampling approximately 3 microseconds (μsec) after the **first node**.

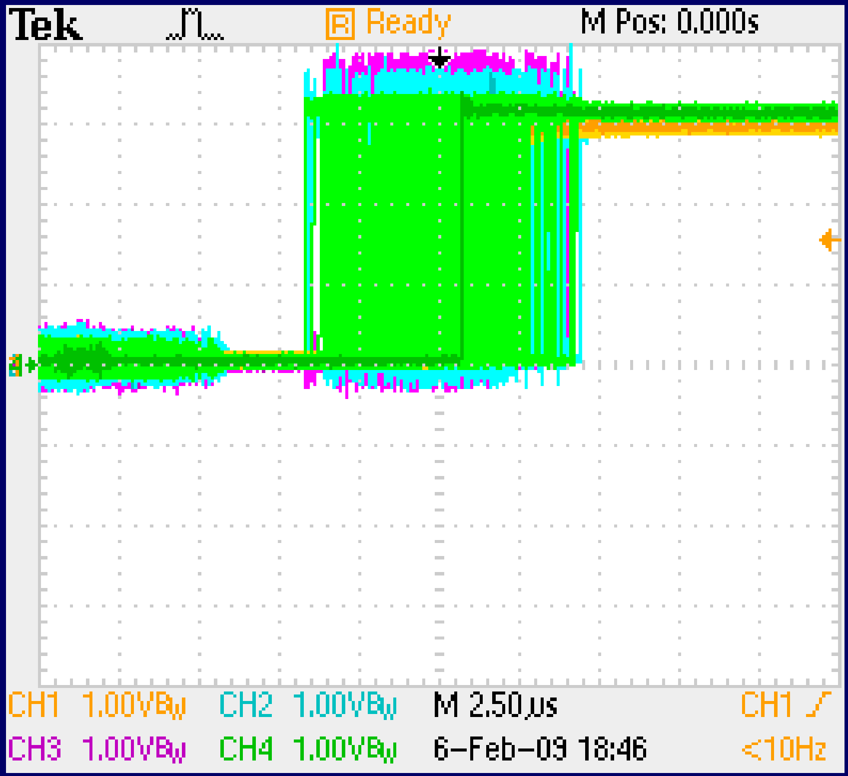
Scope traces



Broadcast Synchronization Results

- After repeating the broadcast trigger command 250 times, the timing differences are bound within an envelope of ±4 μsec. This represents the initial synchronization accuracy for the group of nodes.

Scope traces



Sources of timing jitter

- Differences in physical propagation delay are relatively small. Example: RF signal travels at approximately 1ft/ns, therefore approximately 300 ns delay for a node at 100m.
- Packet reception and decoding is handled by a hardware state machine in radio chip, with a max jitter of ~400 ns. Actual (measured) jitter was +/- 4 μs due to embedded processes.

Results:

Wireless & Wired Network Timing:

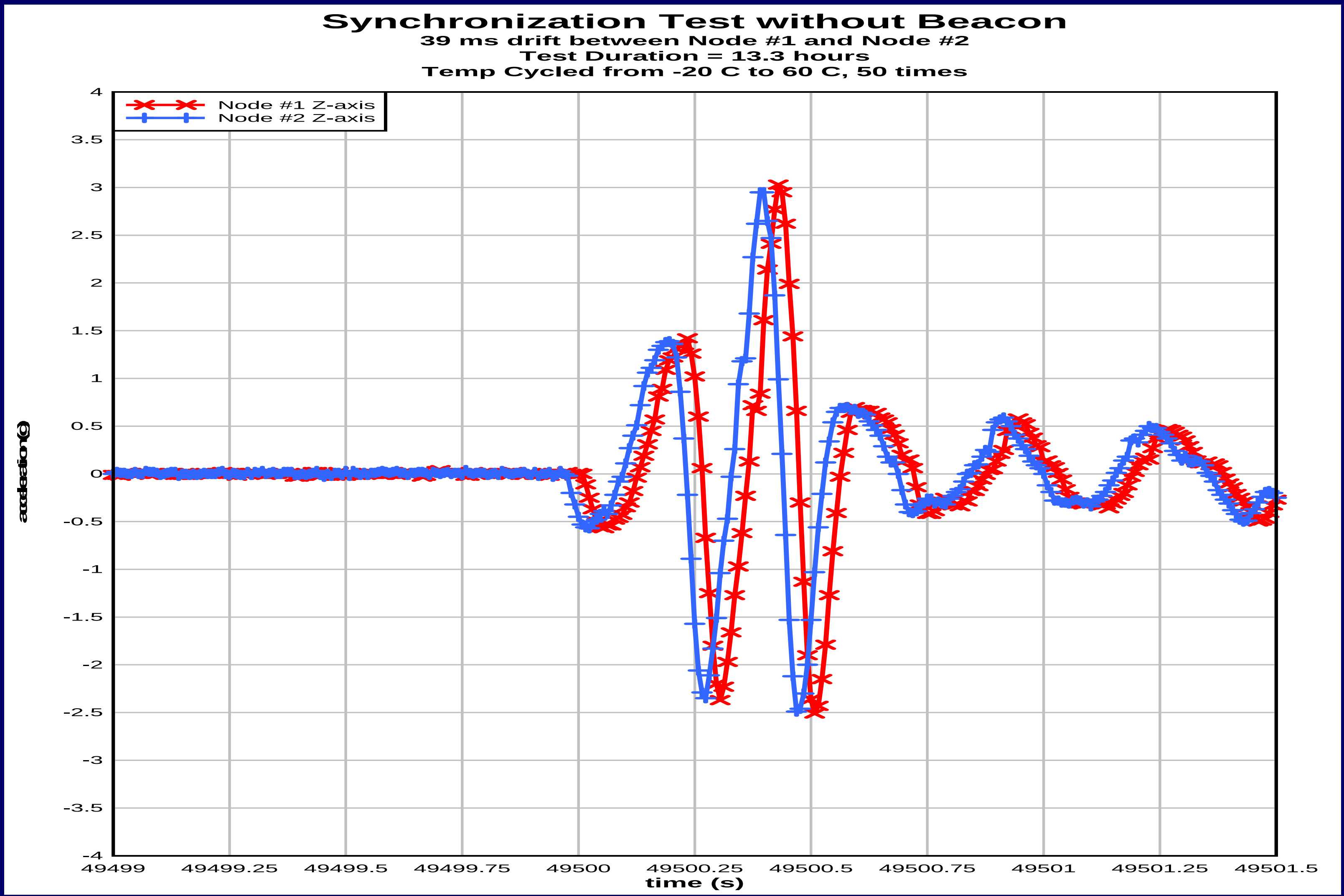
How well synced w/ beaconing?

Timing Validation Test Setup

- Synchronized digital data collection from wireless (2 vibration, 2 strain) & one hard-wired (inertial) node
- Timing beacon interval set to 60 seconds
- Vibrations sampled at 128 samples/sec
- Strain sampled at 16 samples/sec,
- Orientation sampled at 100 samples/sec

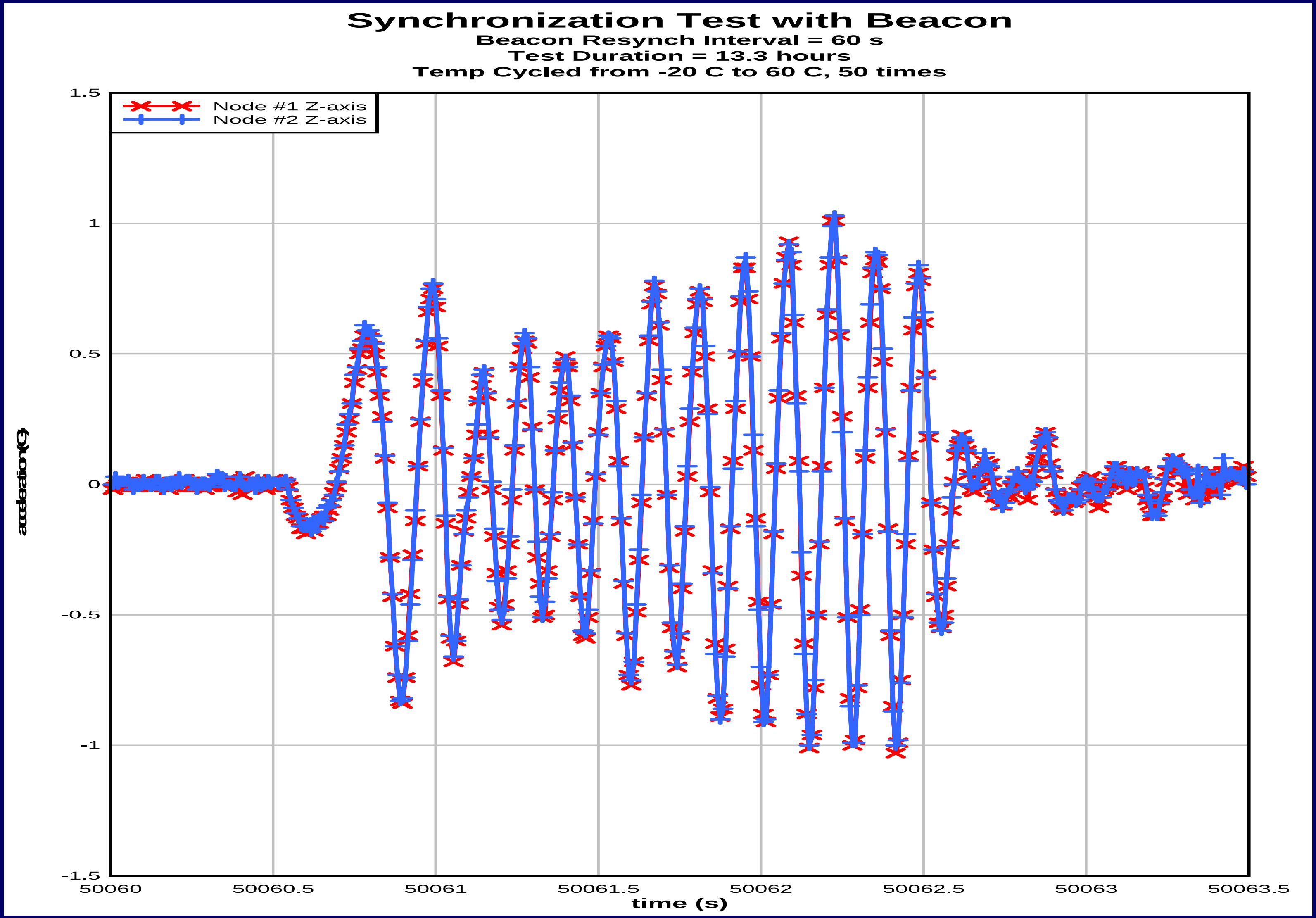
Wireless Node Synchronization

No beacon update: 39 millisecond drift



Wireless Node Synchronization

w/ 60 sec beacon, ~ +/- 50 microsecond drift



With a sample rate of 128 Hz, the timing resolution of these tests are inherently limited to 7.8 milliseconds.

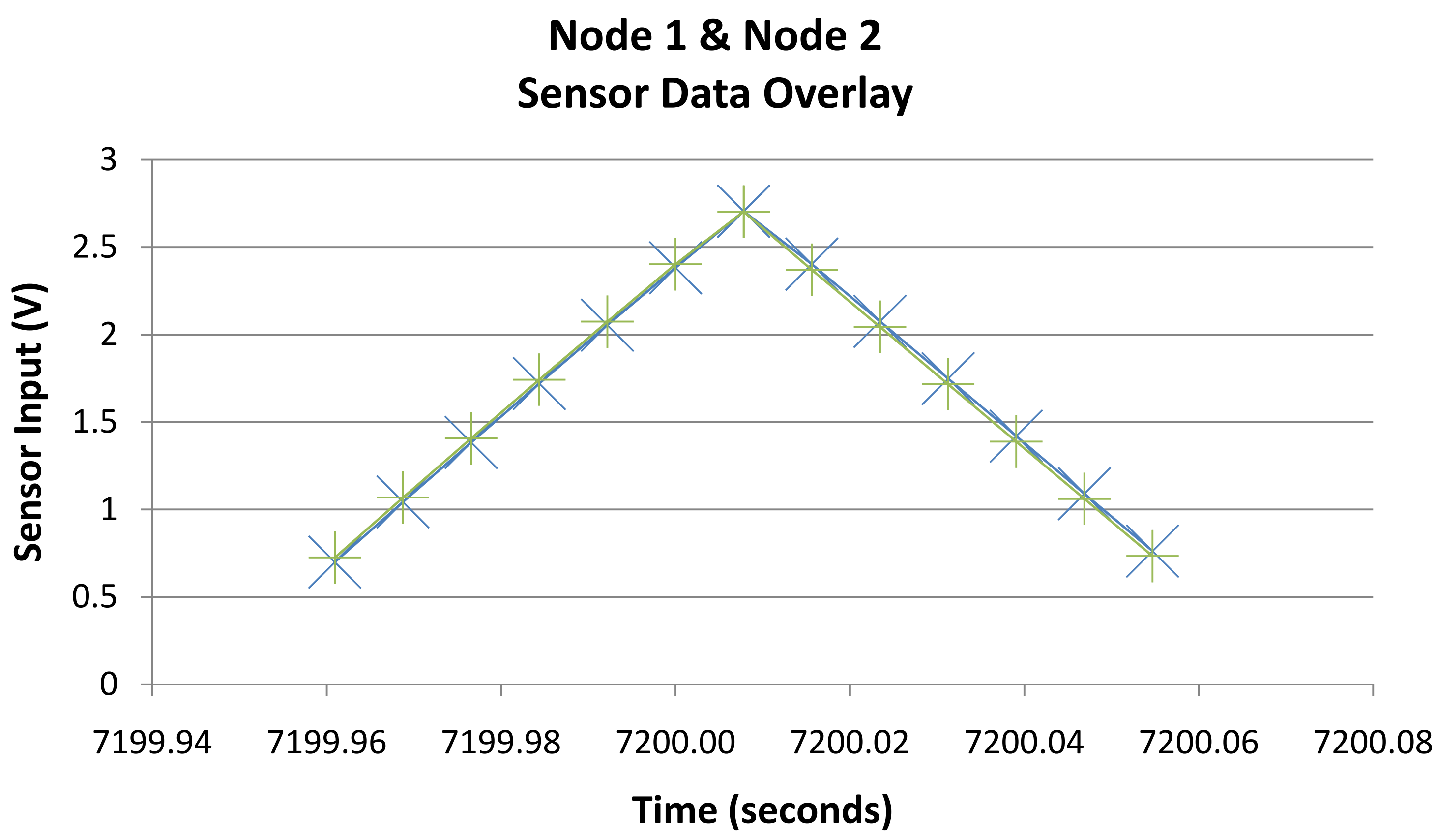
A second series of tests were performed to overcome this limitation - using saw tooth voltage input waveforms.

Saw tooth Waveform Tests

- Two (2) SG-Links sampled the same data using their single-ended 0-3V analog input(s)
- Input was from external signal generator provided common 10 Hz (& 1 Hz) saw tooth input waveform(s).
- The sample rate for both SG-Links was 128 hertz.
- 2 hour duration tests were performed at room temperature and after six thermal cycles in a chamber cycled between -40 and +85 degrees Celsius, at a ramp rate of 12.5 degrees C per minute.
- Timing synchronization beacon sent once - at start of test

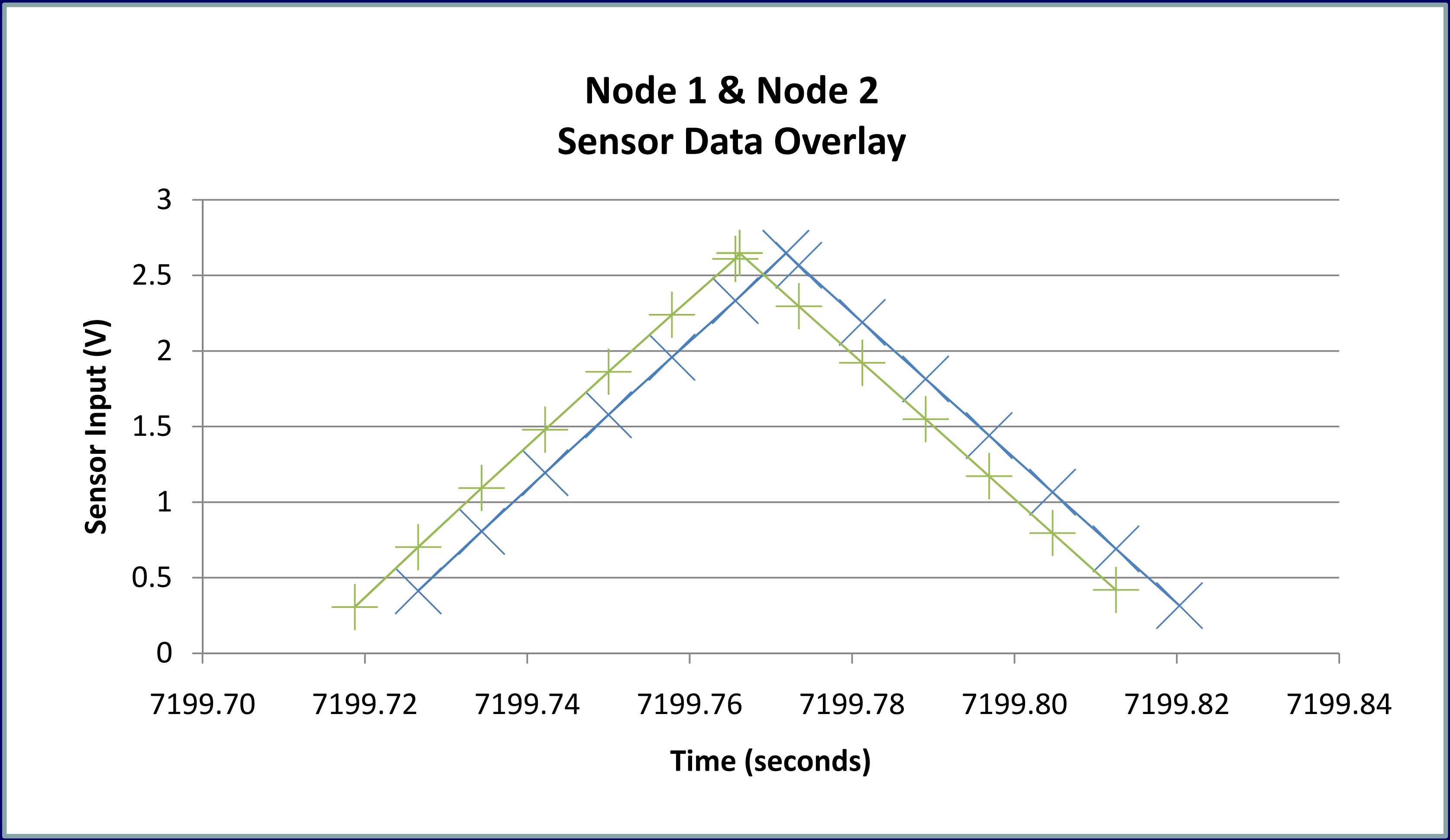
Saw tooth Test Results

2 hour test, room temperature, 10 Hz saw tooth -
clock drift: ~325 us (45 ppb) between the two sensor nodes
Timing beacon sent once – at start of test only.



Saw Tooth Tests over Temperature

2 hr test , -40 to +85 deg C, 10 Hz Sawtooth: clock drift 5.71 msec (793 ppb)
w/ 1 Hz saw tooth: clock drift 5.04 msec (700 ppb)
Timing beacon sent once – at start of test only.



Timing Results Summary

- Synch beacon sent once - at start of test only - provided ~5 ms timing accuracy over 2 hours, subjected to -40 to +85 C.

- Synch w/ periodic (60 sec) beacon provided +/- 50 us timing accuracy over 13 hours, subjected to -40 to +85 C.

- Conservative approach: send resync beacon every 20 minutes to achieve sub-millisecond timing accuracy when temperatures may be extreme.

Conclusions

- An energy harvesting wireless pitch link load sensor Bell 412 has been developed, bench tested, & flight tested
- Under extremely low usage levels, the amount of energy generated exceeds the amount of energy consumed
- This enables an on-board wireless load sensor to operate perpetually without battery maintenance.

Patents pending

Conclusions (con't)

- An accurate time synchronization capability has been developed for wireless & hard-wired sensor networks that does not require GPS to maintain synchronization.
- The system supports a wide range of e-harvesting nodes, including strain, pressure, torque, & temperature; as well as wired inertial & GPS sensors.
- Wireless/Wired Sensor Data Aggregator (WSDA) node is stand-alone, includes mobile phone capability & provides scalable web-enabled database

References:

- M.J. Hamel et al., Energy Harvesting for Wireless Sensor Operation and Data Transmission, *US Patent Appl. Publ. US 2004/0078662A1, filed March 2003*
- D.L. Churchill et al., Strain Energy Harvesting for Wireless Sensor Networks, *Smart Structures and Materials, SPIE, vol. 5005, pp. 319–327, 2003*
- S.W. Arms et al., Shaft Mounted Energy Harvesting System for Wireless Sensor Operation and Data Transmission, *US Patent Appl. Publ. US 2005/0017602A1, filed Jan 2004*
- S.W. Arms et al., Wireless Strain Measurement Systems for Aircraft Test**,** *Aerospace Test Expo, Anaheim, CA, Nov 2006*
- S.W. Arms et al., Energy Harvesting Wireless Sensors for Helicopter Damage Tracking**,** *American Helicopter Society Annual Forum, Phoenix, AZ, May 2006*
- S.W. Arms, C.P. Townsend, D.L. Churchill, M. Augustin, D.Yeary, P. Darden, N. Phan, Tracking Pitch Link Dynamic Loads with Energy Harvesting Wireless Sensors, *AHS 63nd Annual Forum, Virginia Beach, VA, May 2007*

Need More Info?

- www.microstrain.com

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Thank You!