Wire Less Sensors

Getting more out of what you have,
or doing the same job with less.

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Laboratory for Electromagnetic and Electronic Systems
MIT

Buildings Today

- Centralized or no control
- Haphazard monitoring
- Invasive wiring and wireless connections

No Watt Left Behind

- Distribute control
- Deploy central monitoring
- Signal processing for diagnostics/prognostics
- Preserve data privacy

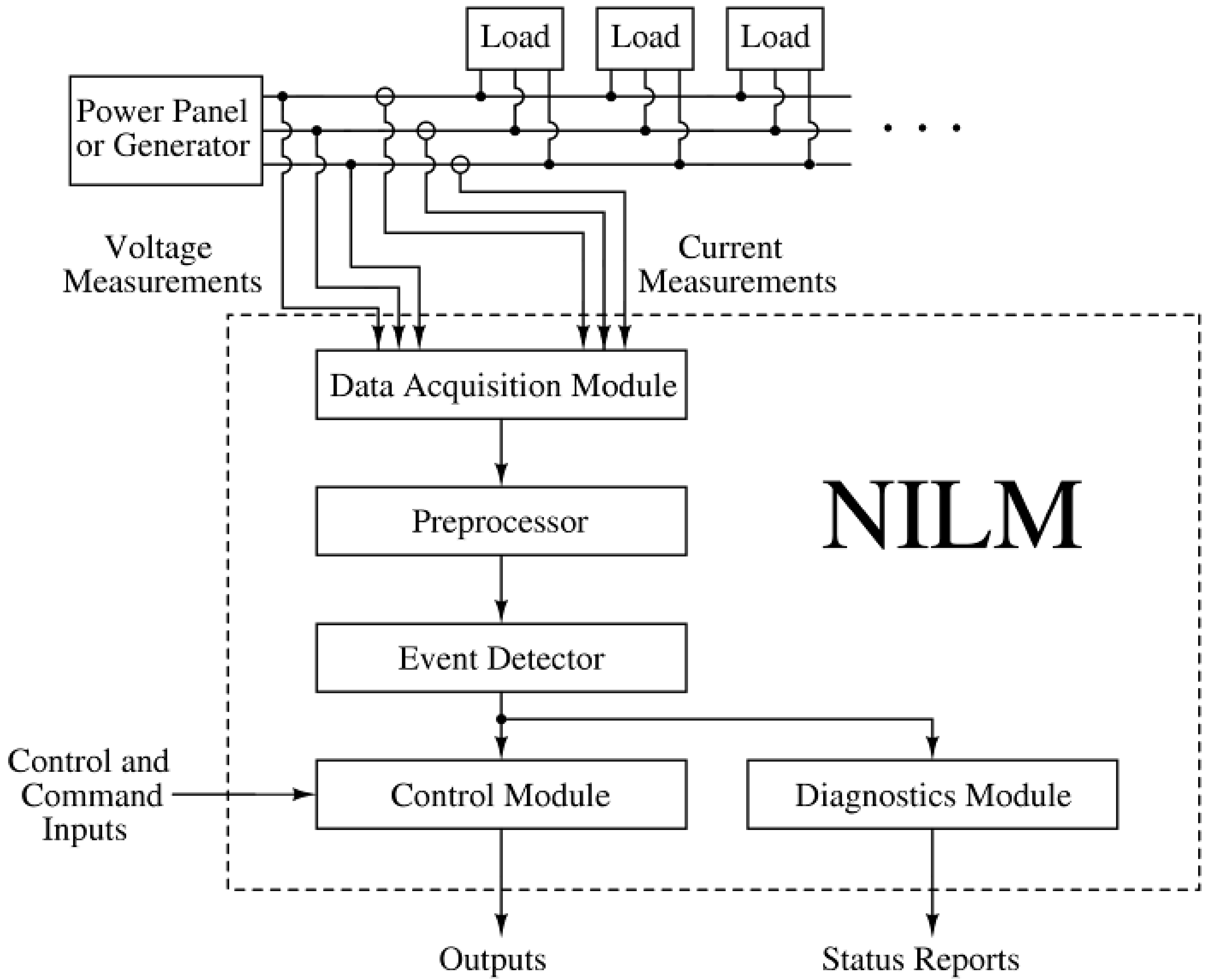
Many cut-off ears…

Many cut-off ears…

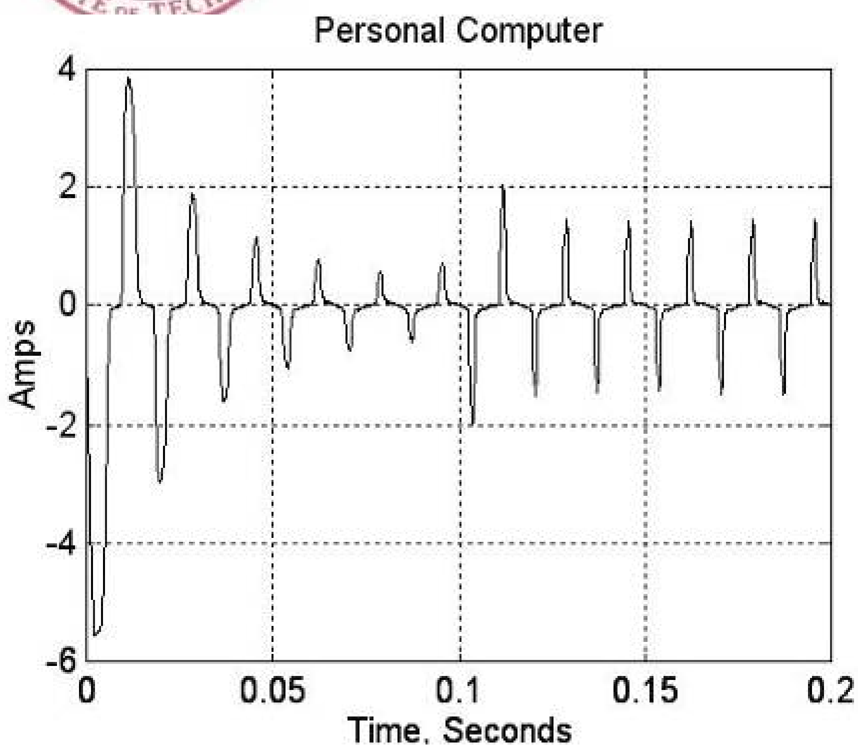
But do we have any Van Goghs?

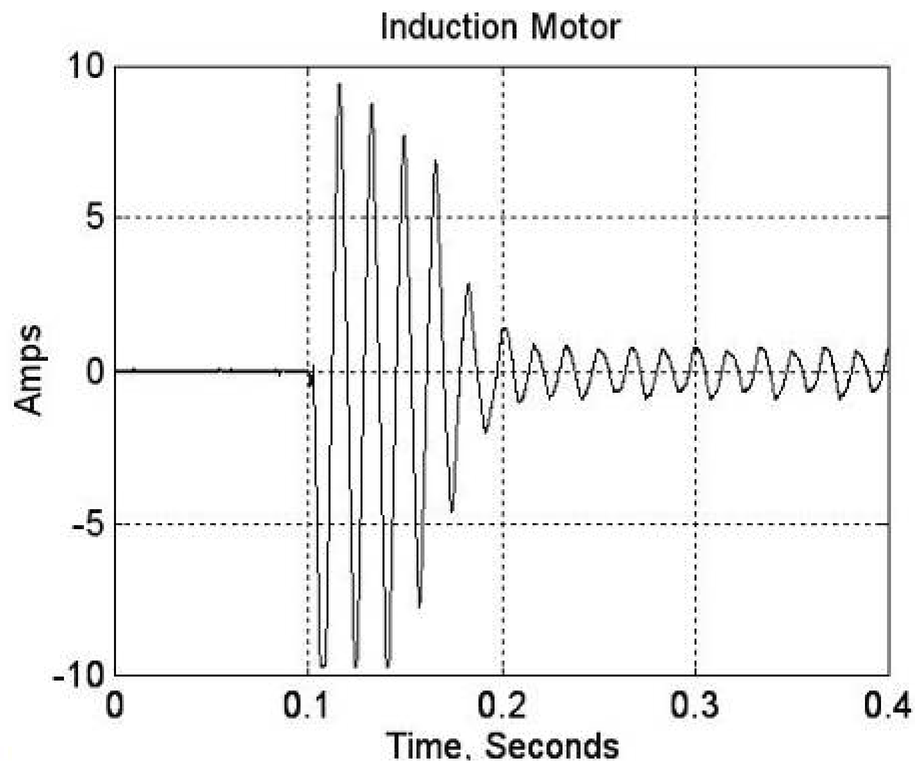
(with thanks to Jim Williams)

Non-Intrusive Sensing



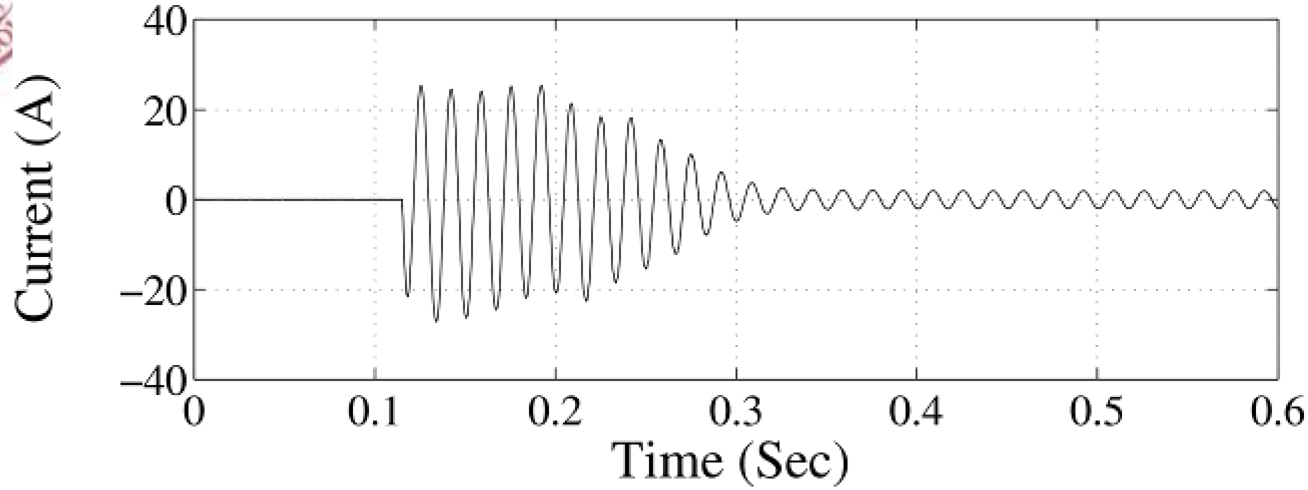
Transient-Based Identification

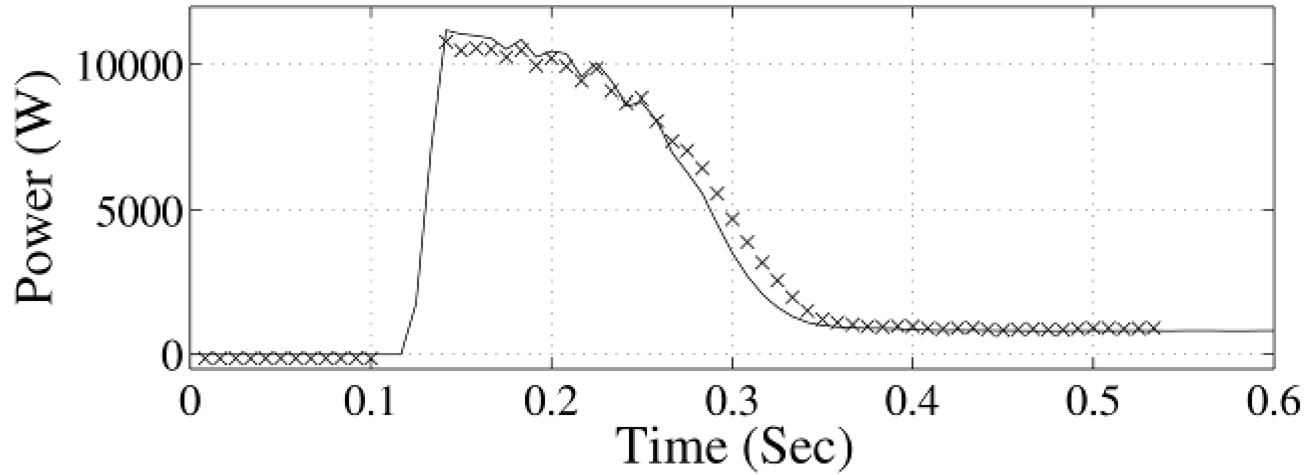




- Transient electrical behavior is strongly influenced by the physical task performed by the load

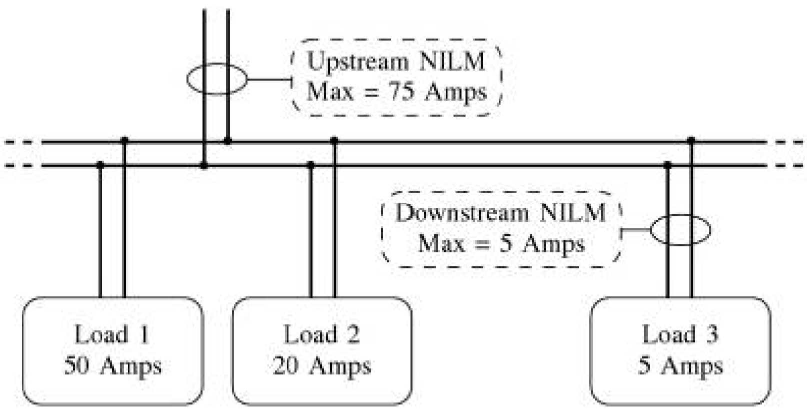
Spectral Envelopes

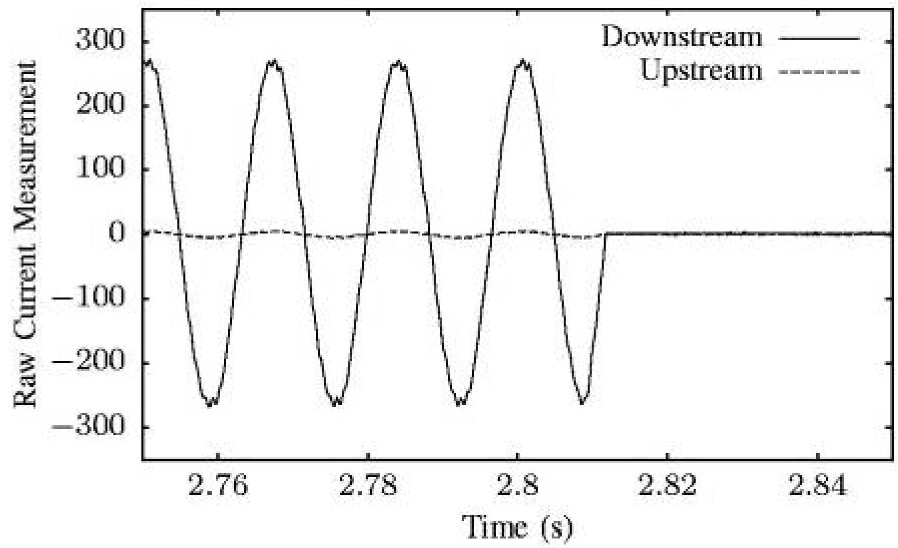




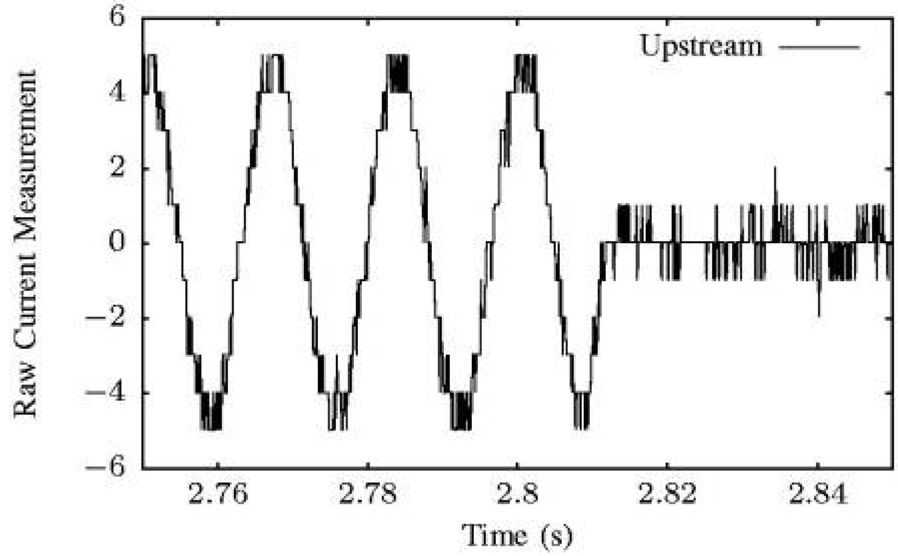
- Stator current and P_1 for a 3-phase induction motor

Upstream and Downstream



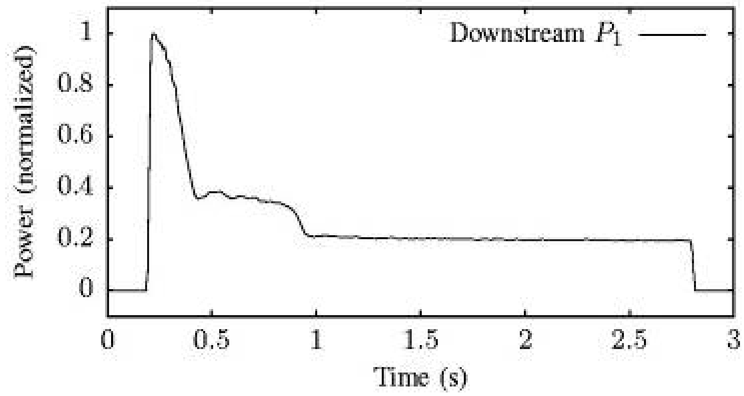


(a) Raw data from both configurations on the same scale.

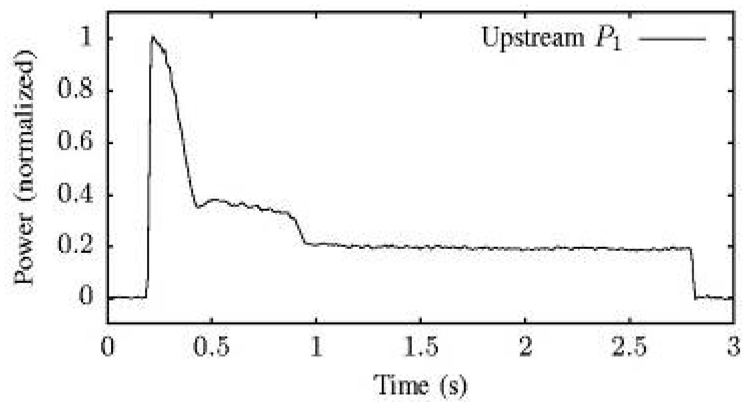


(b) Raw upstream data, enlarged to show detail.

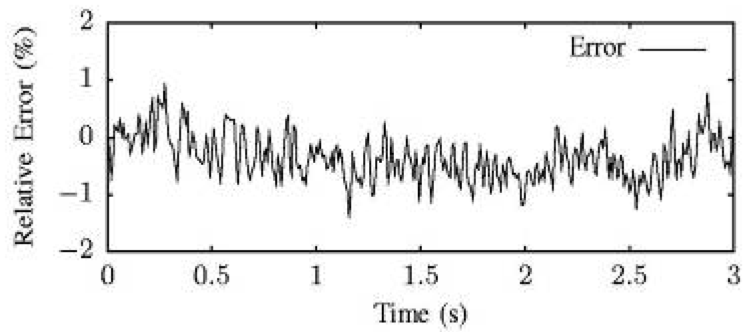
Spectral Envelopes



(a) Spectral envelope of the downstream measurement.



(b) Spectral envelope of the upstream measurement.



(c) Difference, as a percentage of the full transient amplitude

Applications

Works for any system with a power distribution network (AC or DC):





Connections with
Massachusetts School Building Authority

- Field tests to be conducted at sites selected in collaboration with MSBA.
- Additional opportunity for educational outreach.

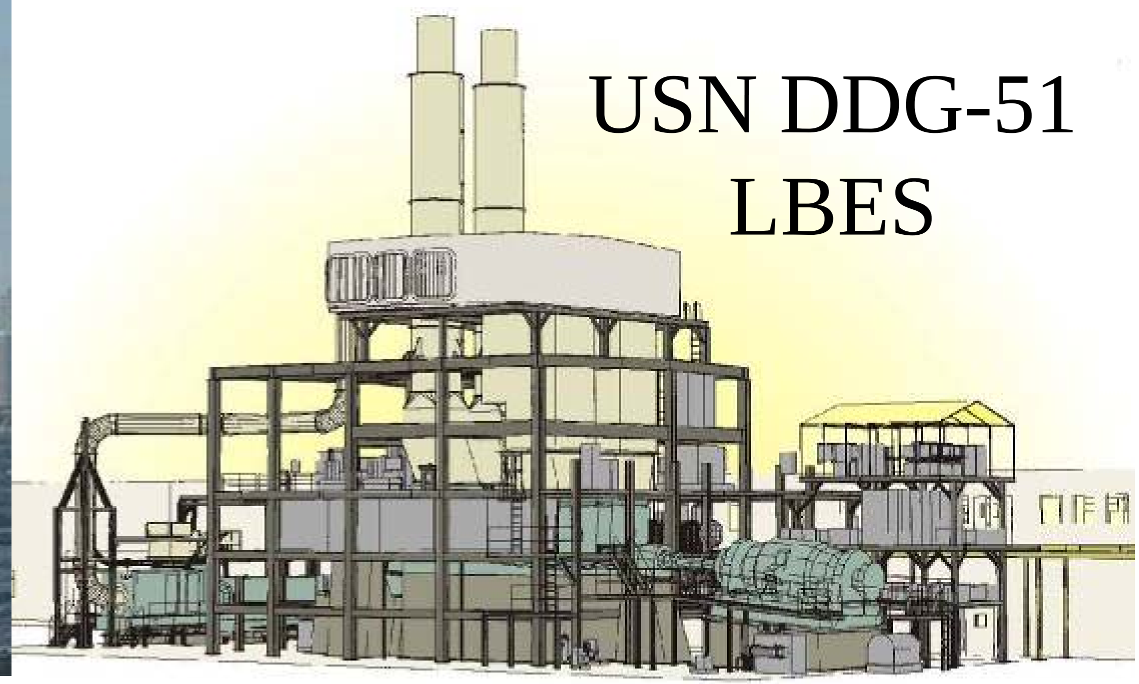




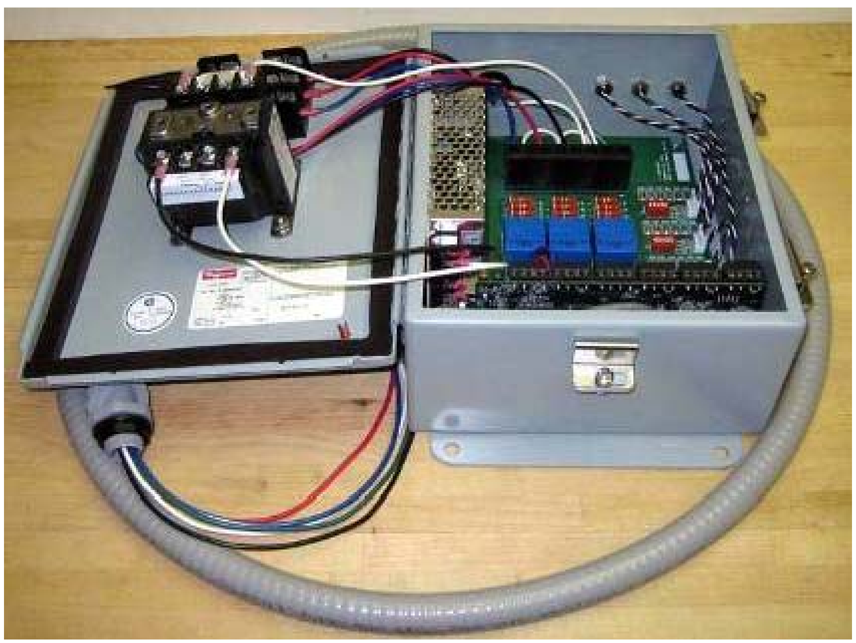
Field Experiments

USCG Cutters
Seneca and *Escanaba*

USN DDG-51
LBES



Ship-board Installation

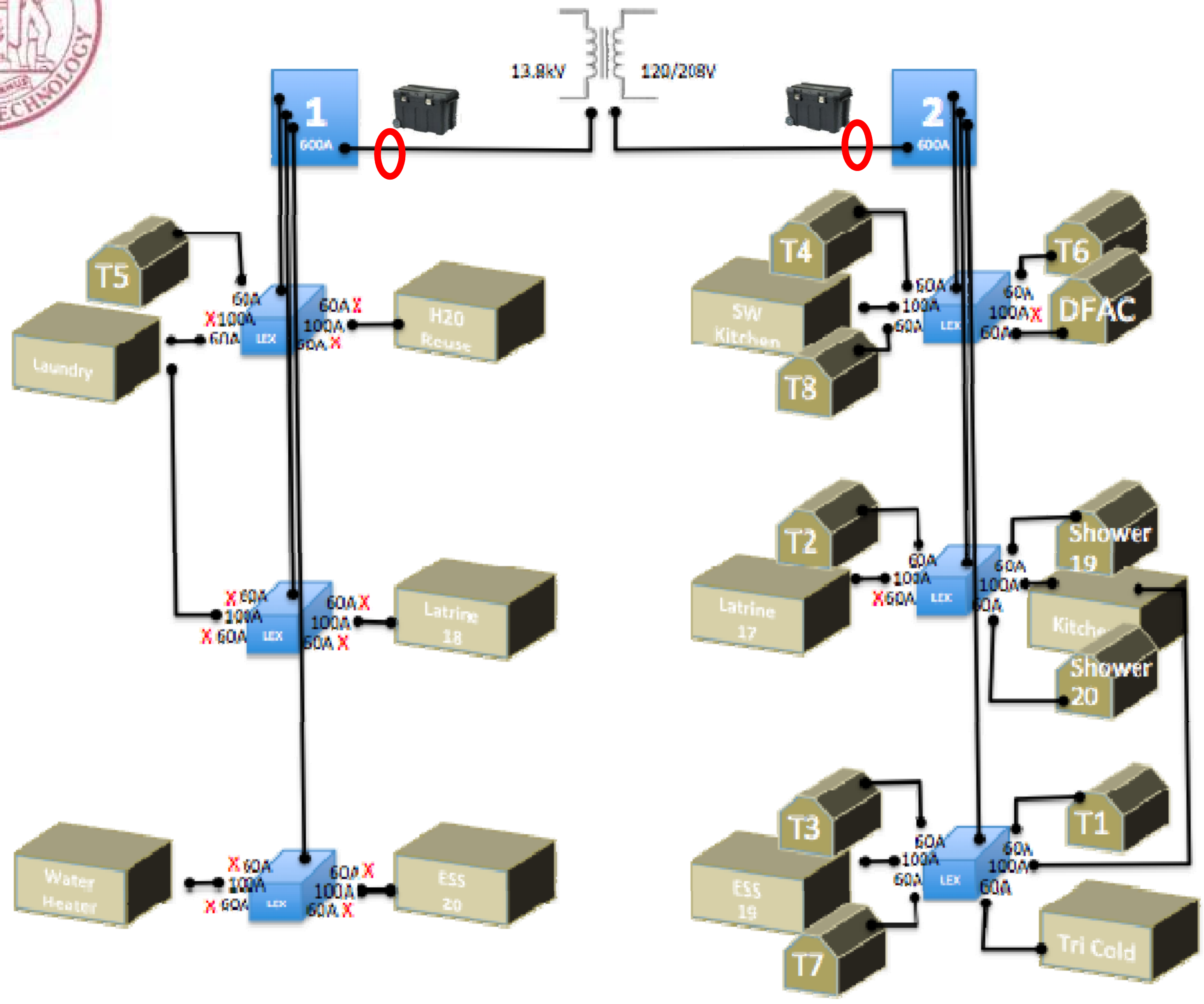


NILM on a Microgrid

One device per panel…

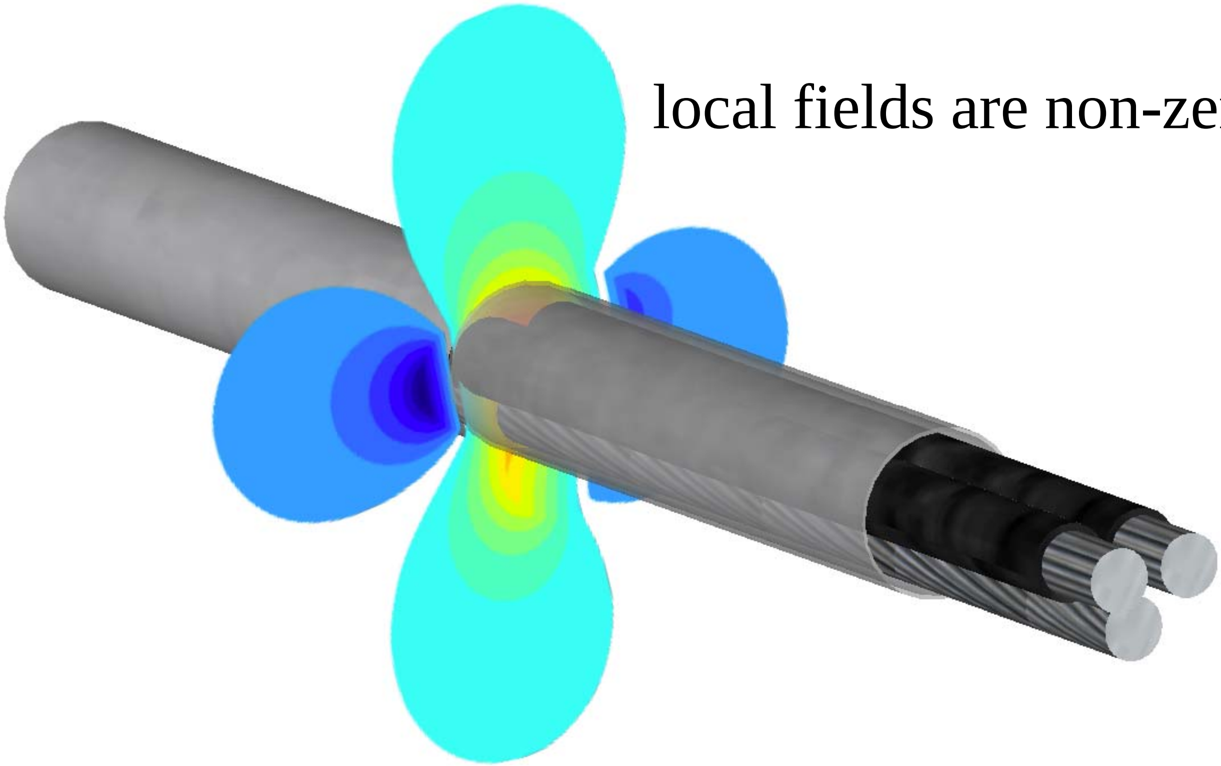
is collecting measurements from the microgrid serving 150 people.

One-line Diagram



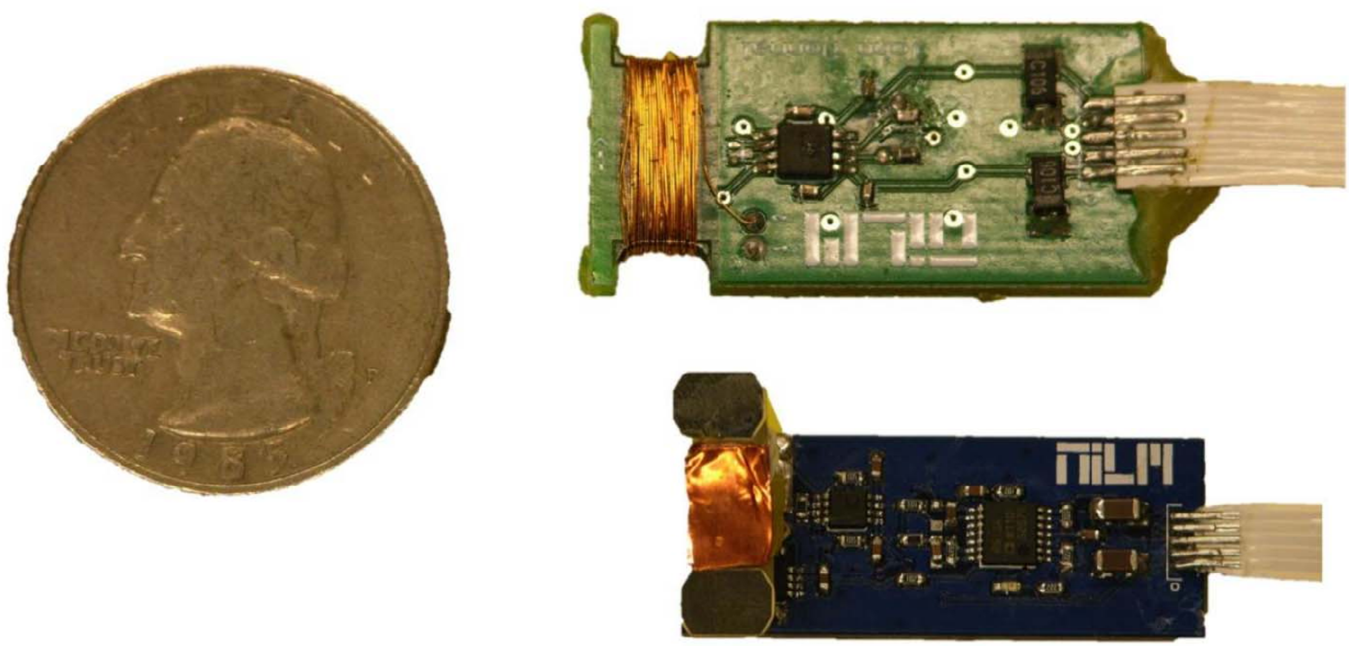
Electrical Sensing

Non-Contact Current Sensor

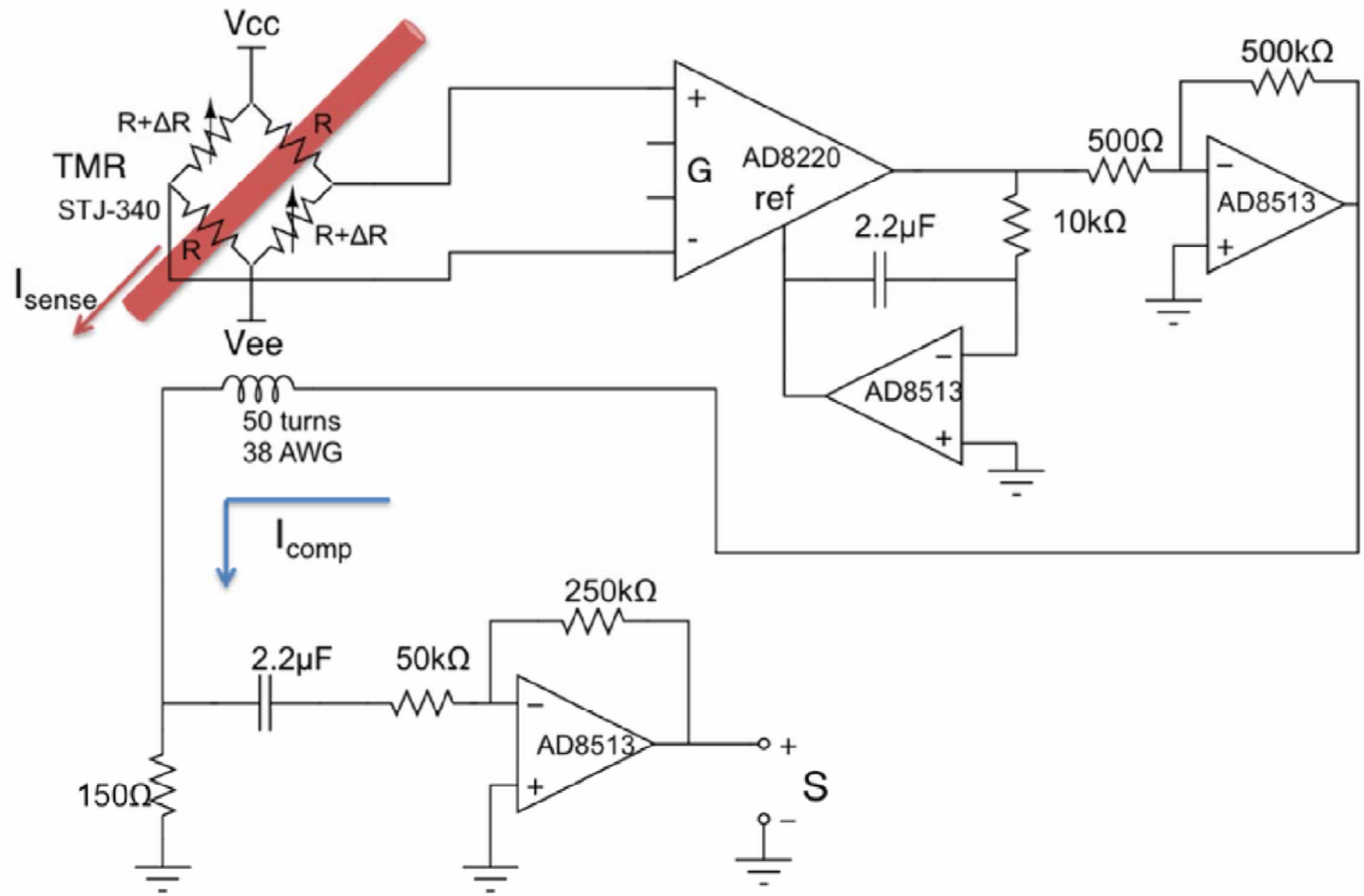


local fields are non-zero

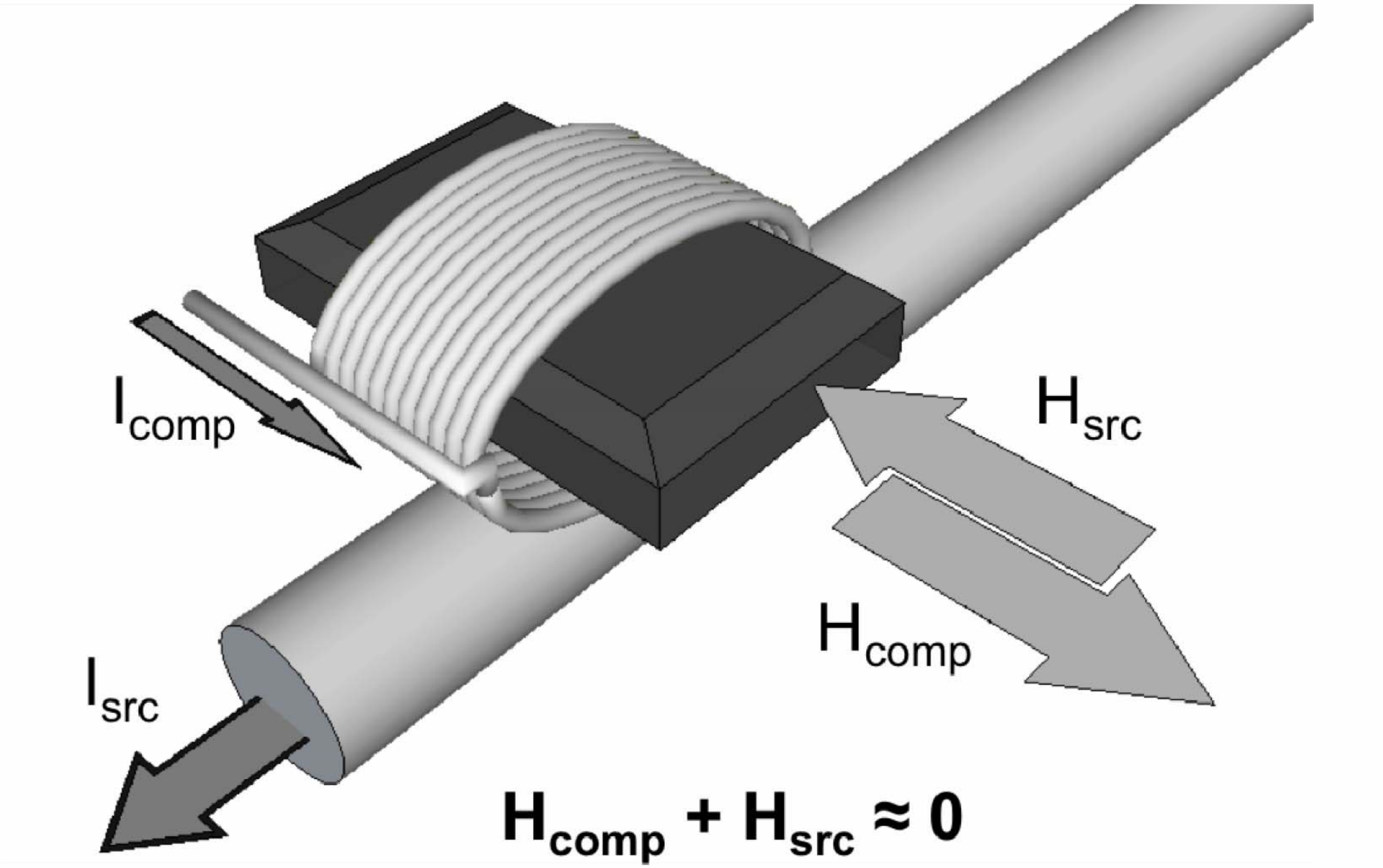
Noncontact current/voltage sensing



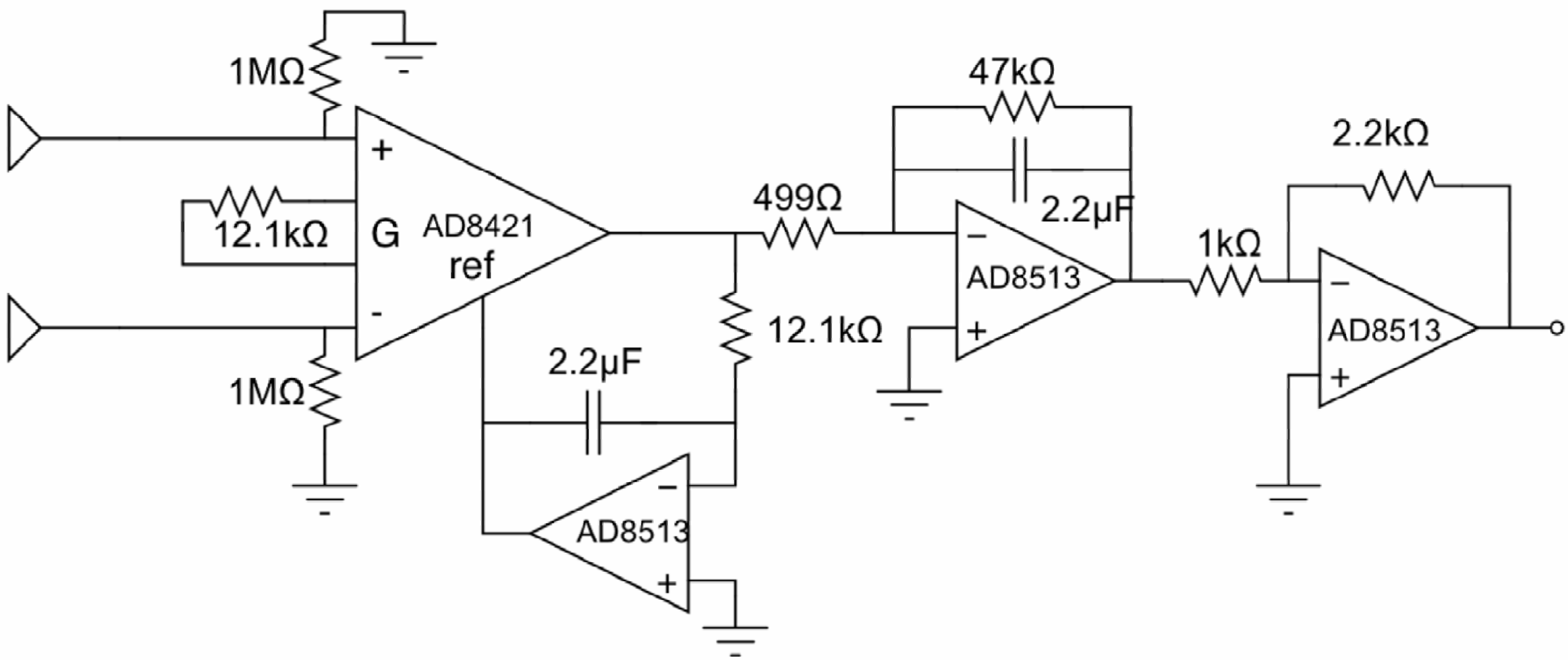
TMR current sensor



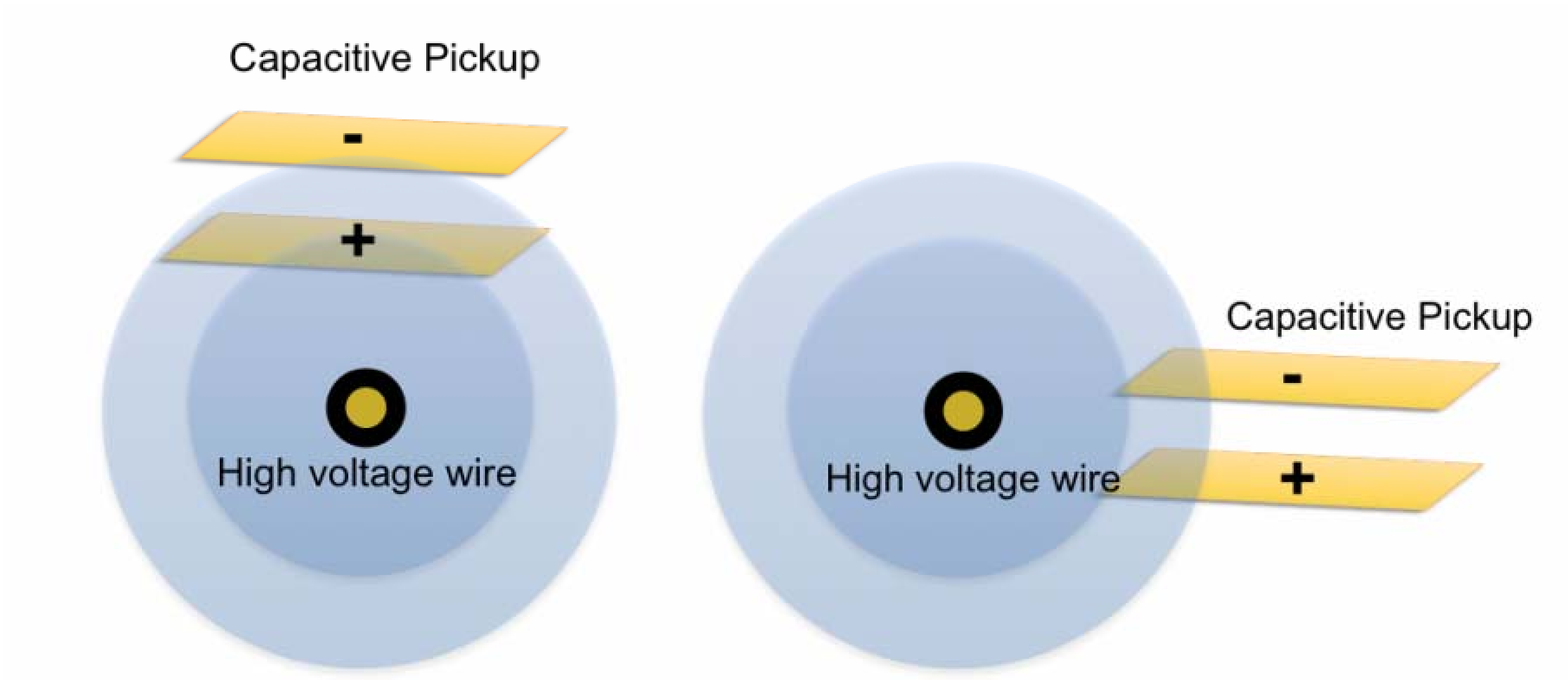
TMR Feedback



Capacitive Voltage Sensor



Differential Voltage Sense

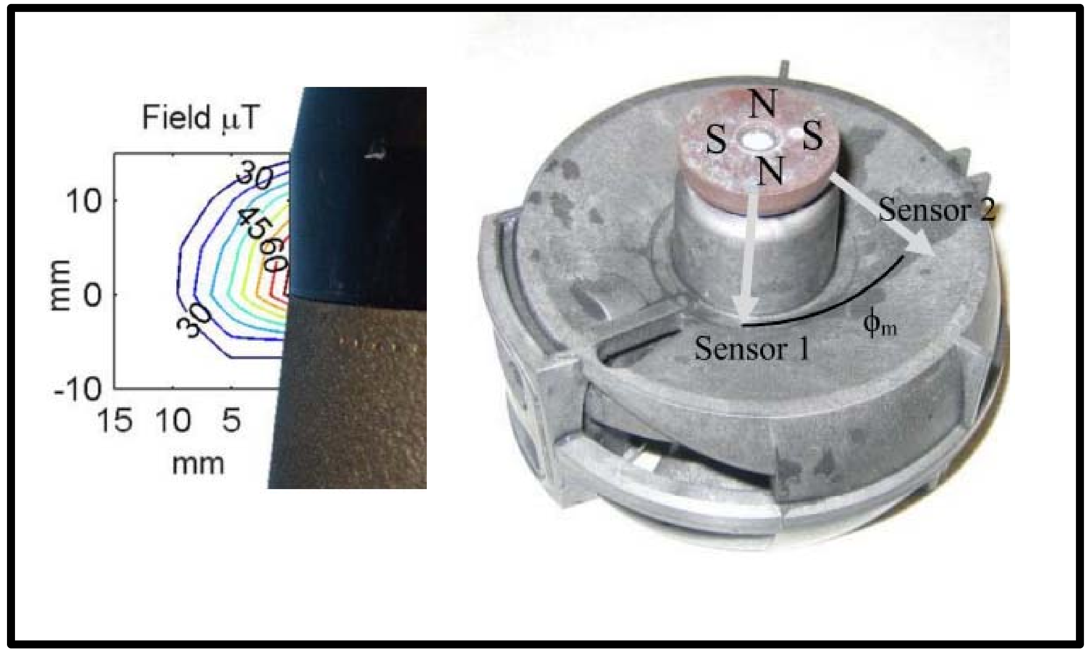


Easy Installation

WaterWOLF

Turning a standard water meter into a high bandwidth flow monitor

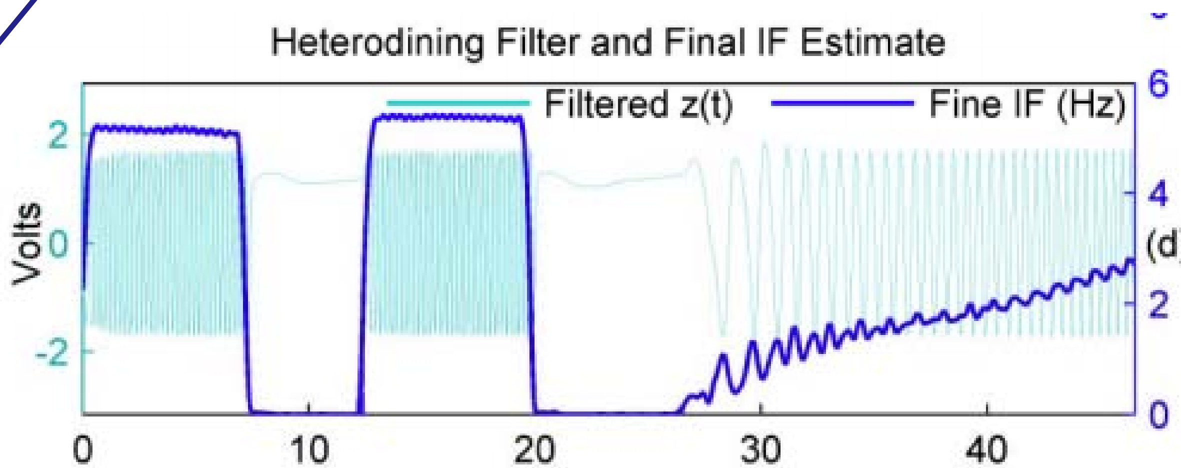
WaterWOLF



Internal fly wheel couples magnetically to external metering device.

WaterWOLF

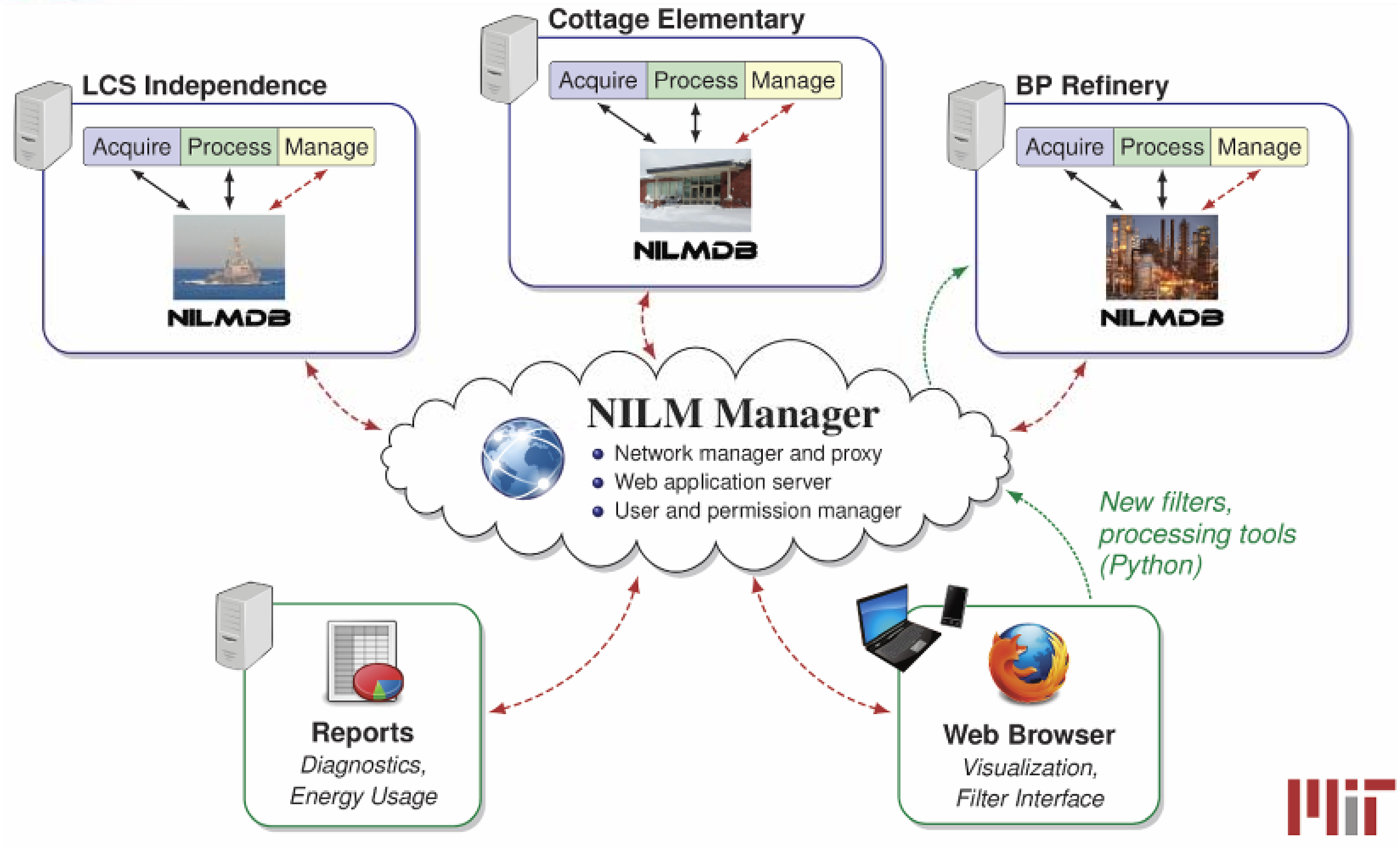
Two compensated TMR sensors

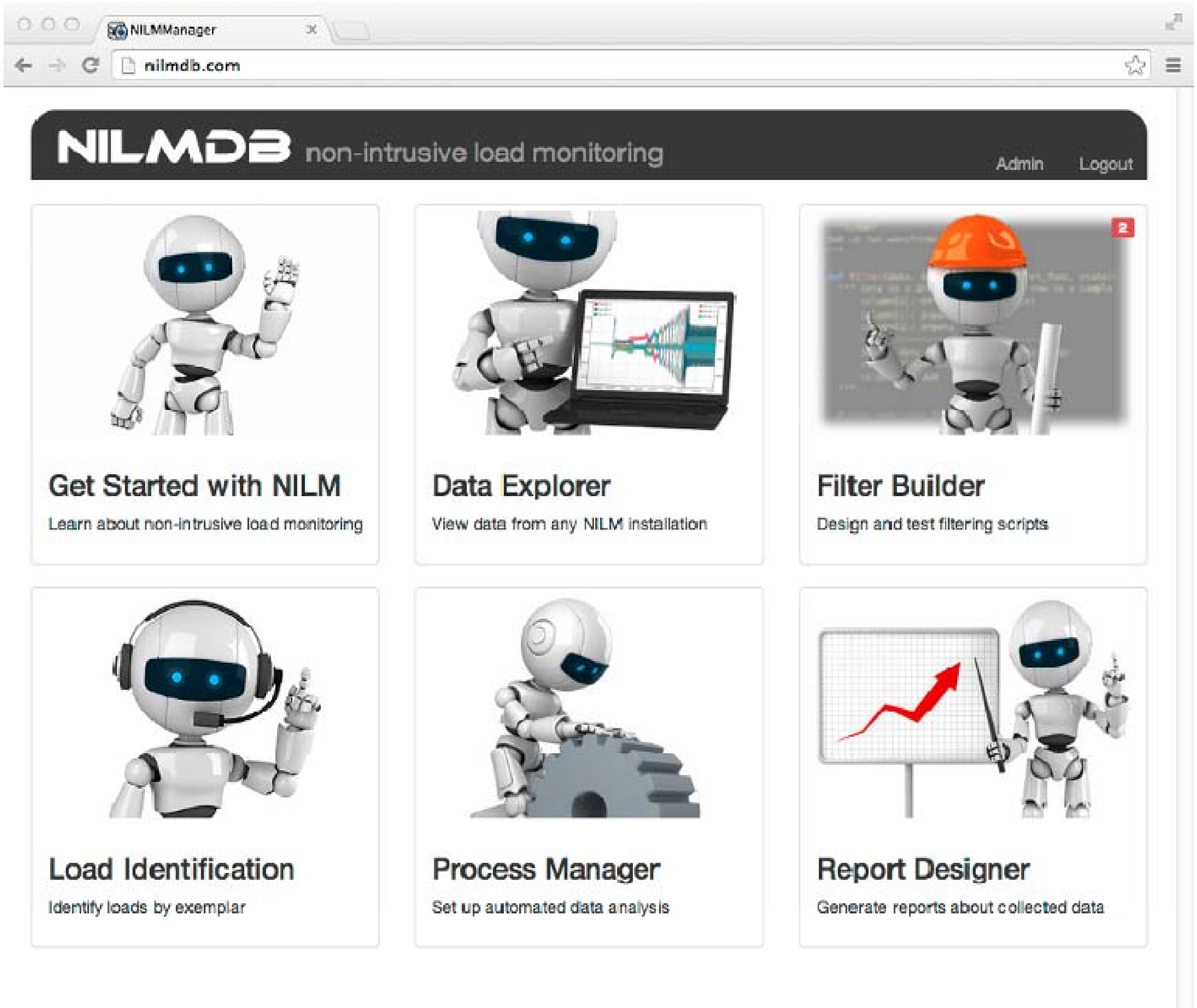


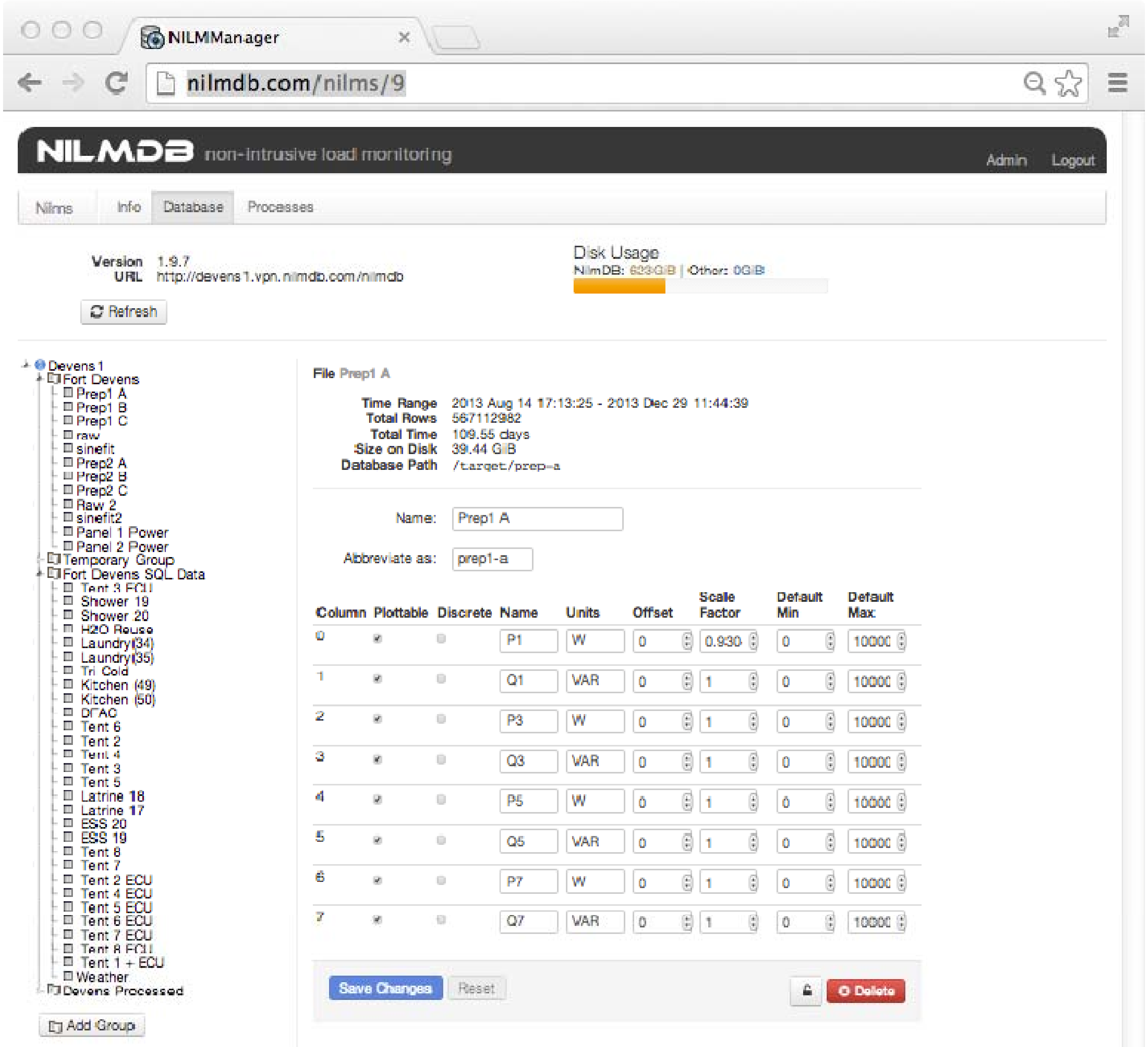
WaterWOLF retrofit converts any standard meter into a real time, high bandwidth water monitor.

Global Access and Security

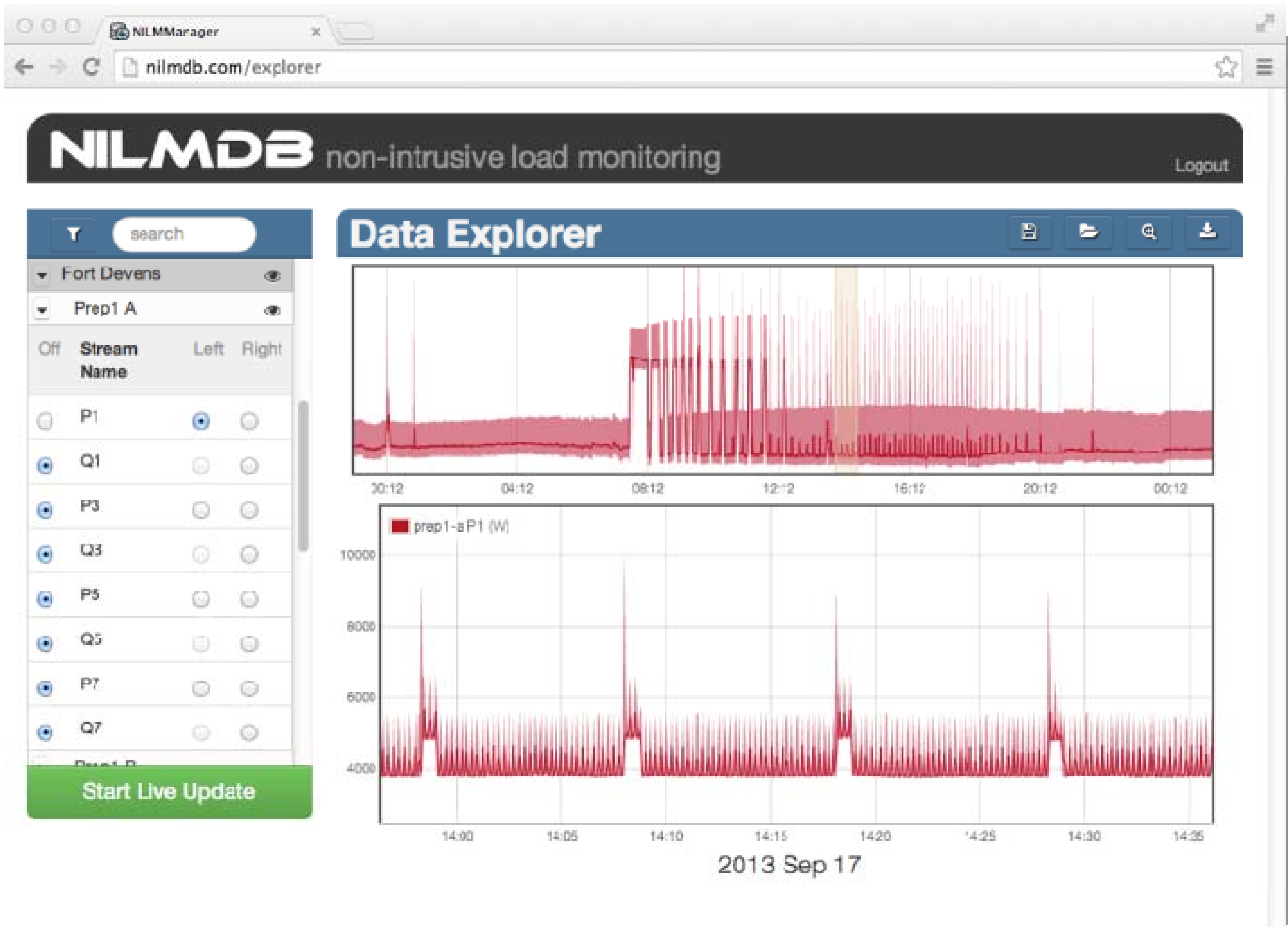
Solving the "Big Data" Problem

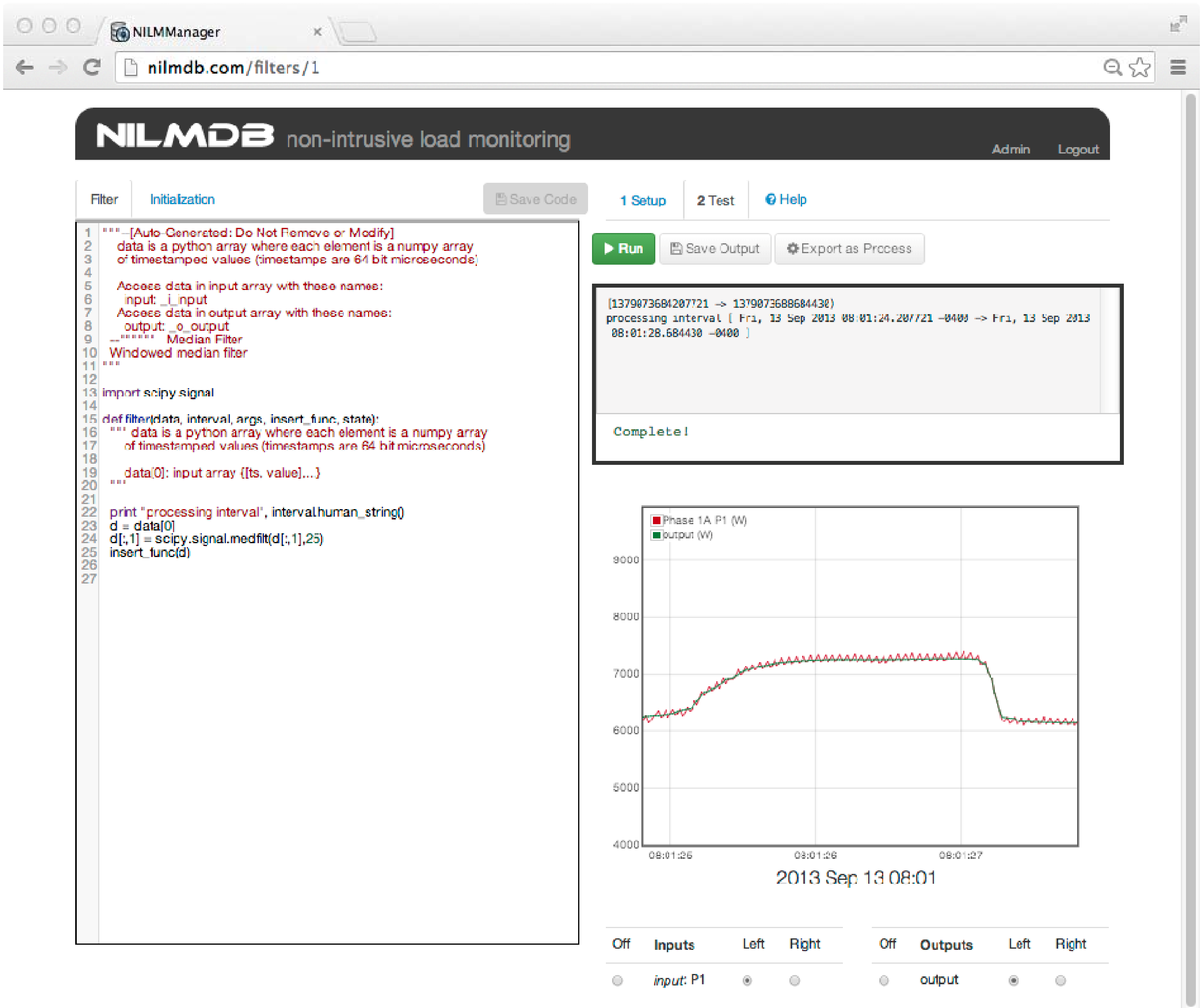


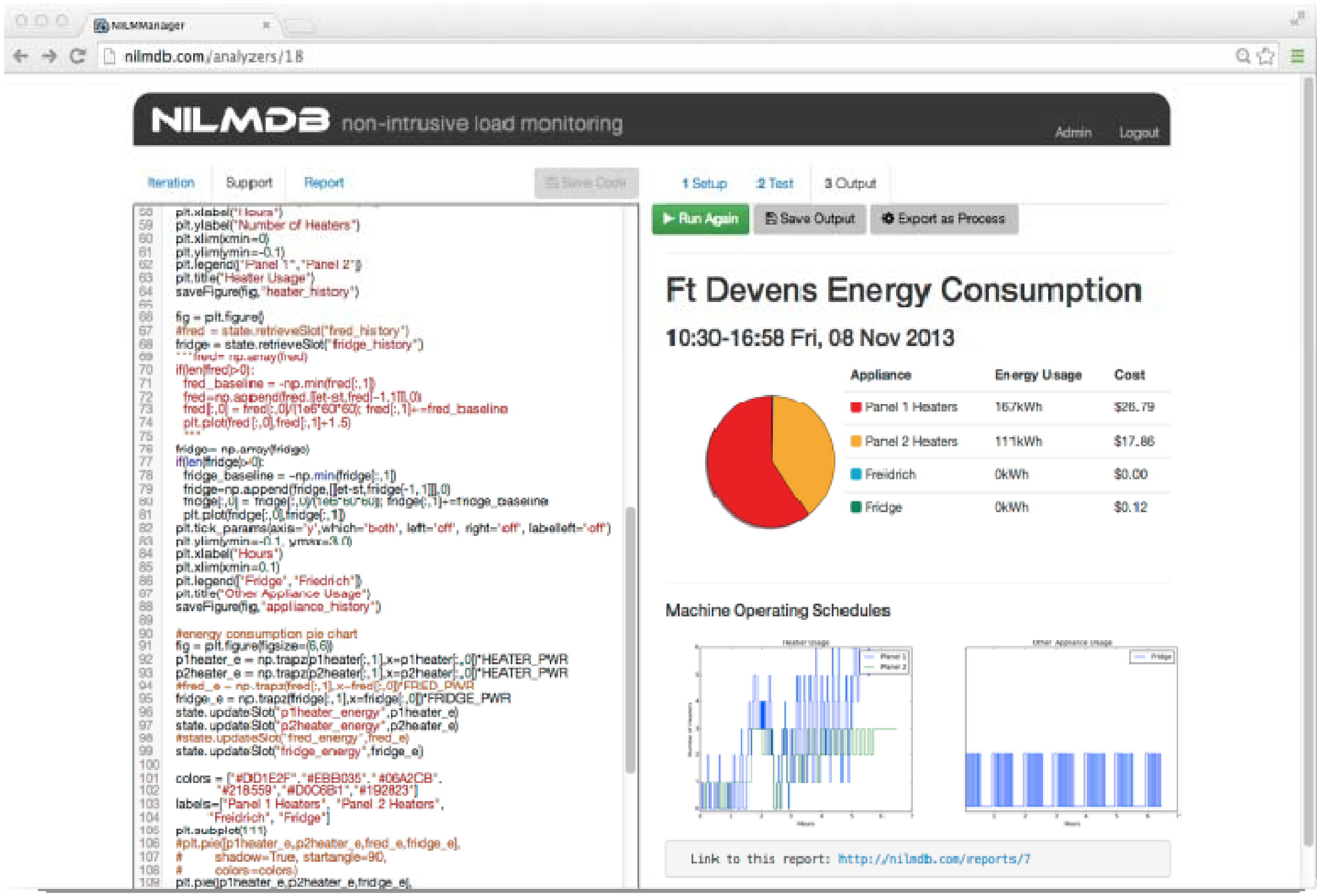

NILMManager
nilmdb.com
NILMDB non-intrusive load monitoring
Admin
Logout
Get Started with NILM
Learn about non-intrusive load monitoring
Data Explorer
View data from any NILM installation
Filter Builder
Design and test filtering scripts
Load Identification
Identify loads by exemplar
Process Manager
Set up automated data analysis
Report Designer
Generate reports about collected data



NILMManager
nilmdb.com/nilms/9
NILMDB non-intrusive load monitoring
Admin
Logout
Nilms
Info
Database
Processes
Version 1.9.7
URL http://devens1.vpn.nilmdb.com/nilmdb
Refresh
Disk Usage
NilmDB: 623GiB | Other: 0GiB
Devens1
Fort Devens
Prep1 A
Prep1 B
Prep1 C
raw
sinefit
Prep2 A
Prep2 B
Prep2 C
Raw 2
sinefit2
Panel 1 Power
Panel 2 Power
Temporary Group
Fort Devens SQL Data
Shower 19
Shower 20
H2O Reuse
Laundry(34)
Laundry(35)
Tri Cold
Kitchen (49)
Kitchen (50)
Tent 6
Tent 2
Tent 3
Tent 5
Latrine 18
Latrine 17
ESS 20
ESS 19
Tent 8
Tent 7
Tent 2 ECU
Tent 4 ECU
Tent 5 ECU
Tent 6 ECU
Tent 7 ECU
Tent 1 + ECU
Weather
Devens Processed
Add Group
File Prep1 A
Time Range 2013 Aug 14 17:13:25 - 2013 Dec 29 11:44:39
Total Rows 567112982
Total Time 109.55 days
Size on Disk 39.44 GiB
Database Path /target/prep-a
Name: Prep1 A
Abbreviate as: prep1-a
Column Plottable Discrete Name Units Offset Scale Factor Default Min Default Max
0 P1 W 0 0.930 0 10000
1 Q1 VAR 0 1 0 10000
2 P3 W 0 1 0 10000
3 Q3 VAR 0 1 0 10000
4 P5 W 0 1 0 10000
5 Q5 VAR 0 1 0 10000
6 P7 W 0 1 0 10000
7 Q7 VAR 0 1 0 10000
Save Changes
Reset
Delete

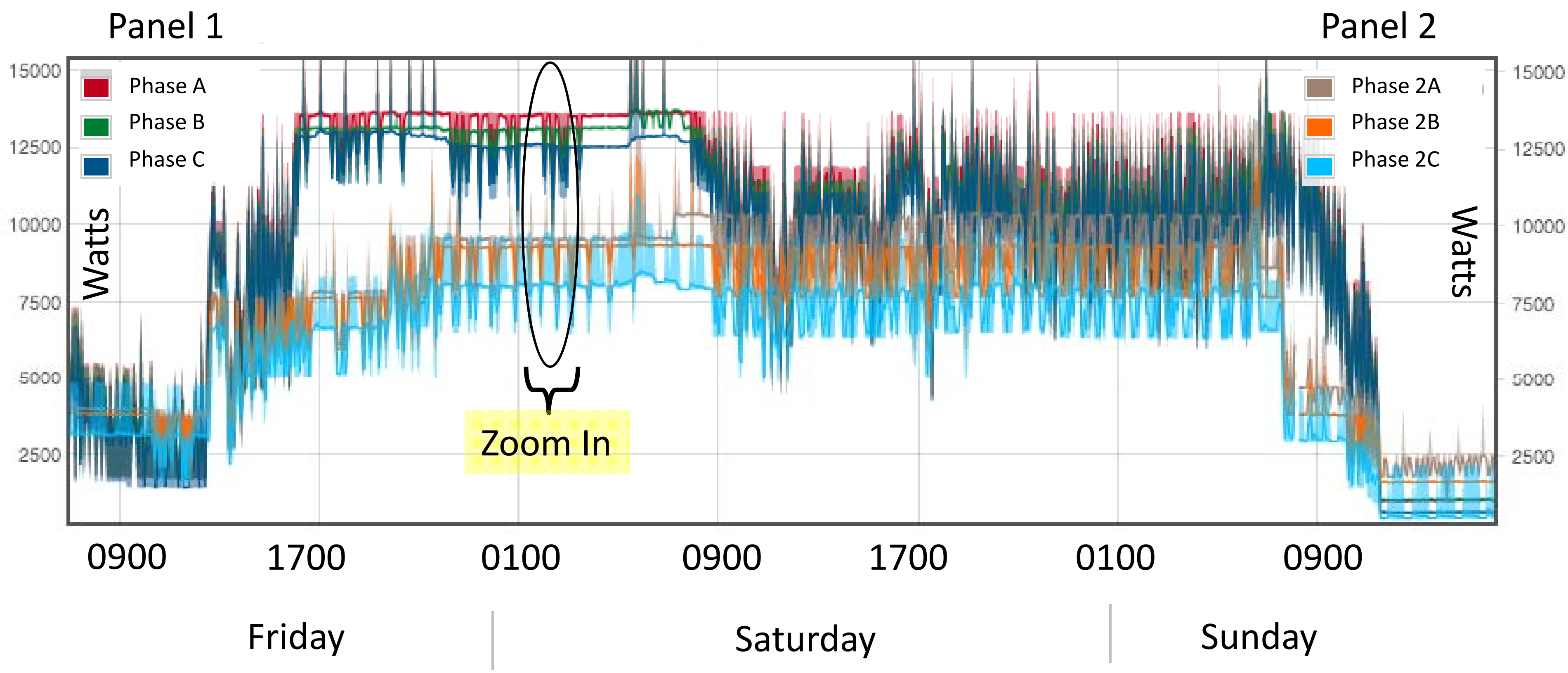

NILMManager
nilmdb.com/explorer
NILMDB non-intrusive load monitoring
Logout
search
Data Explorer
Fort Devens
Prep1 A
Off
Stream Name
Left
Right
P1
Q1
P3
Q3
P5
Q5
P7
Q7
Start Live Update
04:12
08:12
16:12
20:12
00:12
prep1-a P1 (W)
10000
8000
6000
4000
14:00
14:05
14:10
14:15
14:20
14:30
14:35
2013 Sep 17


NILMManager
nilmdb.com/filters/1
NILMDB non-intrusive load monitoring
Admin
Logout
Filter
Initialization
Save Code
1 Setup
2 Test
Help
""" [Auto-Generated: Do Not Remove or Modify]
data is a python array where each element is a numpy array
of timestamped values (timestamps are 64 bit microseconds)
Access data in input array with these names:
input: _i_nput
Access data in output array with these names:
output: _o_output
"""""" Median Filter
Windowed median filter
"""
import scipy.signal
def filter(data, interval, args, insert_func, state):
""" data is a python array where each element is a numpy array
of timestamped values (timestamps are 64 bit microseconds)
data[0]: input array ([ts, value],...)
"""
print "processing interval", interval.human_string()
d = data[0]
d[:,1] = scipy.signal.medfilt(d[:,1],25)
insert_func(d)
Run
Save Output
Export as Process
[1379073684207721 -> 1379073688684430)
processing interval [Fri, 13 Sep 2013 08:01:24.207721 -0400 -> Fri, 13 Sep 2013 08:01:28.684430 -0400]
Complete!
Phase 1A P1 (W)
output (W)
9000
8000
7000
6000
5000
4000
08:01:26
08:01:26
08:01:27
2013 Sep 13 08:01
Off
Inputs
Left
Right
input: P1
Off
Outputs
Left
Right
output


NILMManager
nilmdb.com/analyzers/18
NILMDB non-intrusive load monitoring
Admin
Logout
Iteration
Support
Report
Save Code
1 Setup
2 Test
3 Output
Run Again
Save Output
Export as Process
Ft Devens Energy Consumption
10:30-16:58 Fri, 08 Nov 2013
Appliance
Energy Usage
Cost
Panel 1 Heaters
167kWh
$26.79
Panel 2 Heaters
111kWh
$17.86
Freidrich
0kWh
$0.00
Fridge
0kWh
$0.12
Machine Operating Schedules
Link to this report: http://nilmdb.com/reports/7

Energy Scorekeeping

48 hours of Electrical Data

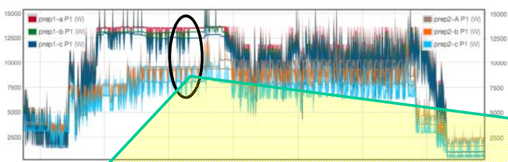


Q: How do we make this data useful?

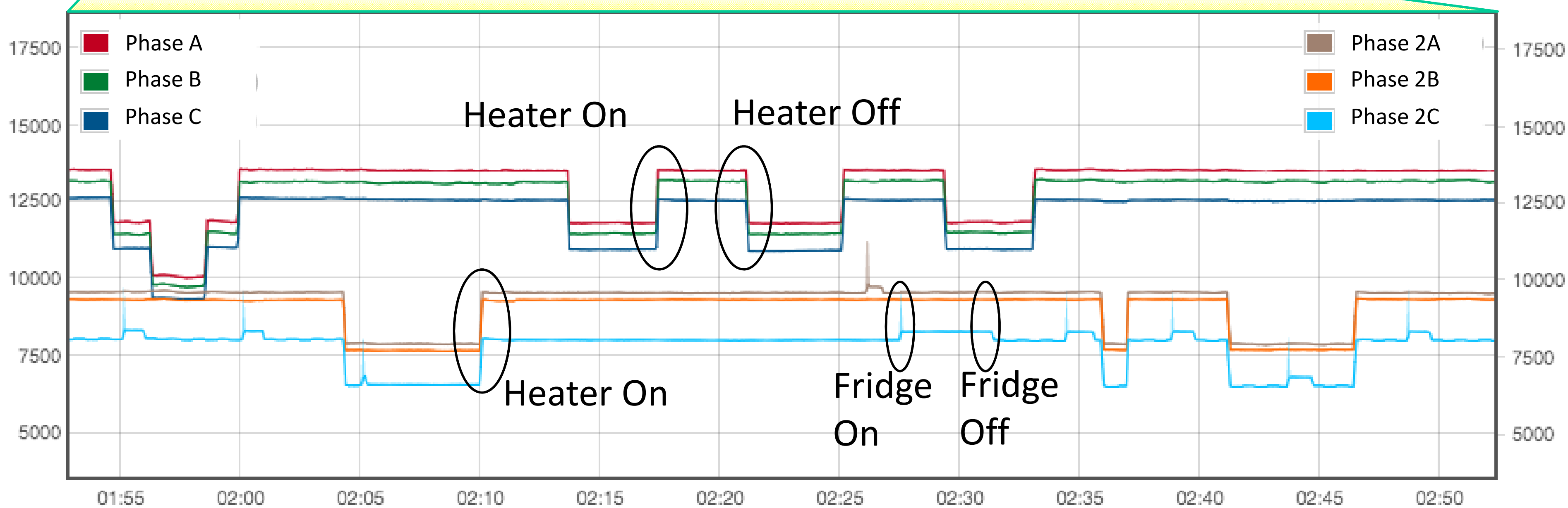
1 hour of electrical data

How can we be sure these are actually heater and fridge events?

Zoom in further…



Zoom in…

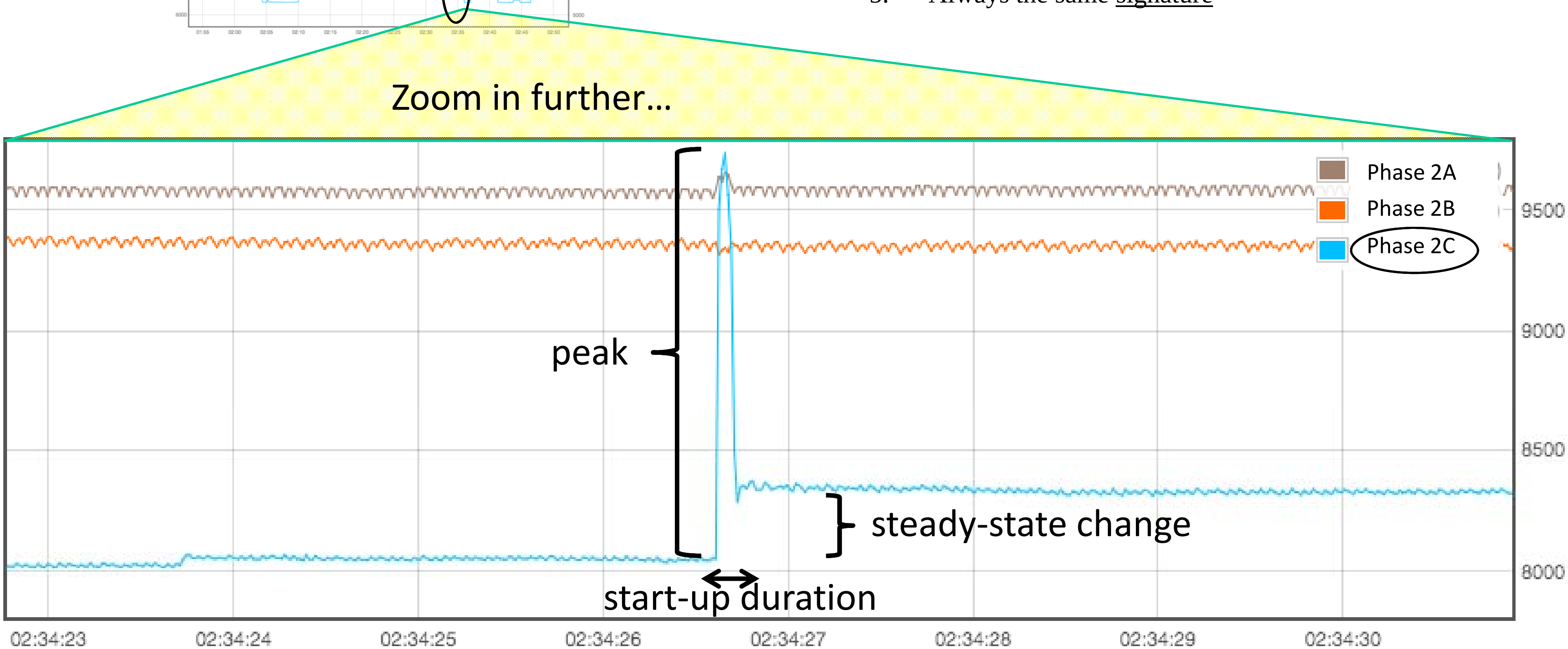


A: By identifying every electrical event

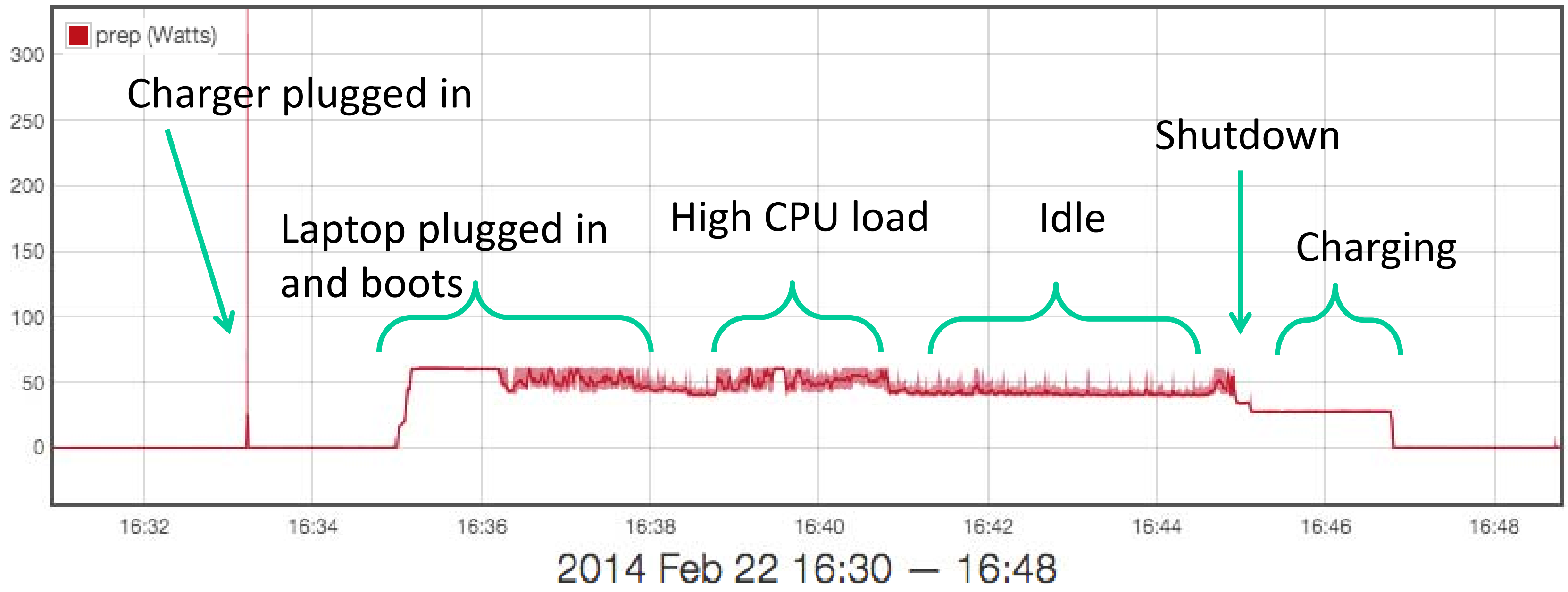
8 seconds of electrical data

Software can find common features:

1. Always the same <u>peak</u> value
2. Always the same <u>steady-state change</u>
3. Always the same <u>start-up duration</u>
4. Always the same <u>phase</u>
5. Always the same <u>signature</u>



Macbook Pro as seen by the NILM



Cross Corroboration

Comparing existing sub-meter data from every tent/structure over the same **48 hour** period:

Ft. Devens sub-meters	4876 kWh
⌘ **NILM Estimate**	4852 kWh

Major loads accounted for over **99%** of total consumption

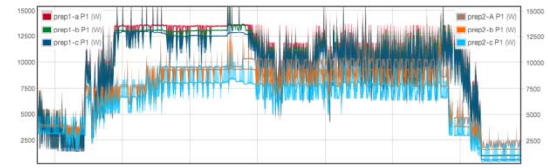
Note: NILM estimate = $\sum_{k=1}^{33} hours\ operated_k \times watts_k$

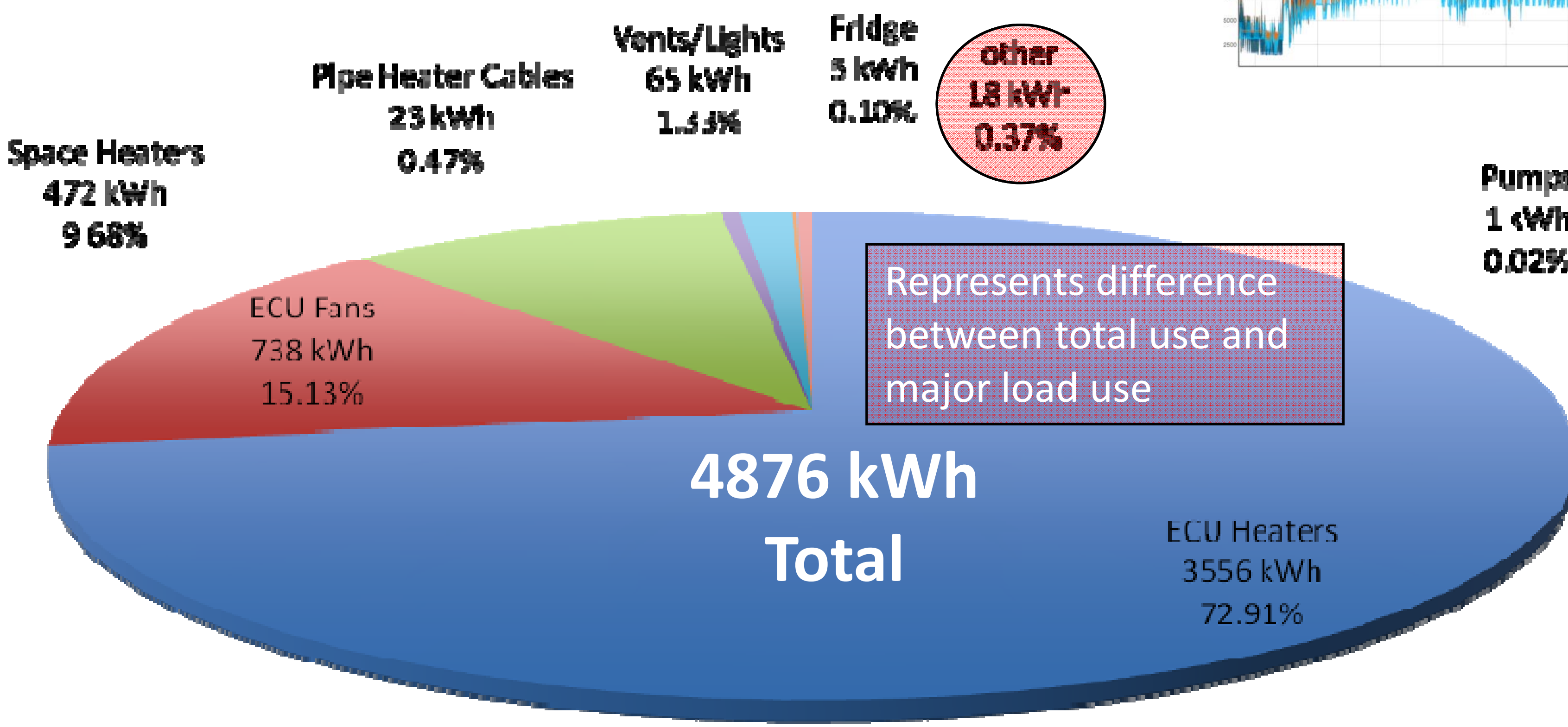
Activity tracking and scheduling verification

Power Consumption (kWh)

during the training weekend

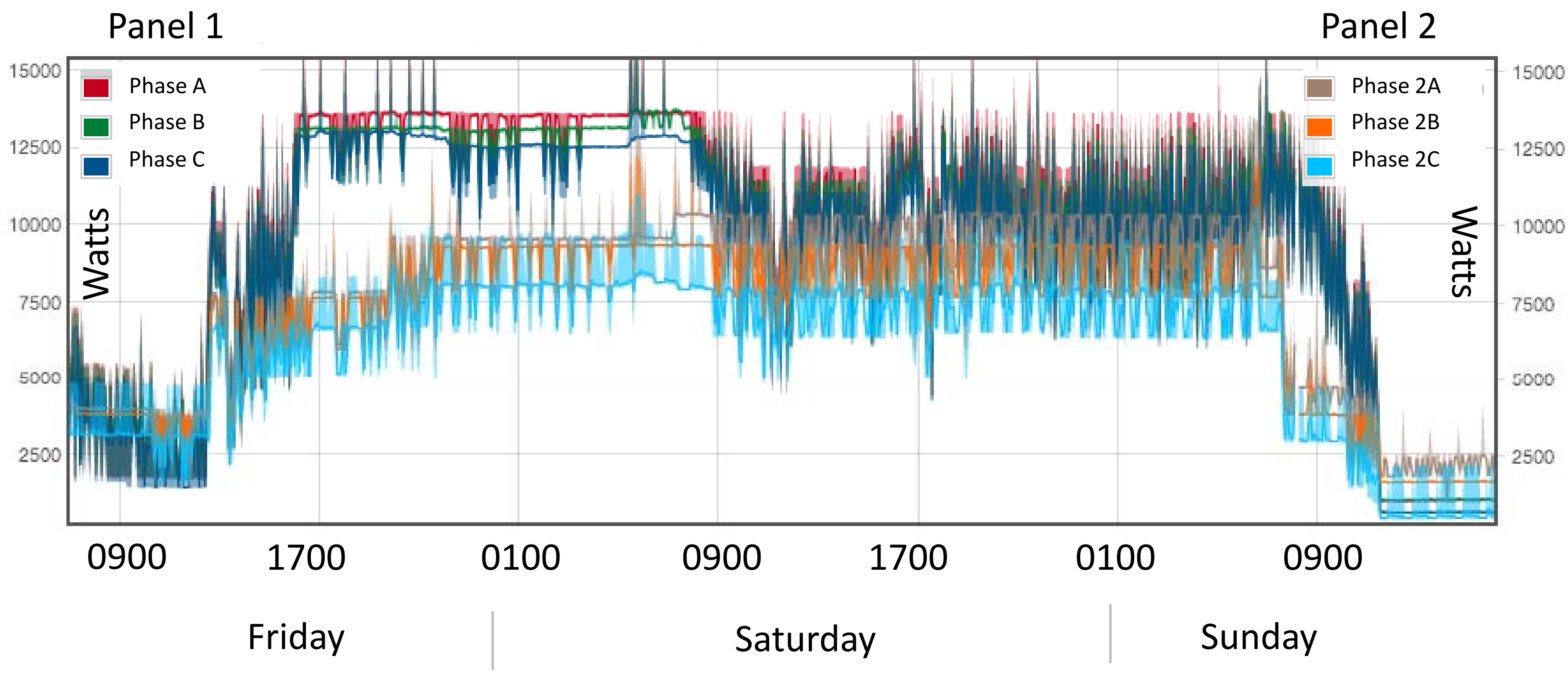
Extracted from





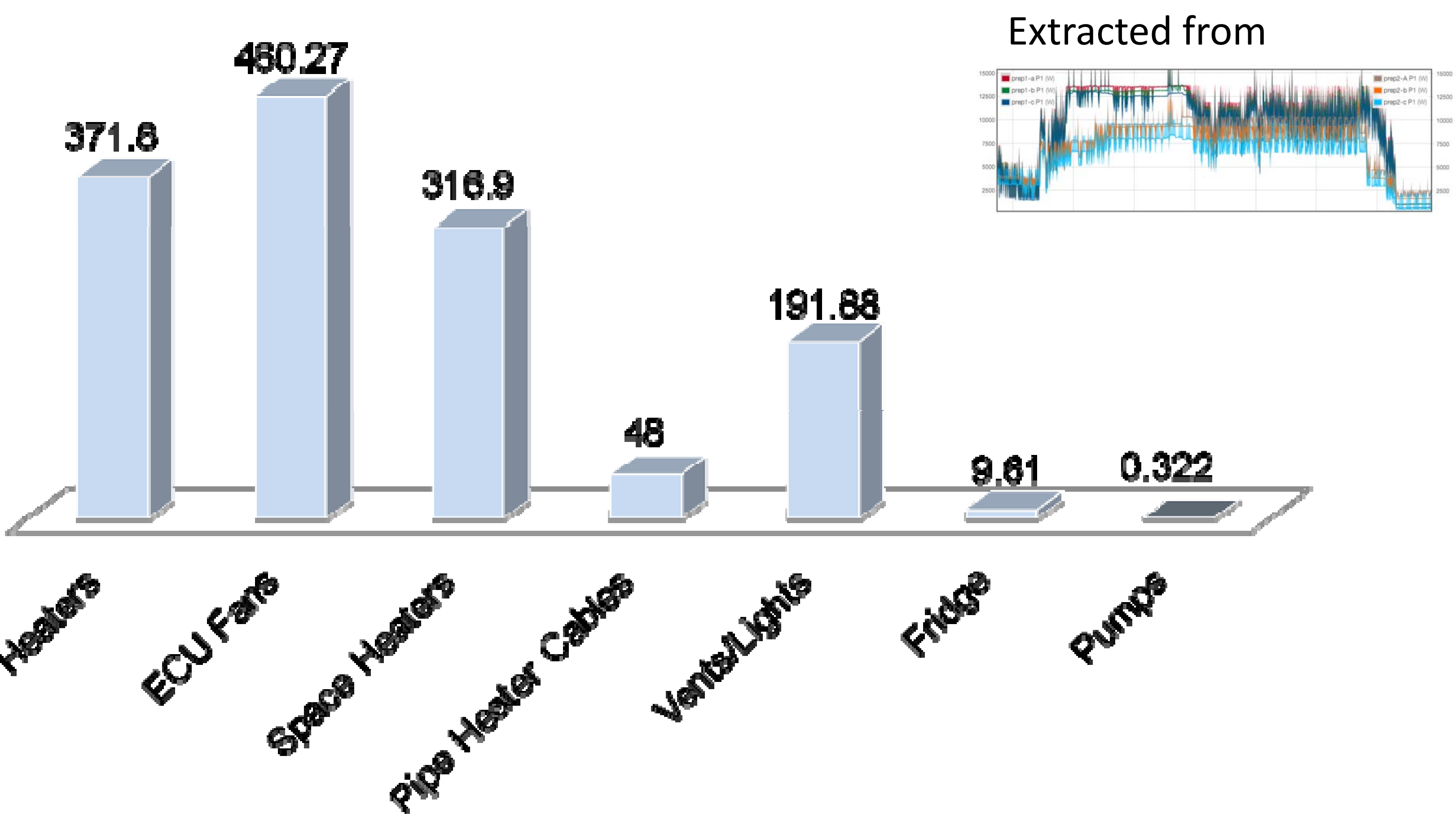
* 48 hour time period, Nov 2013

48 hours of Electrical Data



Equipment Hours

during the training weekend



* 48 hour time period, 4876 kWh consumed

Pump Events

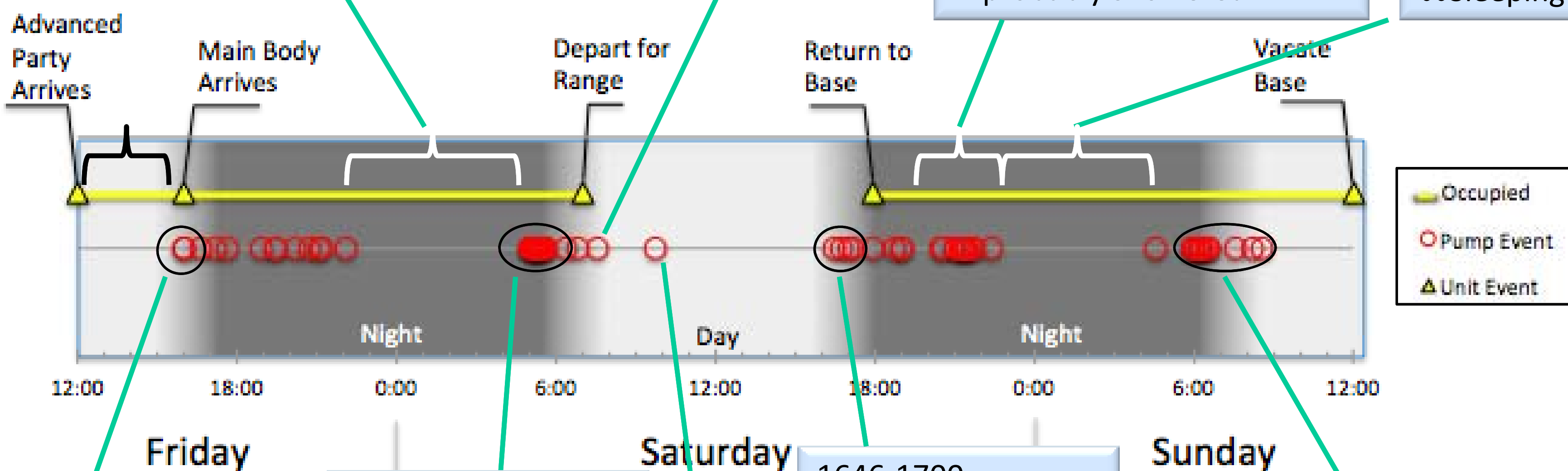
Good indicator of Human Activity

<u>2200 – 0459</u>
No pump events
⌘Sleeping

<u>0700</u>
2 events
⌘Unit departed after 0700

<u>1700-2230</u>
19 events (compared to 8 the previous evening and 13 the previous morning)
⌘probably showered

<u>No events</u>
⌘Sleeping



<u>1559</u>
Three pump events
Unit scheduled to arrive at 1600
⌘Immediately used the bathrooms

<u>0459-0540</u>
13 events
⌘morning hygiene

<u>Only 1 event while at range</u>
⌘personnel stayed behind

<u>1646-1700</u>
3 events
⌘Unit returned before 1700

<u>Events at 0437, 0556, and 0600</u>
⌘Wake up time 0600

<u>13 events between 0600-0830</u>
10 occur before 6:33
⌘Main body probably left by 0900

Note: 4 identical pumps (2 latrine, 2 shower), each with 10-12 gallon septic tank

48 hours of Electrical Data

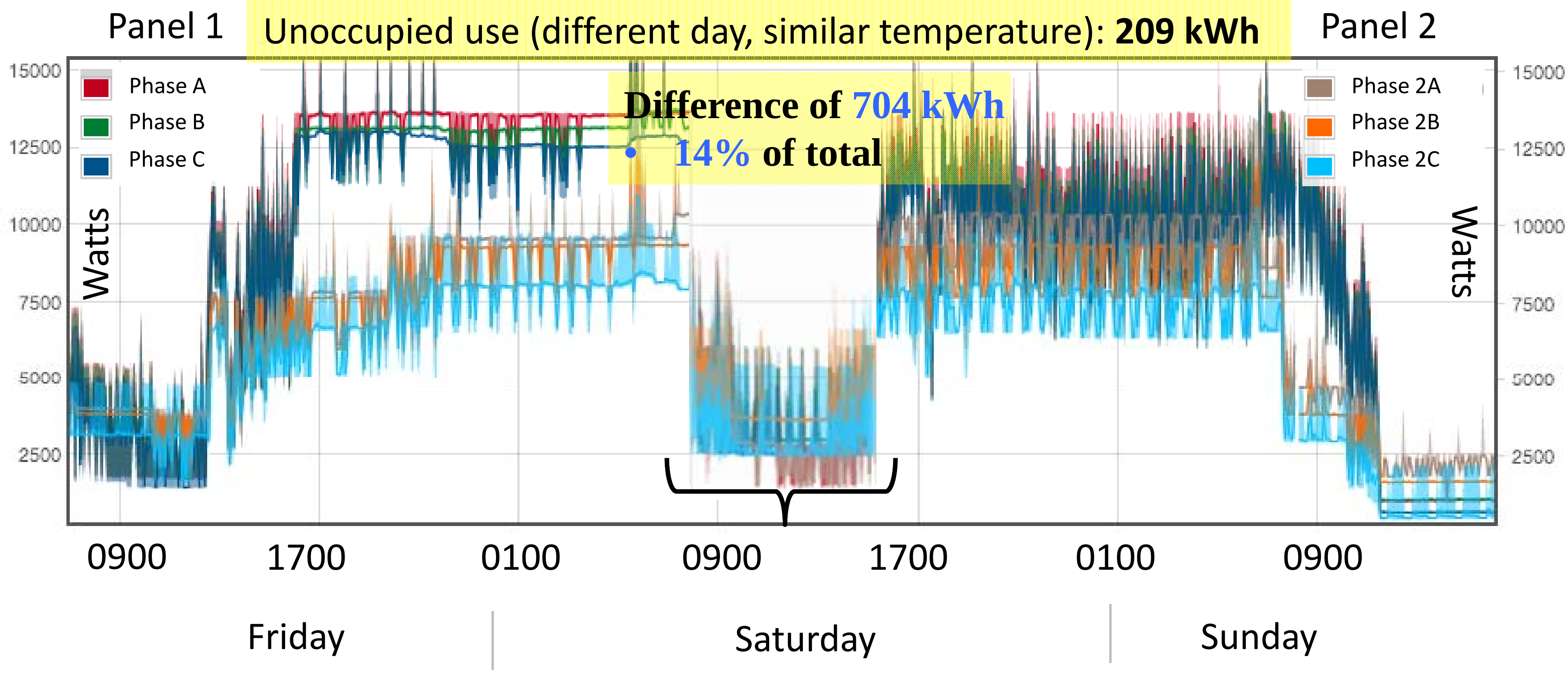
during a training weekend

What they actually used: **913 kWh**

Unoccupied use (different day, similar temperature): **209 kWh**

Difference of 704 kWh

- **14% of total**

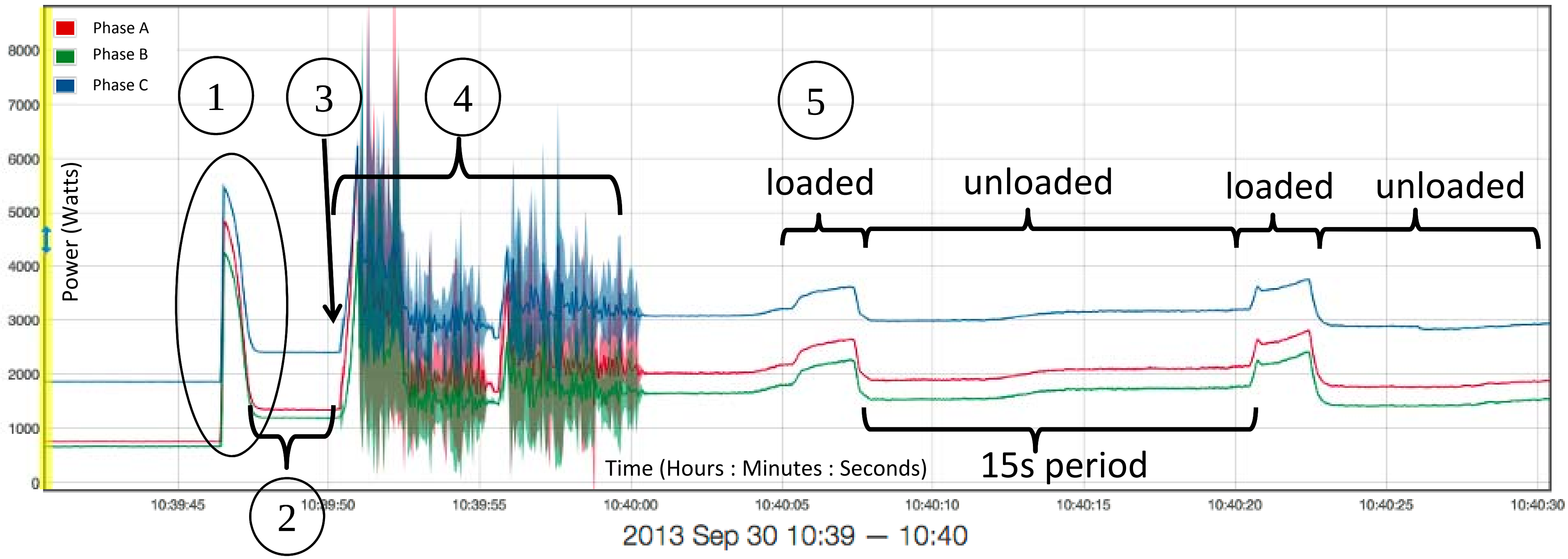


Q: What if unit turned things off while at the range?

Perform Condition-Based Maintenance

Operation of the ECU

(Cool Mode)



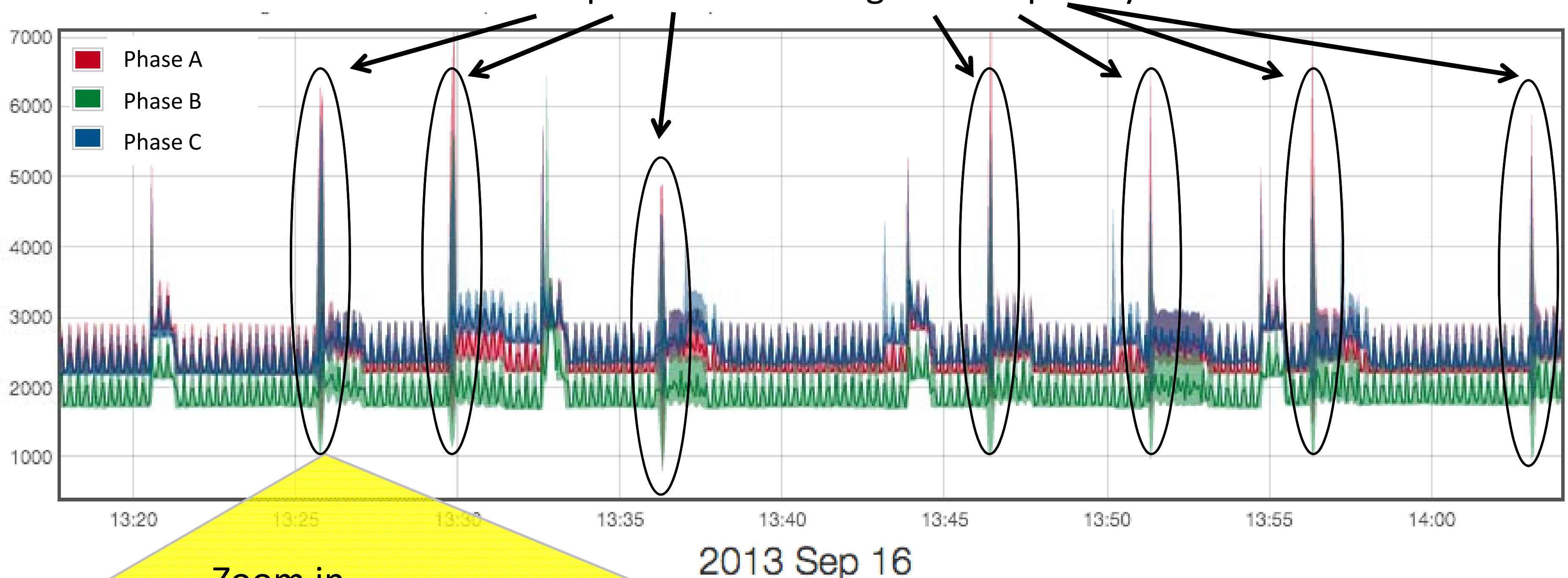
<u>Sequence of operation</u>

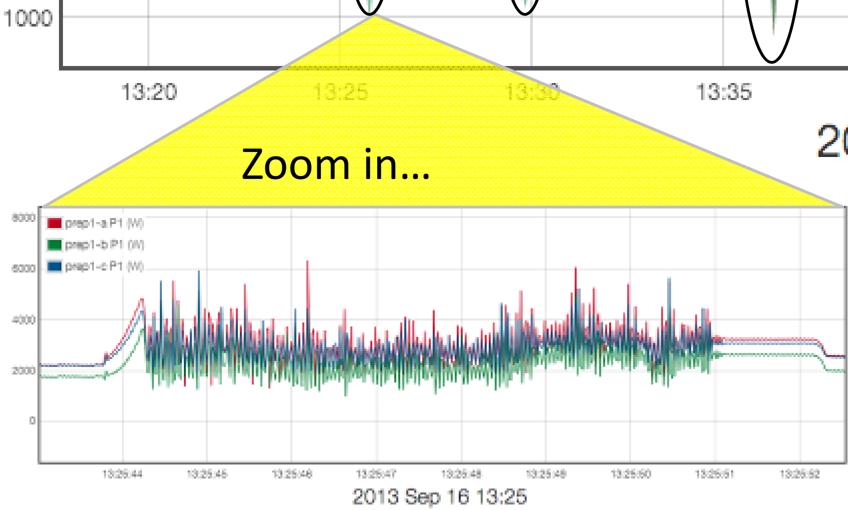
1. Supply fan on
2. 3 second delay
3. Condenser fan on
4. Compressor turns on using "soft start" controller
5. Compressor (two states, loaded and unloaded)
   - Over a 15 second period, compressor is loaded 10% of the time

Fault Identification thru NILM

(ECU Cool Mode)

Compressor Restarting Too Frequently





Explanation: Every 5-10 minutes, this same compressor starts, runs for a short time, and turns off. It could be malfunctioning, or perhaps the A/C is just not needed (space is cool already) and should be turned off. Software code can look for common faults like this and alert the base manager.

Back-up flow meter

- When septic tanks fill, electric pumps activate
- Each pump has it own 10-12 gallon tank

⌘ **Pump cycle = 12 gallons used**

Example:

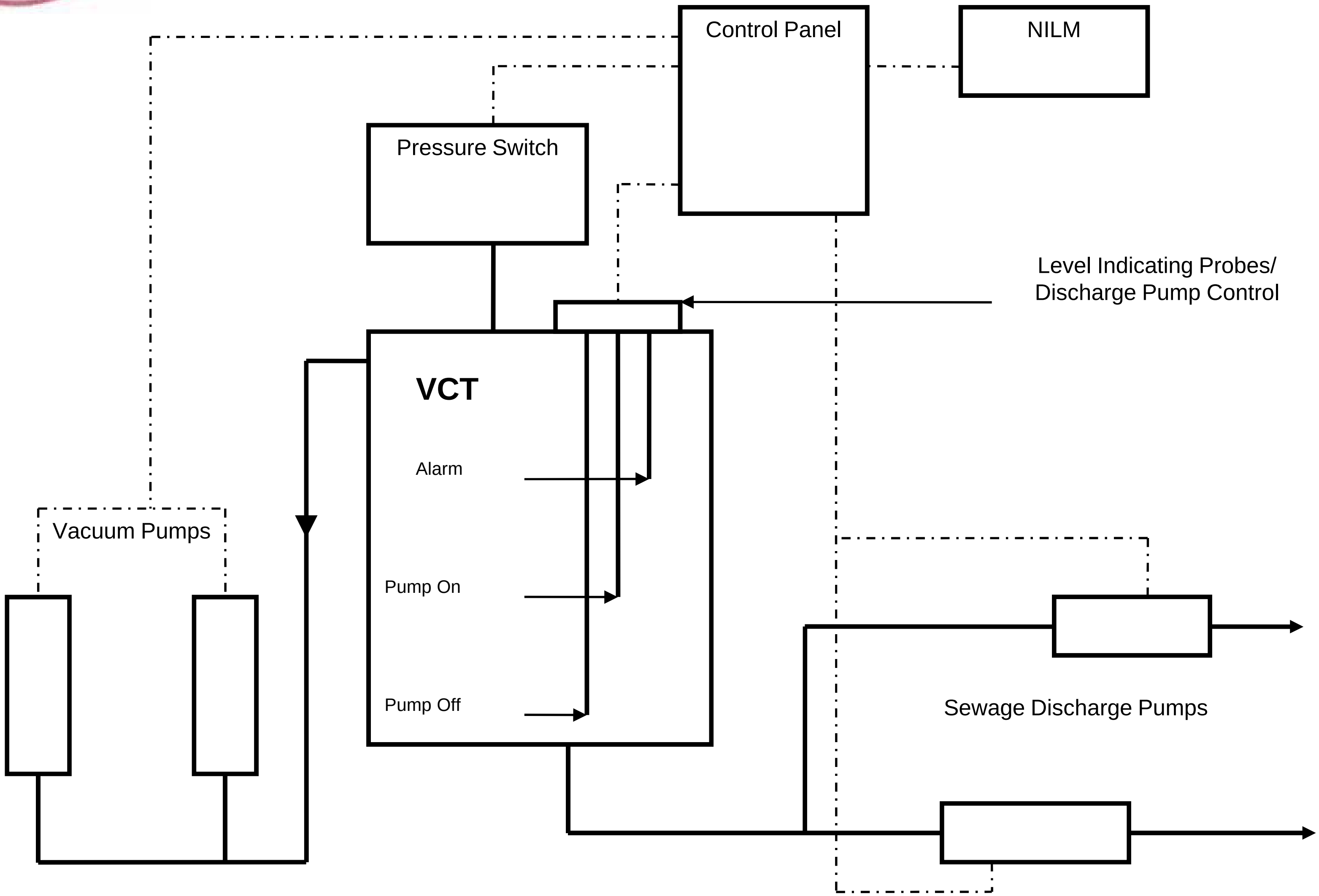
27 (8AM) -29 (10AM) September – BCIL was occupied
•flow meter measured 1150 gallons used

NILM counted **46 pump events** (monitoring 2 of 4 pumps…)
⌘ **~max 552 gallons** (times 2 = 1104 gallons, decent estimate!)

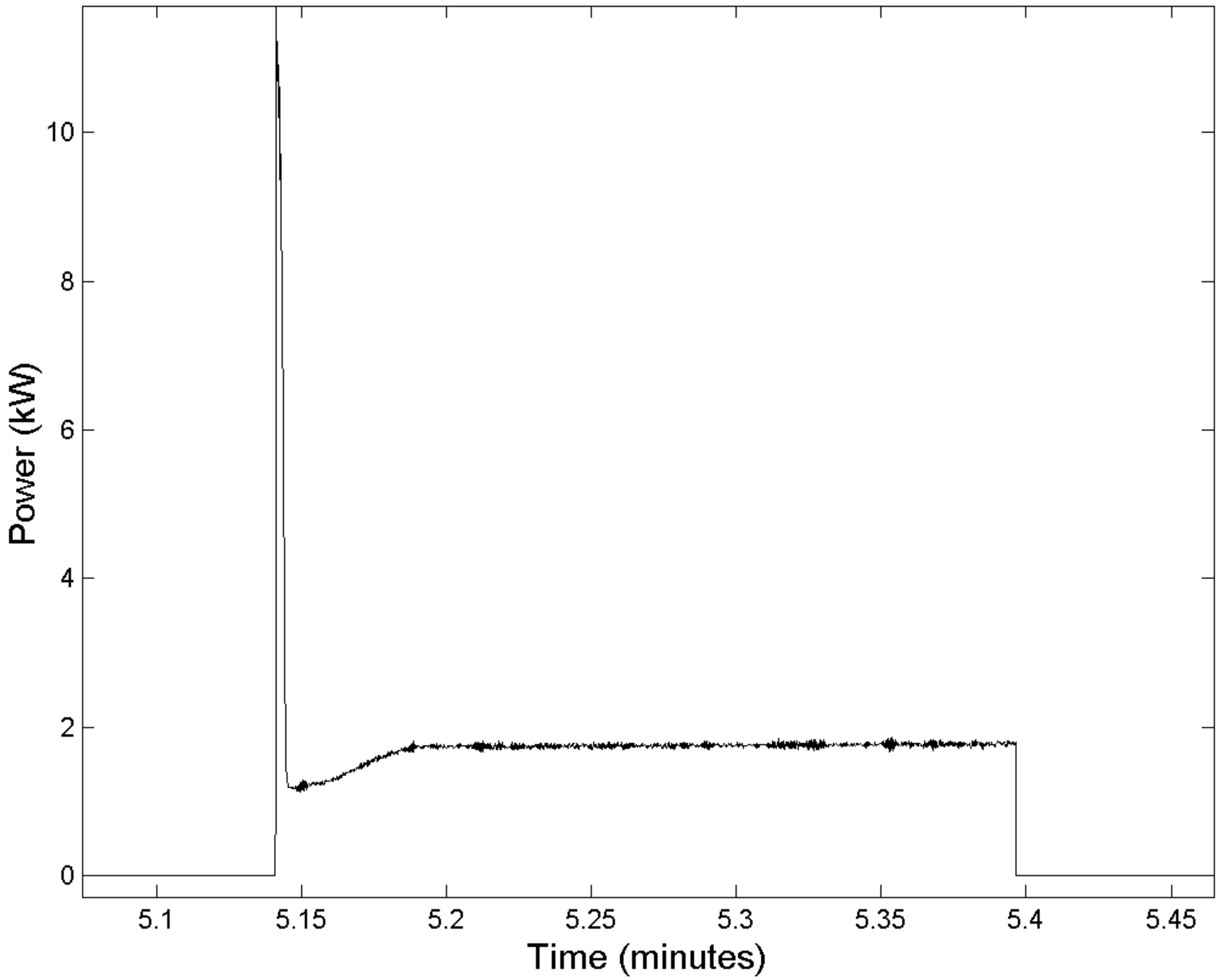
Cycling System Faults

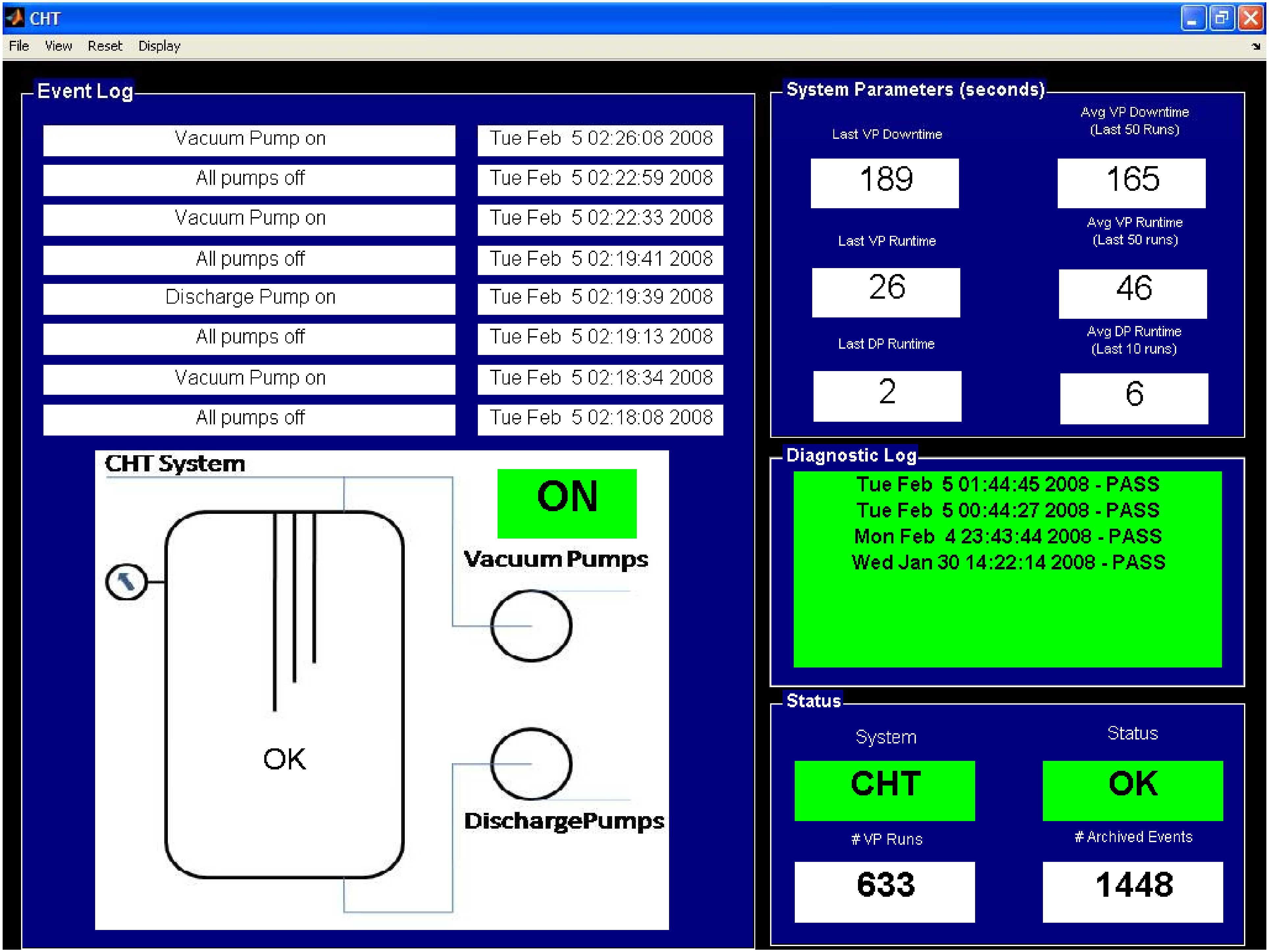
- Examples:
  - Waste-disposal systems
  - LP air systems
- Leaks are frequent
- Leaks and high usage have the same effect on the actuator
- Example: *SENECA*'s waste disposal system

System Overview



Pump Operation

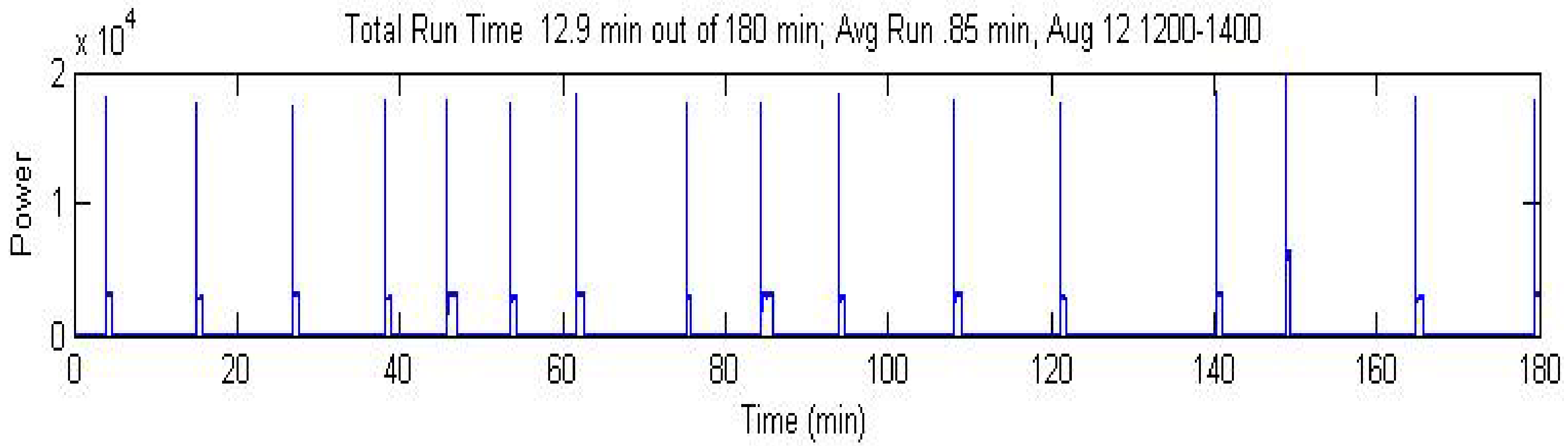


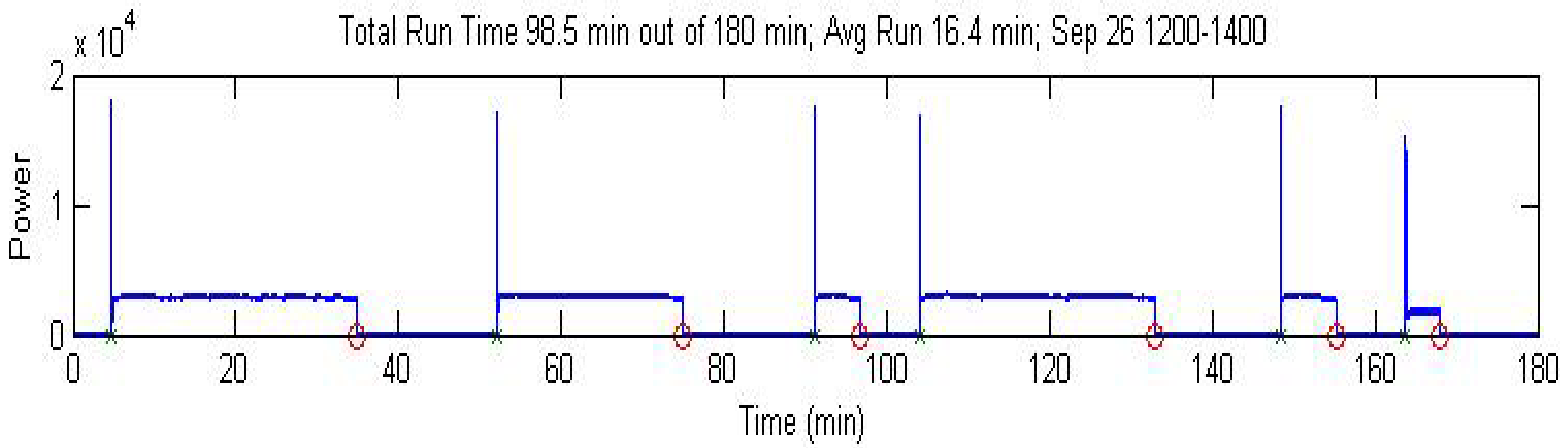

CHT
File View Reset Display
Event Log
Vacuum Pump on
Tue Feb 5 02:26:08 2008
All pumps off
Tue Feb 5 02:22:59 2008
Vacuum Pump on
Tue Feb 5 02:22:33 2008
All pumps off
Tue Feb 5 02:19:41 2008
Discharge Pump on
Tue Feb 5 02:19:39 2008
All pumps off
Tue Feb 5 02:19:13 2008
Vacuum Pump on
Tue Feb 5 02:18:34 2008
All pumps off
Tue Feb 5 02:18:08 2008
CHT System
ON
Vacuum Pumps
OK
DischargePumps
System Parameters (seconds)
Last VP Downtime
189
Avg VP Downtime (Last 50 Runs)
165
Last VP Runtime
26
Avg VP Runtime (Last 50 runs)
46
Last DP Runtime
2
Avg DP Runtime (Last 10 runs)
6
Diagnostic Log
Tue Feb 5 01:44:45 2008 - PASS
Tue Feb 5 00:44:27 2008 - PASS
Mon Feb 4 23:43:44 2008 - PASS
Wed Jan 30 14:22:14 2008 - PASS
Status
System
CHT
Status
OK
VP Runs
633
Archived Events
1448

Sensor Line Clog

Clogged pressure switch gauge line VCT orifice before (left) and after (right) cleaning in response to a casualty.

Clog Signature

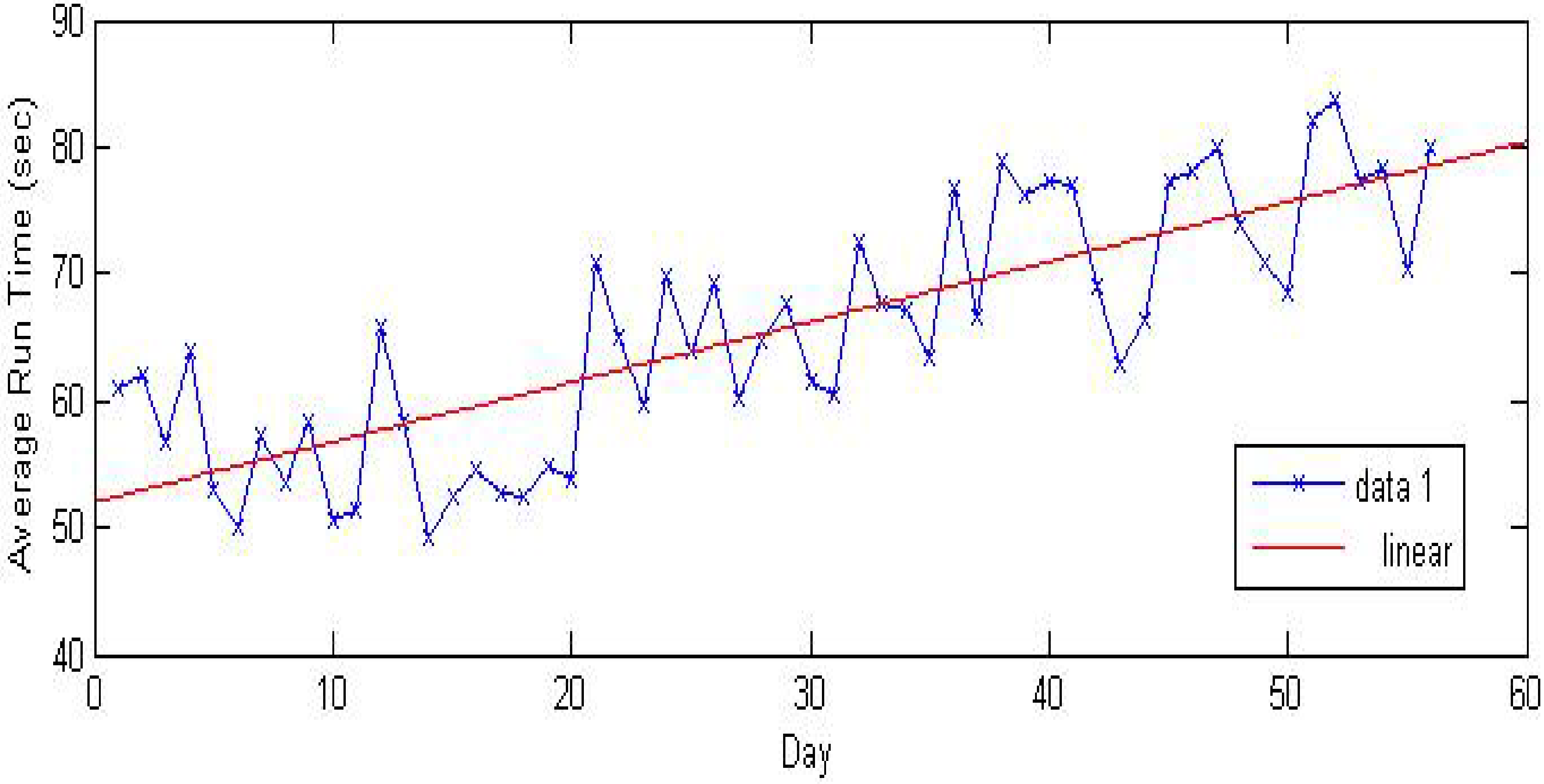




Normal three-hour power plot (top)

Pressure switch casualty power plot (bottom).

Clog Signature

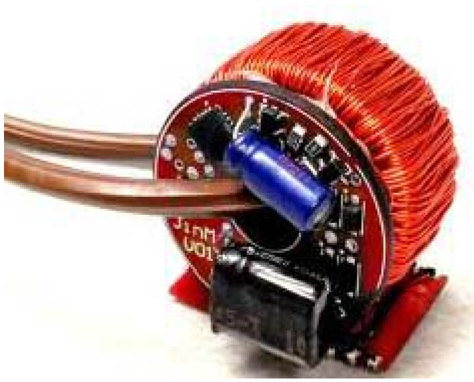


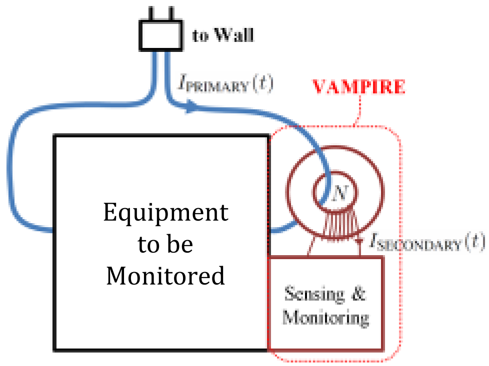
When nonintrusive is tough….

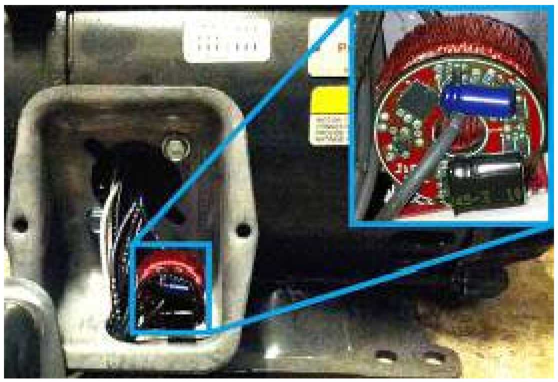
VAMPIRE Power Electronics

VAMPIRE

Vibration Assessment Monitoring Point with Integrated Recovery of Energy



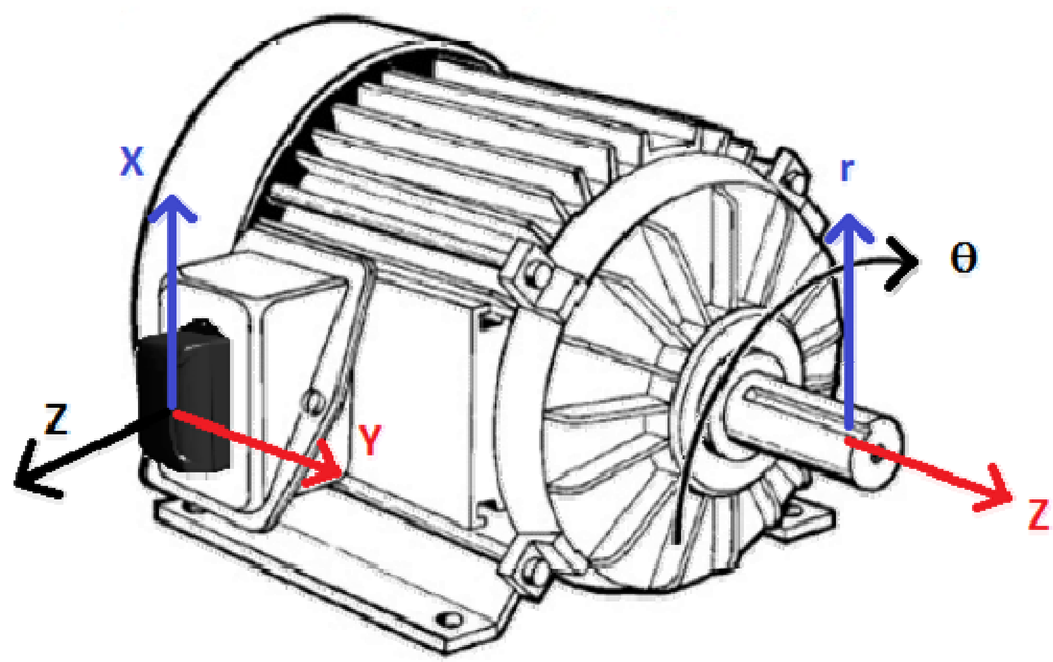




- Motives
  - Minimally intrusive
  - No battery & No special power wiring
  - No data wiring: wireless communication
  - Service-free after the installation

Vibration Monitoring

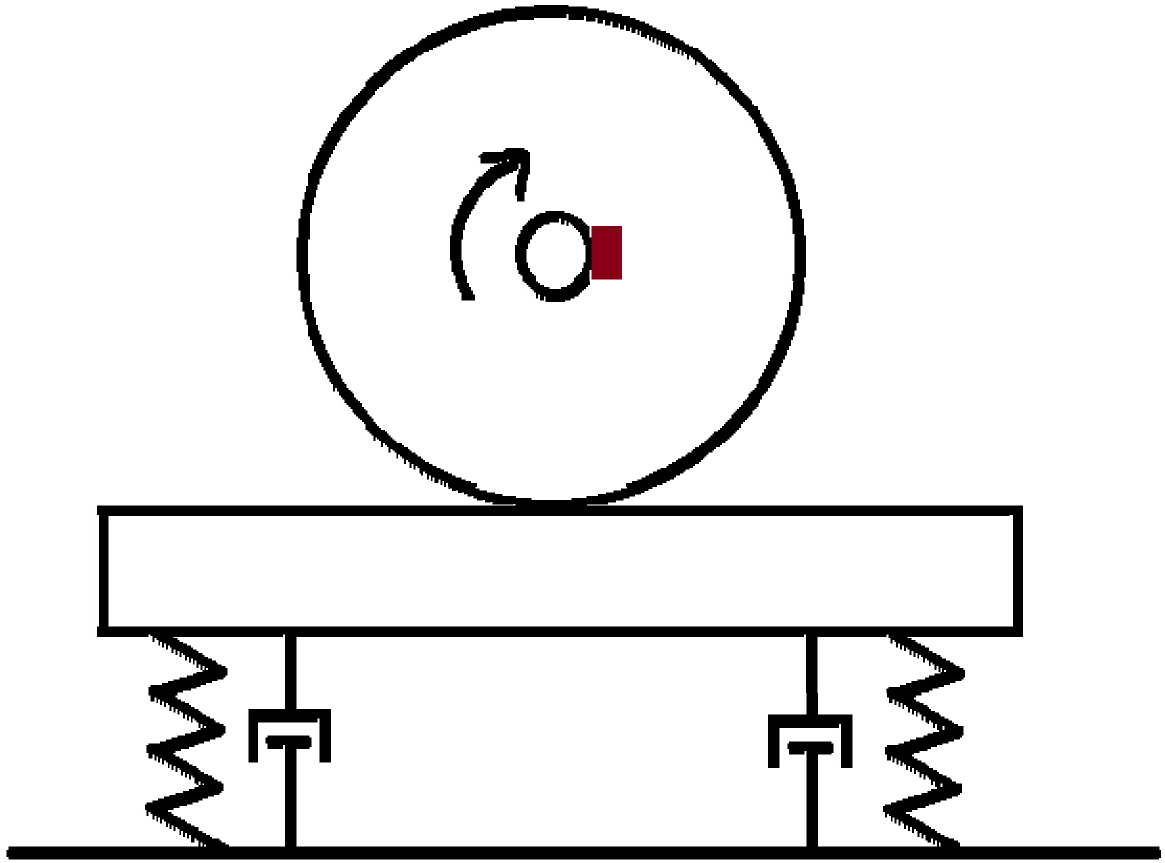
- Data logger (up to 32 Gb)
- 140 g mass, affixed rated to 4kg
- 3 axis acceleration at 3.2 kHz bandwidth



Machine Imbalance for Virtual Vibe Input

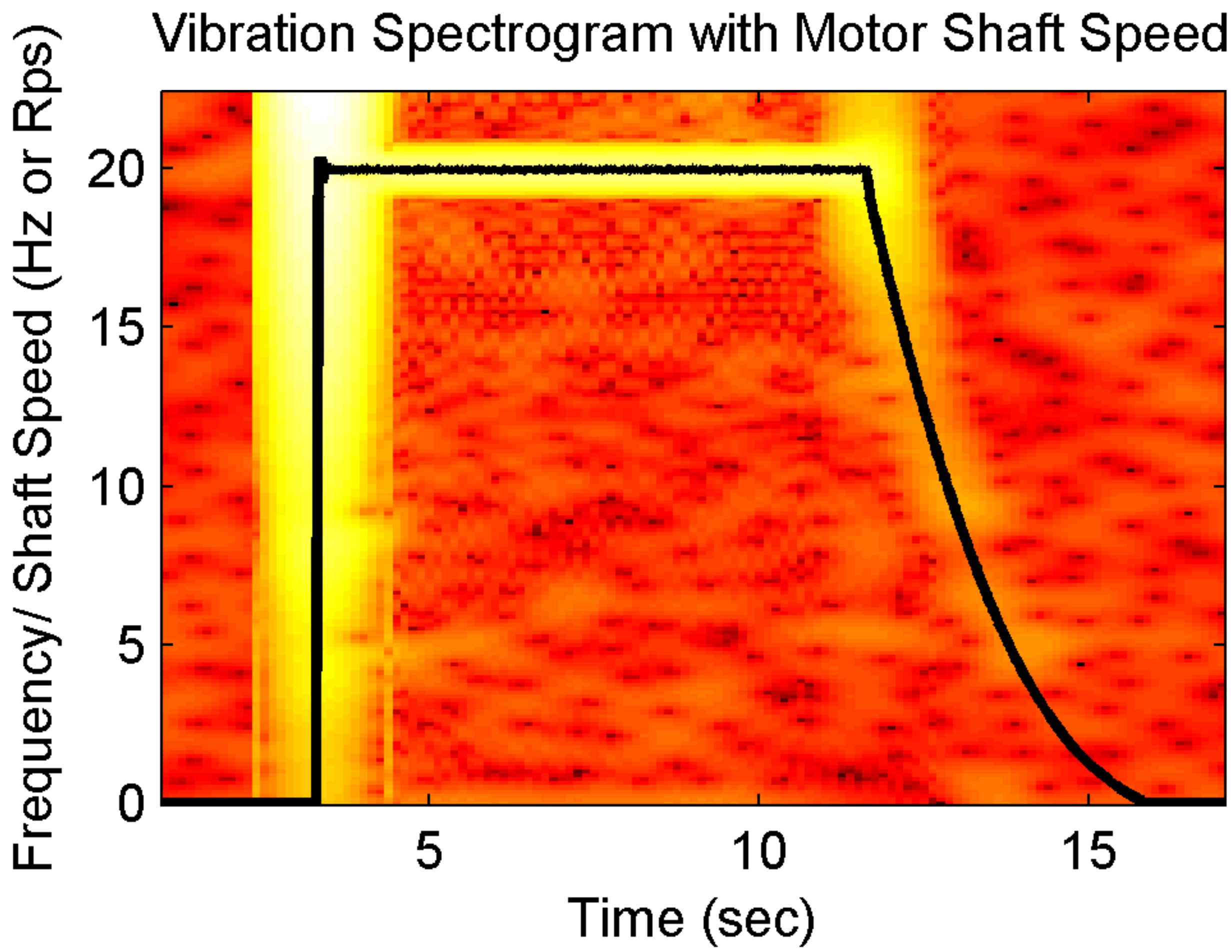
Rotating Imbalance:

- Amplitude proportional to speed squared
- Freq equal to shaft speed
- Sweeps Vibration Mounting Resonance

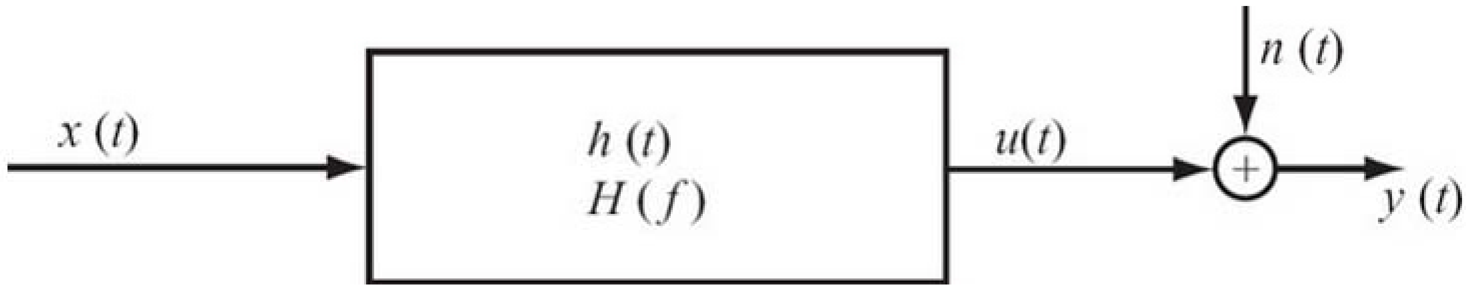


Mounting System Identification

- Virtual Vibration Input from Spin-down
- Measured Vibration Output



H1 FRF Estimator



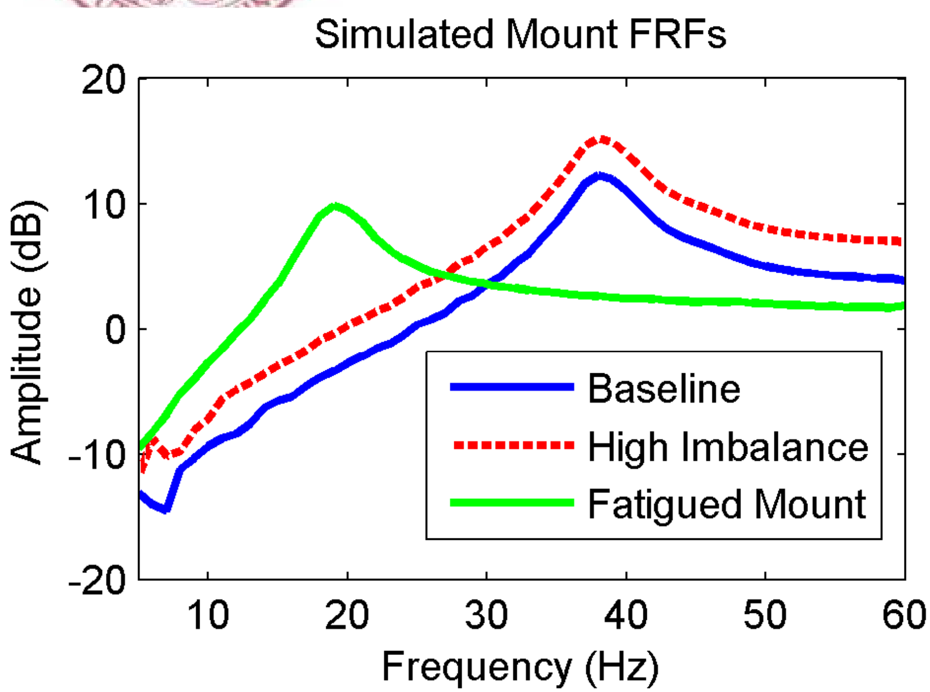
$$Y(f) = X(f)H(f) + N(f)$$

$$H1(f) = G(XY)(f)./G(XX)(f)$$

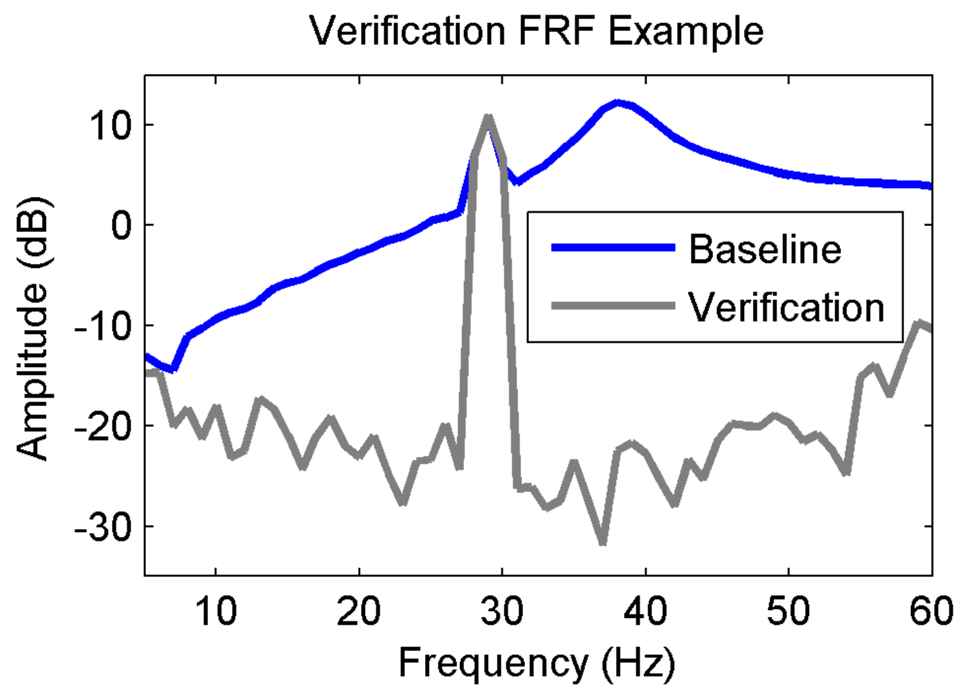
- Virtual Vibration Input from Spin-down: x(t)
- Measured Vibration Output: y(t)
- Noise/uncorrelated signal from environment: n(t)

Figure Credit: Noise and Vibration Analysis: Signal Analysis and Experimental Procedures by Anders Brandt

Mounts and Error Check



(a)



(b)

- Simulated Mount Condition FRF (a)
- Check for Steady Environment Error With Delayed Signal FRF (b)

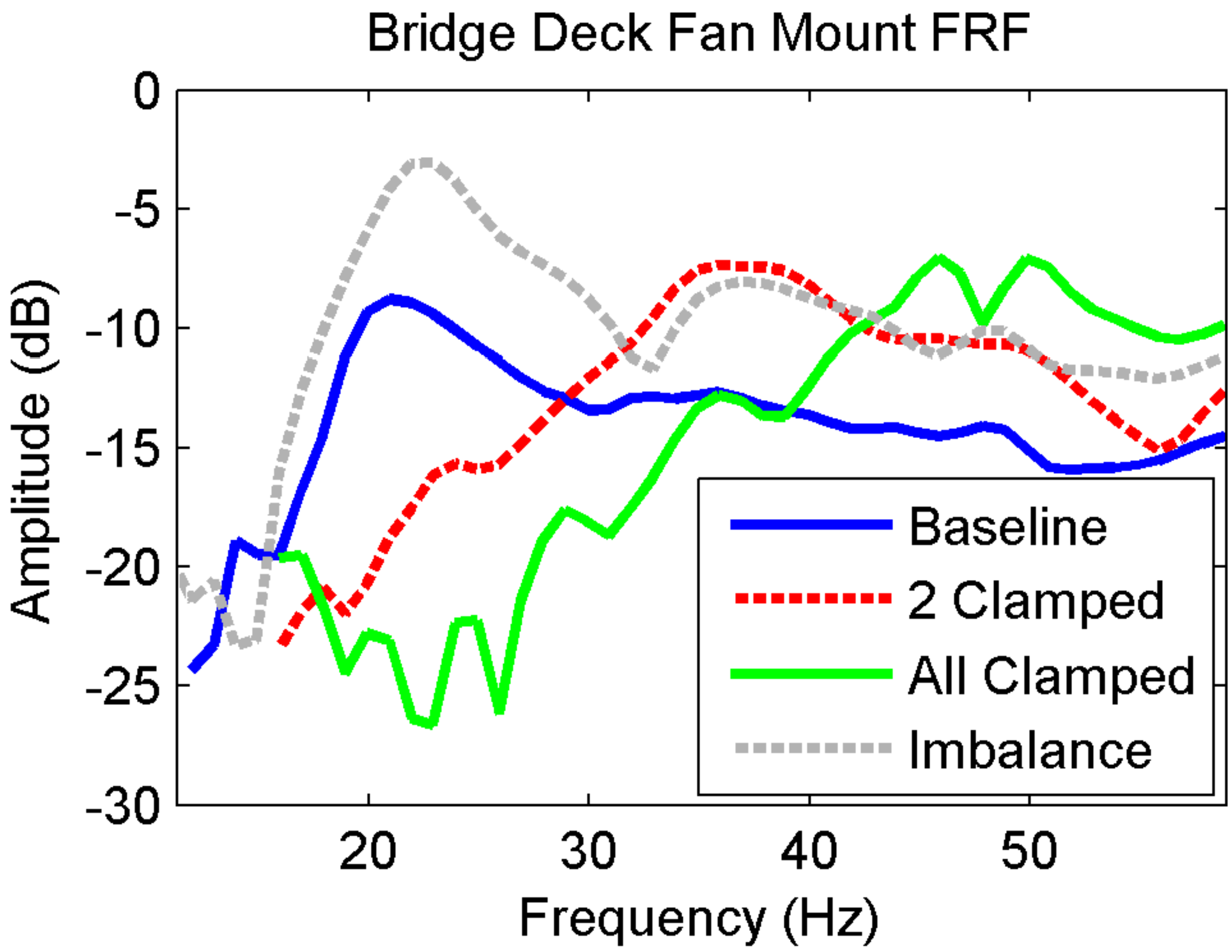
USCGC SENECA

Experiment USCGC SENECA Vent Fan

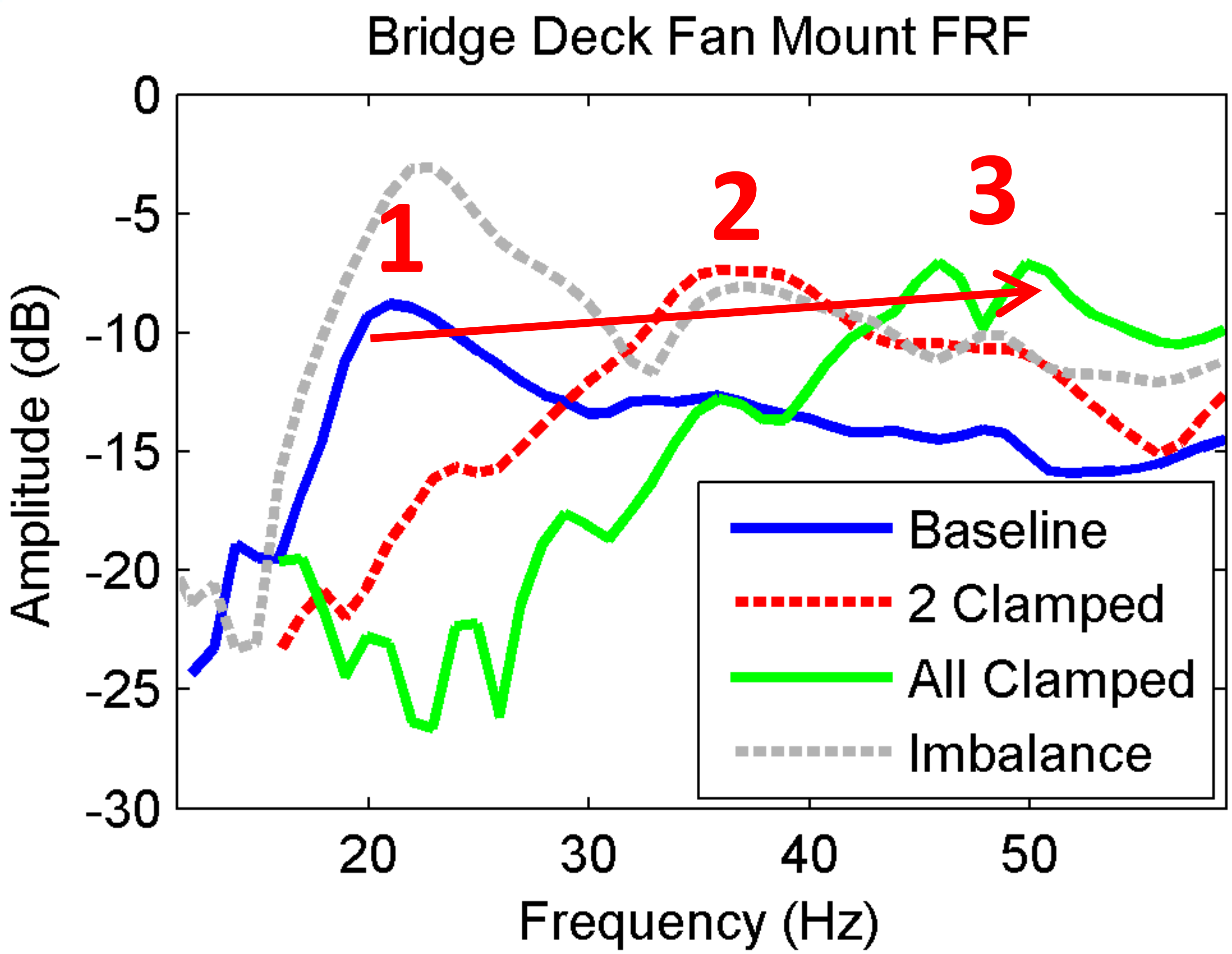
Mount Stiffening

Fan Imbalance Wire Bundle

SENECA Fan FRFs



SENECA Fan FRFs



- Increasing Stiffness and Resonance Frequency

Wire less sensors…

An opportunity to look at your system or product and squeeze it for more…