Wind Turbine Testing

Why Test?

- Limited number of machines suitable for polar applications
- Identify the good and bad machines
- Identify the good and bad manufacturers
- Gain familiarity with the systems
- Decrease failure rates to promote greater project success

PFS-South Test Site

- 8,200’ elevation in southern Colorado
  - Air density 20% less than sea level
- Subject to very high wind speeds
- Also (we know now) extreme turbulence
- Fairly cold temps – but not polar cold
- Accessibility: Ability to monitor in person and remotely
- No difficult code or zoning issues
- No permit required

The Testing Setup

- 50’ guyed, tilt-up type tower from SWWP provides economical system, easy to access turbine (about 15 - 20 minutes to lower)
- Robust foundation and grounding system
- 2.5” schedule 40 pipe can handle up to 1kW machines
- WLAN/broadband satellite communications
- APRS World supplied monitoring system
- Back-up solar (PV) system to keep batteries charged

Earth Grounding Detail

Foundation Detail

Raise/Lower System

Initial Tower Raising

What Machine to Test?

- APRS World - WT10/14
  - Nicely balanced design
  - Light yet powerful
  - 3-Phase AC output from turbine
  - Black finish
  - Designed for fast field installation
  - Reconfigurable for different wind regimes
  - Initial discussions suggested an interested and engaged manufacturer

WT14 Wind Turbine

- 3 blades, horizontal axis, upwind
- Rotor
  - 1.4 m (4.7 ft) rotor diameter
  - Glass filled nylon blades
- Generator
  - Permanent magnet
  - 3Ø
  - Variable voltage and frequency
  - 1kW nominal capacity
- 11 kg (24 lbs) weight

WT14 Manufacturer Ratings

- Battery charging 24 or 48 volt battery
  - 4.5 m/s (10 MPH): cut in speed
  - 5.4 m/s (12 MPH): 50 watts!
  - 13.5 m/s (30 MPH): 300 watts
  - 55 m/s (123 MPH): survival speed

- *“Optimized for power production in moderate wind regimes. Survives occasional intense high wind.”*

WT10 Wind Turbine

- 3 blades, horizontal axis, upwind
- Rotor
  - 1.0 m (3.3 ft) rotor diameter
  - Glass filled nylon blades
- Generator
  - Permanent magnet
  - 3Ø
  - Variable voltage and frequency
  - 1kW nominal capacity
- 10 kg (23 lbs) weight

WT10 Manufacturer Ratings

- Battery charging 24 or 48 volt battery
  - 4.5 m/s (10 MPH): cut in speed
  - 13.5 m/s (30 MPH): ~300 watts
  - 31.5 m/s (70 MPH): ~750 watts
  - >70 m/s (>157 MPH): survival speed
- *"Optimized for high wind energy sites."*

WTAPRS Polar Relevant Features

- Light weight and compact
- Installation
  - Tool less assembly while wearing gloves
    - Connectorized electrical (standard)
    - Quick attach tail (standard)
    - Quick attach blades (option)
    - Quick attach to mast (option)
  - Very quick installation
  - Materials selected for resilience at low temperatures
  - Easy to rig
    - Carabineer hole for lifting
    - Can be attached to harness and carried up tower

WTAPRS Polar Relevant Features (continued)

- Operation
  - Entirely sealed
    - O-rings for chassis components
    - Sealed bearings
  - Black to promote ice melt
  - Anodized aluminum and stainless steel hardware
  - No electronics in turbine

Test Setup

- Independent autonomous system
- Charges 24 volt battery
- Excess power is dumped to dump load
- Turbine and meteorological data
  - Logged to SD card
  - Sent via 802.11b / Hughes to WorldData
  - Sent via APRS World / SPOT Modem to WorldData

Test Setup – Meteorological Sensors

Meteorological Sensors

- Anemometer and wind vane
  - At ~45ft up tower on sensor boom
- Temperature
  - At ~6ft on tower in solar radiation shield
  - Enclosure temperature
- IP Camera
  - Turbine and top half of tower

Turbine Sensors

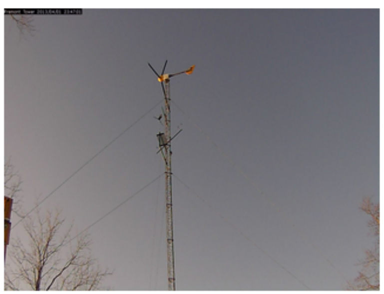
- Battery voltage
- Turbine current
- Turbine RPM
  - Sensed from turbine wild AC
- Dump load
  - Duty cycle (% of available load)
  - kWh dumped
  - Battery temperature

Live (Internet) Data Website

WTAPRS Fremont - Mozilla Firefox

File Edit View History Bookmarks ScrapBook Tools Help

Web Cameras



Weather / Turbine RPM

	GL Tower XRW1: view_A2744_wtaprs
Report Date:	9 seconds ago 2013-04-01 23:47:02 UTC
Anemometer 0:	14.3 MPH average 14.8 MPH gusting to 16.0 MPH
Anemometer 1:	13.4 MPH average 11.6 MPH gusting to 16.1 MPH
Wind Vane:	297°
Turbine RPM:	600 RPM average 621 RPM gusting to 666 RPM
48V Turbine Output:	99 watts average (1.802 amps @ 55.20 volts) 102 watts now (1.857 amps @ 55.20 volts)
Temperature (LM335 Sensor):	-0.7°C / 30.7°F
Temperature (Water System):	16.5°C / 61.7°F
Temperature (Workbench):	16.8°C / 62.2°F
Power Source Voltage:	11.9 VDC
XRW2G Uptime:	65,535 minutes

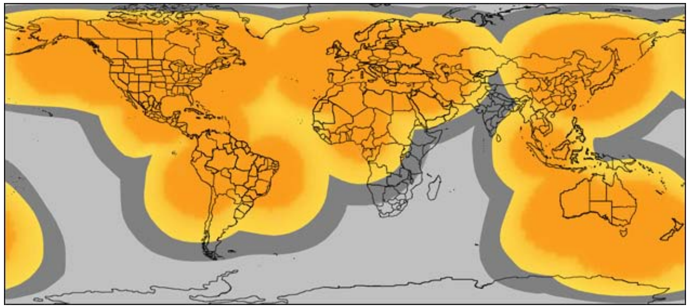
Dump Controllers

	48 Volt Battery System TS1: tristar_A2744_11190011
Report Date:	9 seconds ago 2013-04-01 23:47:02 UTC
Calculated Power:	89 watts
Battery Voltage:	55.20 VDC
Load Current:	1.61 amps
Dump PWM Duty Cycle:	3.9%
kWh Dumped:	118 kWh
Amp Hour Total:	37,629 amp hours
Hours:	6,830 hours
Heatsink Temperature:	27°C / 80°F
Battery Temperature:	19°C / 66°F
State:	PWM
Alarm:	No Alarms
Fault:	No Faults

Note: This screenshot isn't from Tracy's PFS site due to internet bandwidth limitations. This is a test unit in Minnesota. Live data at: http://data.aprsworld.com/sites/wtaprs/fremont/

Telemetry - Satellite

- APRS World / SPOT Satellite Telemetry
  - Globalstar network
  - Low cost SPOT network
  - <$400 hardware & <$100 year data
  - 6 hour highly compressed message with
    - Wind speed / gust / average
    - Turbine RPM / average RPM / current
    - Temperature
    - Dump Load kWh, duty cycle, battery temperature
    - Battery Voltage



Satellite Telemetry Data Website

Example of "live" data:

Data Date:	2013-04-02 00:01:07 UTC Report received 04:40:49 (hours:minutes:seconds) ago.
Historical Data:	All Historical Data
Dump Load All values are reported by TriStar and not independently measured.	
Battery Voltage:	24.4
kWh Dumped:	38
Duty Cycle:	0%
Battery Temperature:	16°C / 60°F

Environmental	
Wind Speed from Anemometer 0:	4.2 m/s / 9.4 MPH
Wind Speed from Anemometer 1:	0.0 m/s / 0.0 MPH
Wind Gust from either Anemometer:	8.4 m/s / 18.8 MPH
Turbine RPM:	0 RPM
Turbine Gust RPM:	0 RPM
Turbine Current:	1.8 amps
Outdoor Ambient Temperature:	10°C / 50°F

Example of historical data:

February 2013										
Date (UTC)	Dump Load				Environmental					
	Voltage	kWh Dumped	Duty Cycle	Battery Temp	AN0	AN1	Gust	RPM	Max RPM	Outdoor Temp
2013-02-10 12:06:35	30.2 VDC	34 kWh	55%	1°C / 33°F	8.8 m/s / 19.6 MPH	0.0 m/s / 0.0 MPH	28.9 m/s / 64.7 MPH	1061 RPM	3870 RPM	-7°C / 19°F
2013-02-10 00:00:37	29.9 VDC	34 kWh	72%	6°C / 42°F	17.2 m/s / 38.5 MPH	0.0 m/s / 0.0 MPH	25.0 m/s / 56.0 MPH	2033 RPM	3636 RPM	-5°C / 22°F
2013-02-09 06:00:37	25.9 VDC	34 kWh	0%	4°C / 39°F	0.5 m/s / 1.2 MPH	0.0 m/s / 0.0 MPH	12.3 m/s / 27.5 MPH	0 RPM	1132 RPM	-1°C / 29°F
2013-02-08 18:00:37	28.5 VDC	34 kWh	1%	5°C / 41°F	4.1 m/s / 9.1 MPH	0.0 m/s / 0.0 MPH	13.1 m/s / 29.4 MPH	805 RPM	1212 RPM	8°C / 46°F
2013-02-08 12:00:38	24.9 VDC	34 kWh	0%	-1°C / 30°F	0.0 m/s / 0.0 MPH	0.0 m/s / 0.0 MPH	4.1 m/s / 9.2 MPH	0 RPM	0 RPM	-5°C / 22°F
2013-02-08 06:06:35	25.0 VDC	34 kWh	0%	4°C / 39°F	1.7 m/s / 3.9 MPH	0.0 m/s / 0.0 MPH	4.1 m/s / 9.2 MPH	0 RPM	0 RPM	-4°C / 24°F

WT14 @ PFS-South

- Installed 2012-11-25
- Instrumentation not completely commissioned
- Produced energy, lots of it
  - ~45 kWh total production to 2013-01-11
- Wind events
  - Anemometer not connected
  - RPM data implies multiple storms

WT14 Failure 1 @ PFS-South on January 11, 2013

- Problems
  - Internal permanent magnet generator failure
    - Rotor became detached from main shaft
  - Hub / main bearing interference
    - Rotating part wore and came in contact with non-moving nose of turbine
  - Yaw
    - Turbine would yaw 360° in high winds

Video of turbine yaw in high winds: http://youtu.be/LIp3uZJ5oC8

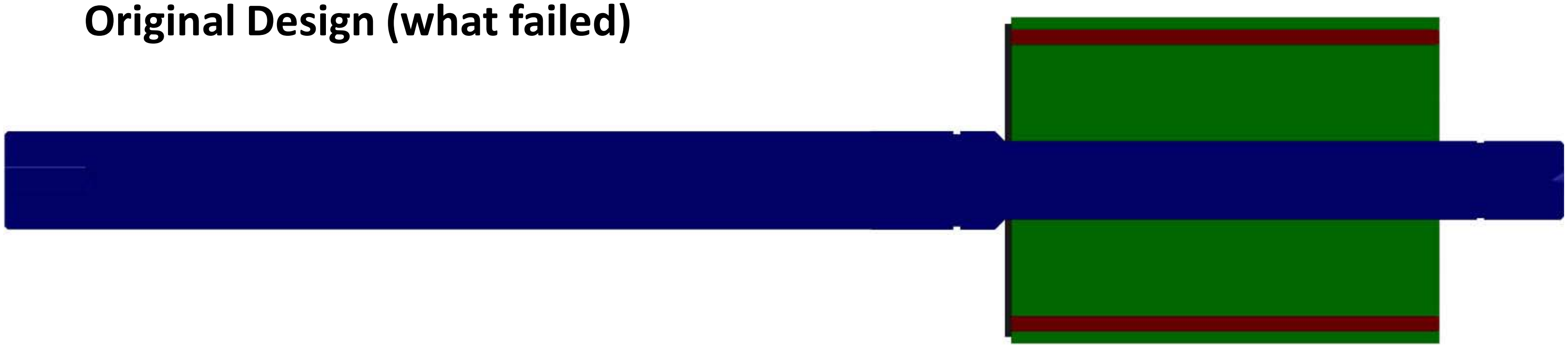
WT14 Failure 1 Causes: Permanent Magnet Generator Failure

- Known weakness in design of rotor to shaft interface
  - Manufacturer is beginning to manufacture improved design with multiple rotor to shaft retention features
- Manufacturer attributes to wind event exceeding ratings of turbine and exasperating known design weakness

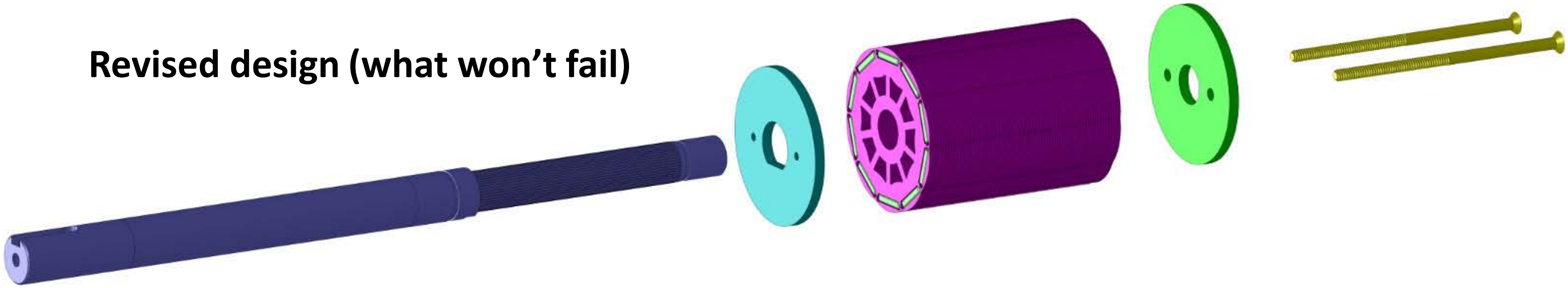
Failed Rotor / Shaft

PMG Rotor Shaft Detail

Original Design (what failed)



Revised design (what won't fail)



WT14 Failure 1 Causes: Hub / Main Bearing Interference

- Defect in design
  - Previous generations had much larger gap between rotating hub and fixed body
  - Smaller gap adopted to minimize area for ice accumulation
  - Wear in component allowed surfaces to rub
- Manufacturer attributes to design defect and premature failure caused by ***excessive turbulence*** in high winds.

Hub / Main Bearing Photo

WT14 Failure 1 Causes: Excessive yaw

- Intrinsic to design of high speed wind turbine
  - Similar behavior documented in many other small high speed wind turbines
- Larger tail was installed
  - Appeared to stabilize the machine – up to a point
- Manufacture argues that excessive yaw is due to site turbulence

  - WT10 has not exhibited yaw instability

Air-X wind turbine exhibiting the same yaw behavior: http://youtu.be/5ilfsqQAULE

WT14 Failure 2 @ PFS-South on 2013-03-04

- Turbine failure in high wind 40 m/s (90 MPH) event
  - Loss of blades
    - All three blades broke at root
    - Root of blades remained bolted to hub
  - Bent tail
    - ~15 degree bend in PROTOTYPE larger tail

WT14 Failure 2 Causes: Loss of Blades

- Hypothesis: Blade injection molding process / mold design causes weak spot at location where blades failed
- High wind events / rotor over-speed stress the blades and caused failure
- Manufacturer is modifying injection molding tooling to eliminate week spot around hold in blade
- Manufacturer attributes failure to turbine exceeding survival speed and design defect in blade tool.

Induced blade failure test by manufacturer: https://www.youtube.com/watch?v=riGjq9Arlec

WT14 Failure 2 Causes: Bent Tail

- Damage to turbine housing where tail installs indicates large motion in tail.
- Likely caused by unbalanced momentary operation of the turbine with 1 or 2 blades.
- Note: This was a prototype tail that is larger than production WT14 tail. Increased size has larger moment and may exceed yield strength of material.

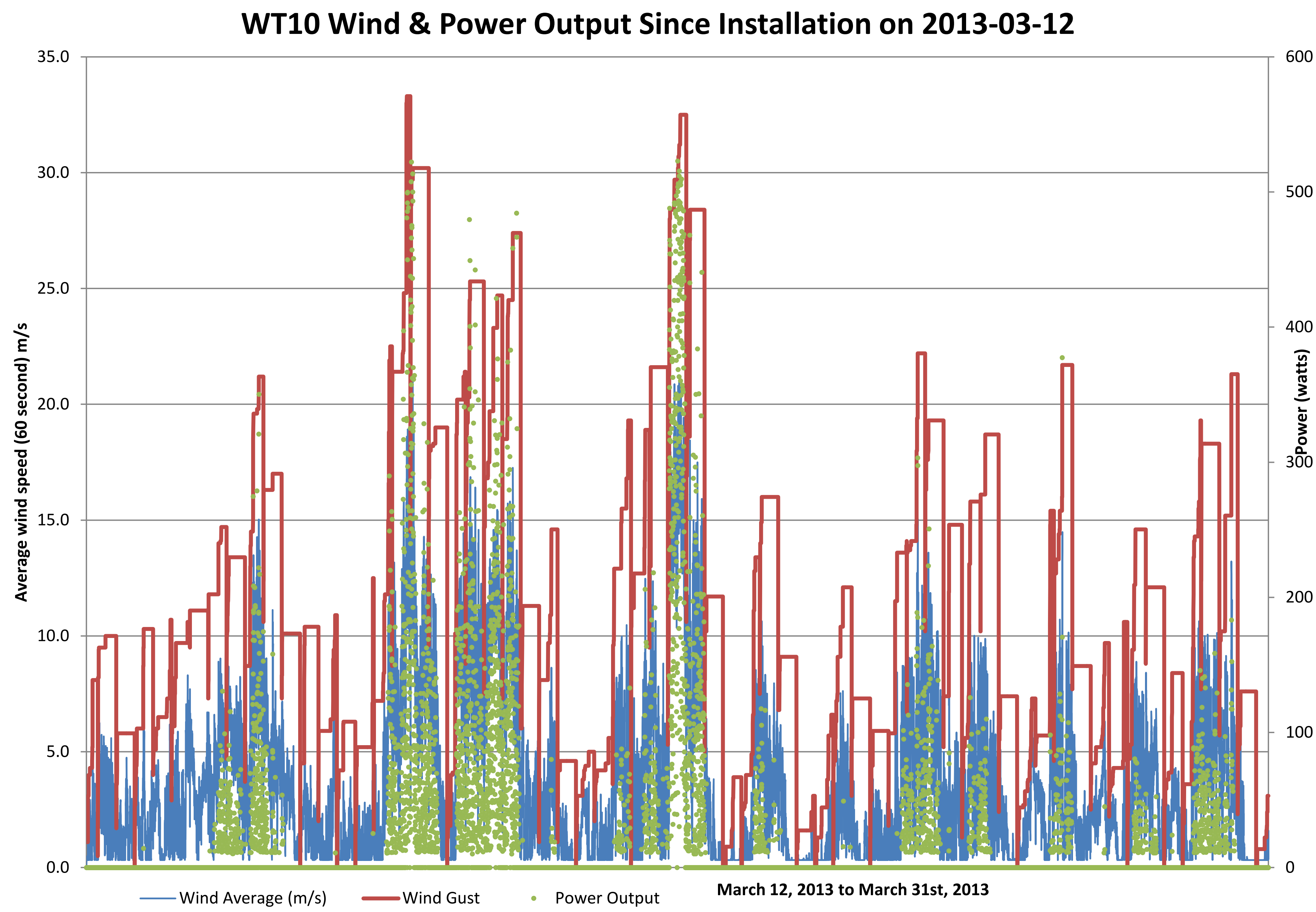
WT14 Failed Blade and Tail

Tracy’s WT14 Observations

- Excellent low speed (12 mph)to mid speed (40 mph) wind performance
- Loud and scary in high wind (>50 mph)
- > 100dBA @ 70+ mph wind speeds
- Not currently suitable for use in high wind areas
  - Design improvements may help
- Not good for turbulent wind!

WT10 @ PFS South

- Installed 2013-03-12



WT10 Wind & Power Output Since Installation on 2013-03-12
Average wind speed (60 second) m/s
Power (watts)
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
600
500
400
300
200
100
0
Wind Average (m/s)
Wind Gust
Power Output
March 12, 2013 to March 31st, 2013

WT10 Observations

- Quiet operation
- Higher starting speed
- Stable operation

Conclusions

- Testing has been mutually beneficial
- WT10 is a solid performer for high speed/turbulent wind regimes, but may not be optimal for lower wind speed areas like North Slope
- WT14 performs very well at low to moderate speeds, but cannot (currently) withstand prolonged high/turbulent winds

Conclusions Continued

- The basic APRS World design is solid, continually improving and suitable for polar applications.
- The ability to reconfigure for different wind regimes seems like a very desirable feature.
- Very cold weather performance not yet qualified, but should be good.
- Possibility for polar extreme model (e.g., ceramic bearings)??
- Great to work with a willing and engaged manufacturer.
  - APRS World is looking for looking for polar testing oprotunities

Questions and Comments?

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Information on the WT10 and WT14 at:
http://www.aprsworld.com/wtaprs/