

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

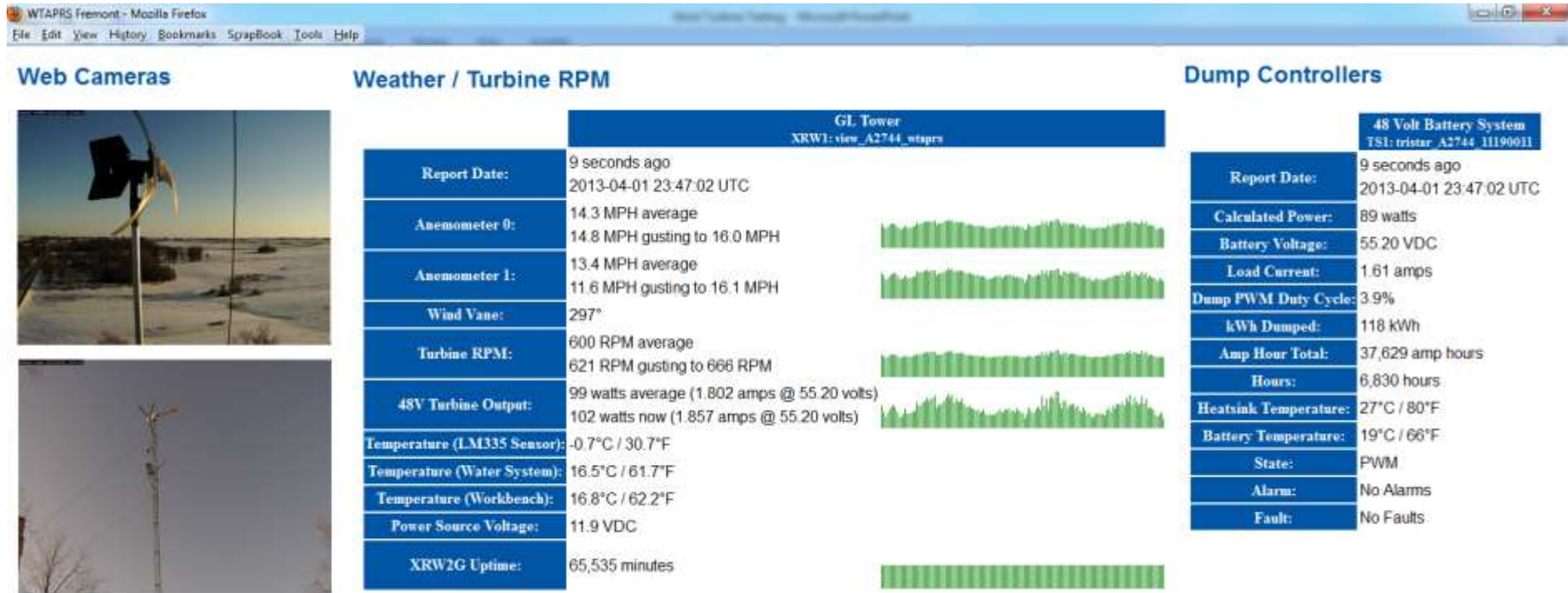
Meteorological Sensors

- 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

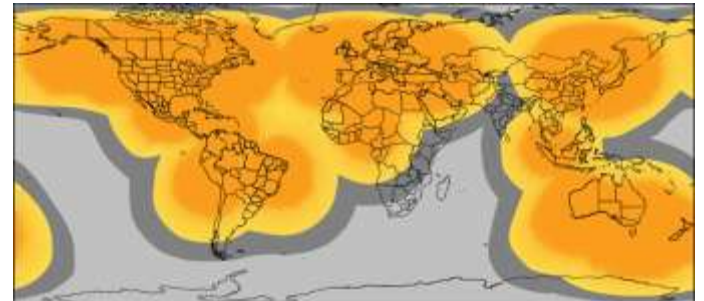
Live (Internet) Data Website



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



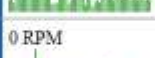



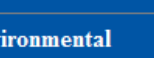
- APRS World / SPOT Satellite Telemetry
 - Globalstar network
 - Low cost SPOT network
 - <\$400 hardware & <\$100 year data
 - 6 hour highly compressed message with
 - Wind speed / gust / average
 - Turbine RPM / average RPM / current
 - Temperature
 - Dump Load kWh, duty cycle, battery temperature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

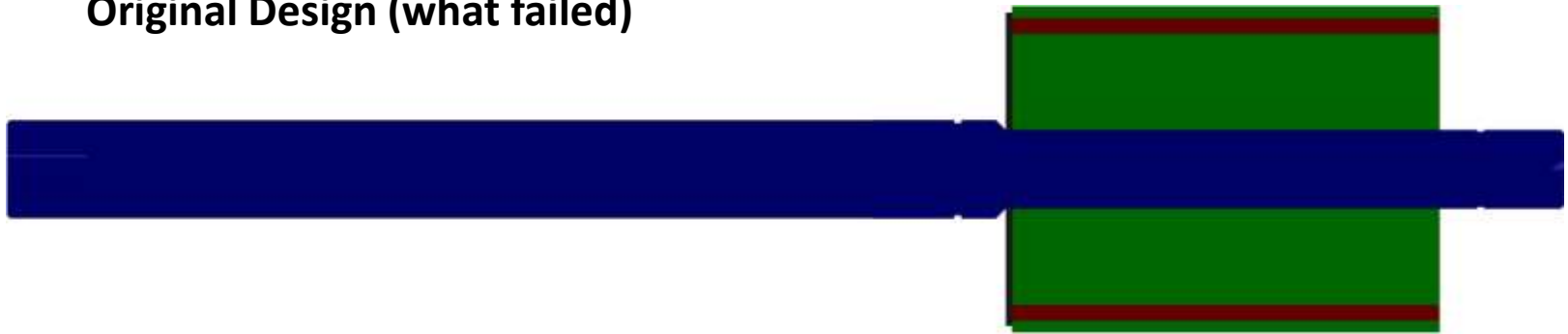
- Known weakness in design of rotor to shaft interface
 - Manufacturer is beginning to manufacture improved design with multiple rotor to shaft retention features
- Manufacturer attributes to wind event exceeding ratings of turbine and exasperating known design weakness

Failed Rotor / Shaft

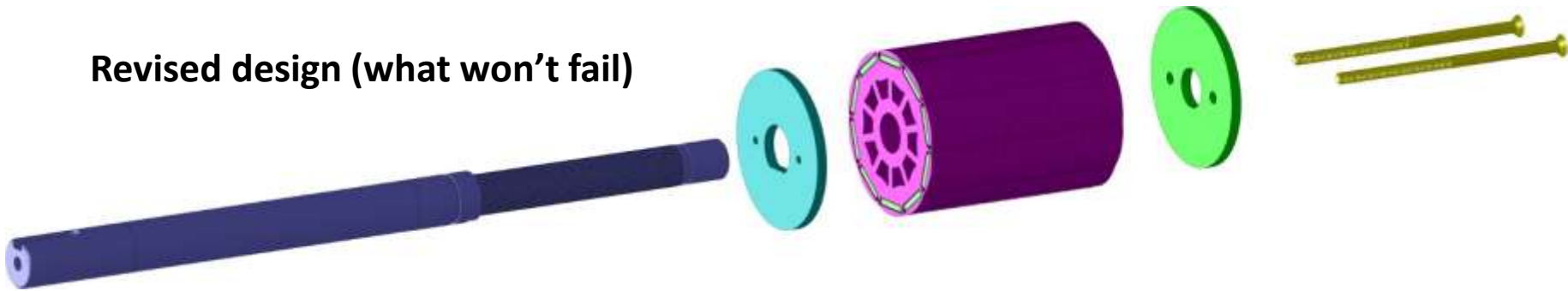


PMG Rotor Shaft Detail

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
 - Bearing wear 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 weak 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 exceeded yield strength of material.

WT14 Failed Blade and Tail



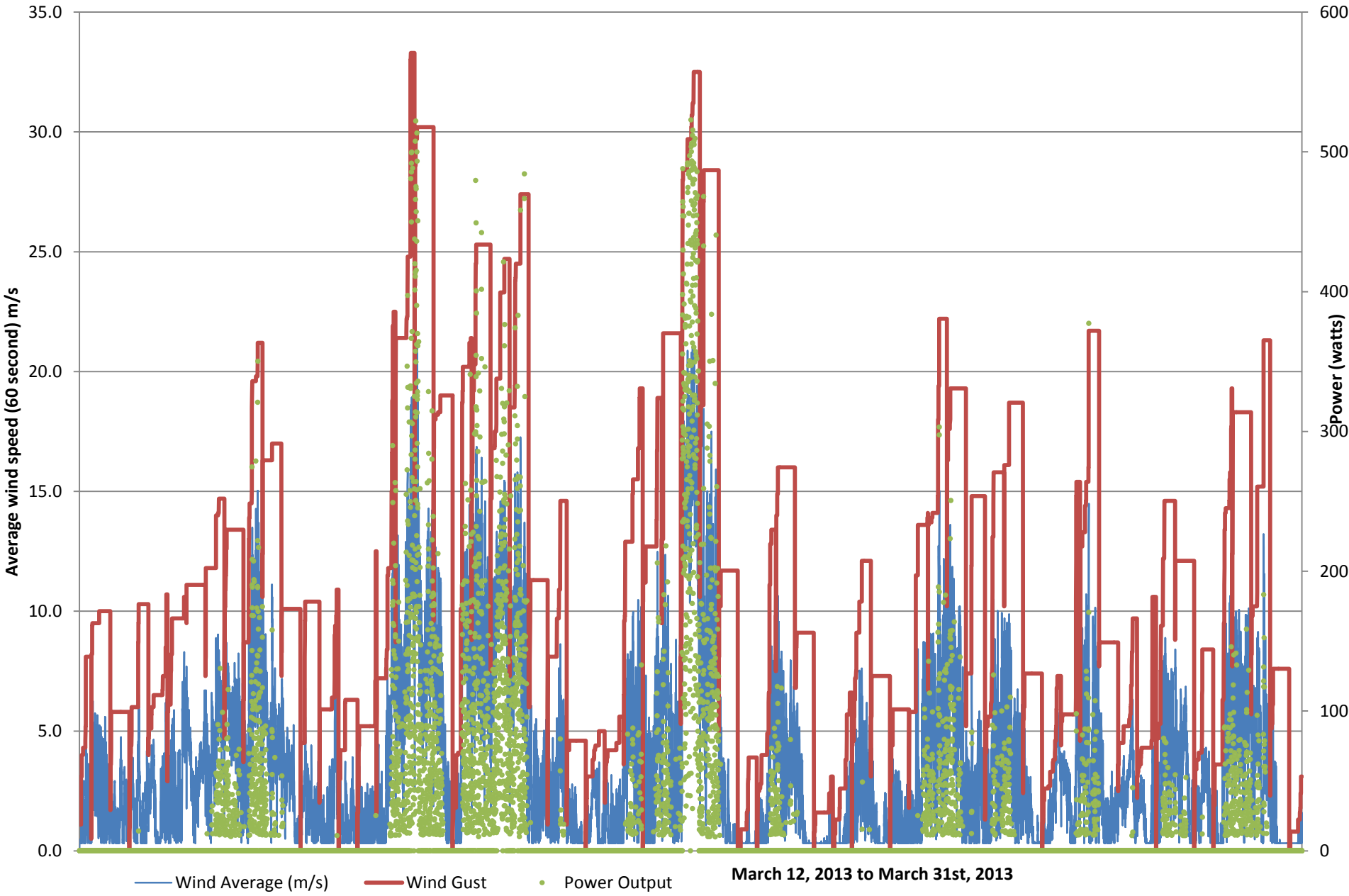
Tracy's WT14 Observations

- 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



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 opportunities

Questions and Comments?

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