Arm Energy Probe Basics

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Arm Energy Probe Basics

- What it is
- Quick electronics 101 recap
- Measuring around regulators
- Wiring your board for AEP usage
- Some actual measurements
- Major sources of measurement error
- Linux Commandline tool

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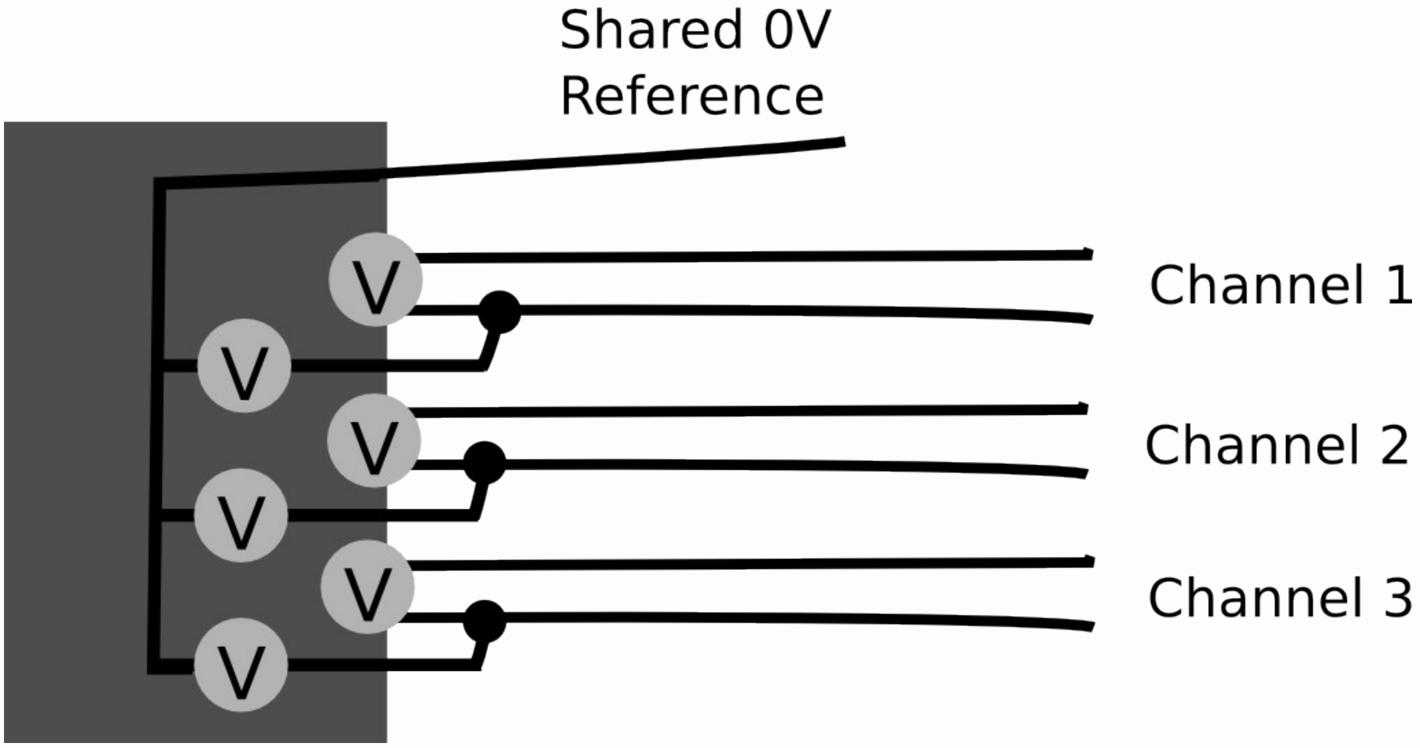
Understanding what it is

- It's a 3-channel USB voltmeter, two voltages reported for each channel



Understanding what it is

- The first voltage (up to 30V) is measured between one of the sense leads and 0V
- The other is an amplified (differential) measurement of the voltage between the two sense leads, limited to 165mV
  - These amplified channels are used to measure the voltage across shunts to calculate current
  - 165mV limit affects shunt resistance selection
  - Probe unable to measure currents below a few mA

USB side

- It has a Cortex M3 LPC1343 that appears to the host PC as a ttyACM CDC serial port class device
- Linux knows what to do with it
- Linaro has a commandline tool “arm-probe” which can drive it
- Check for other things touching ttyACM0!
  - Modem-manager from NetworkManager wants to fiddle with any ttyACM device it sees
  - Software initializes tty device to correct mode

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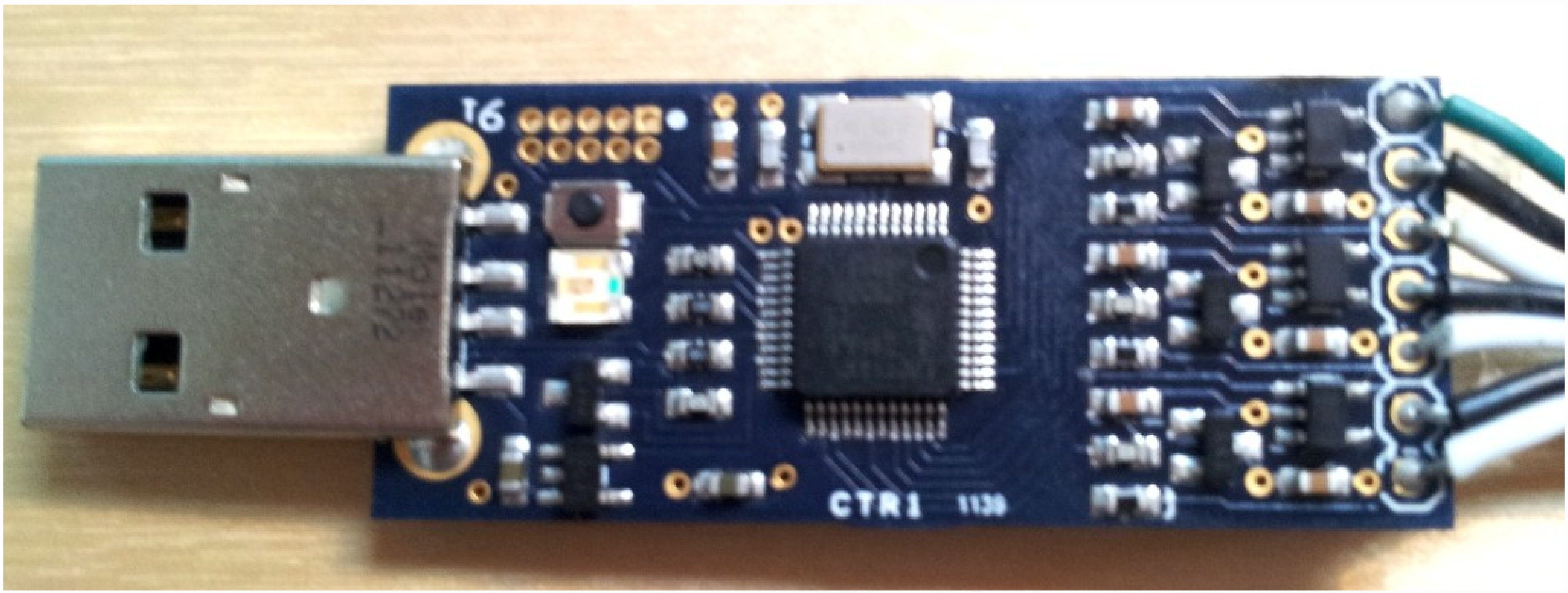
Hardware



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Practical problems...

- **Can only measure one channel at a time!**
  - **But we can capture one channel from all connected probes simultaneously**
    - **Max 3 captures needed for any number of channels**
- Probes do not have unique USB serial #
  - Cannot reliably be identified in multi-probe setup
  - Can probably be fixed by poking firmware and reflashing by hand
    - Reflashing only possible on Windows ^^

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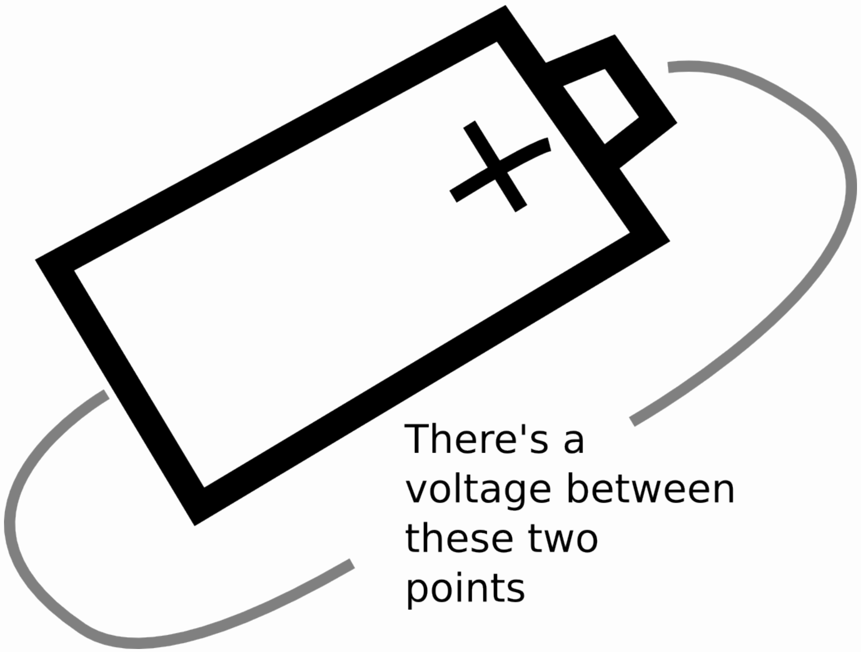
Voltage

- Voltage is the “potential difference” between two points, usually the power rail and a common “0V” or “ground” point, measured in Volts (V)



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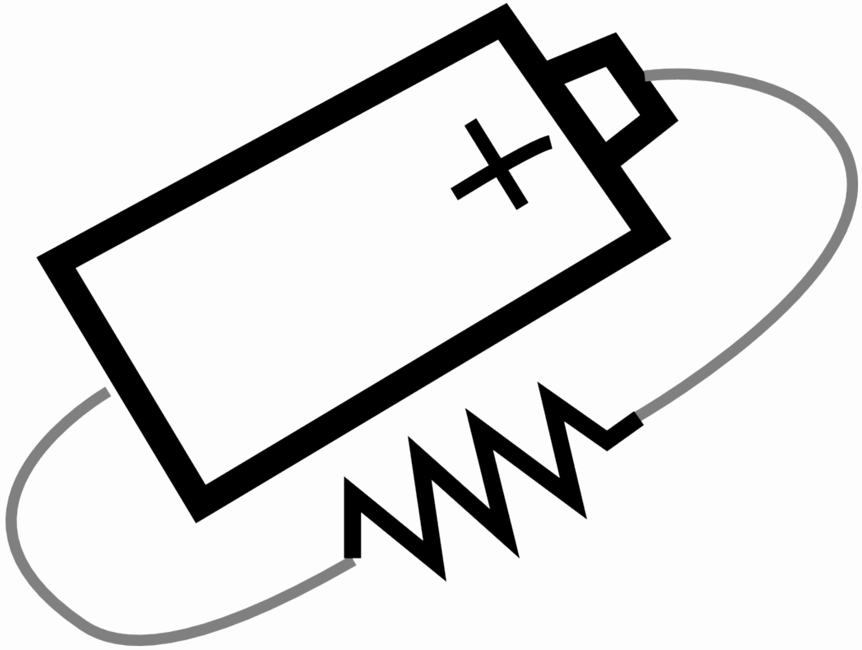
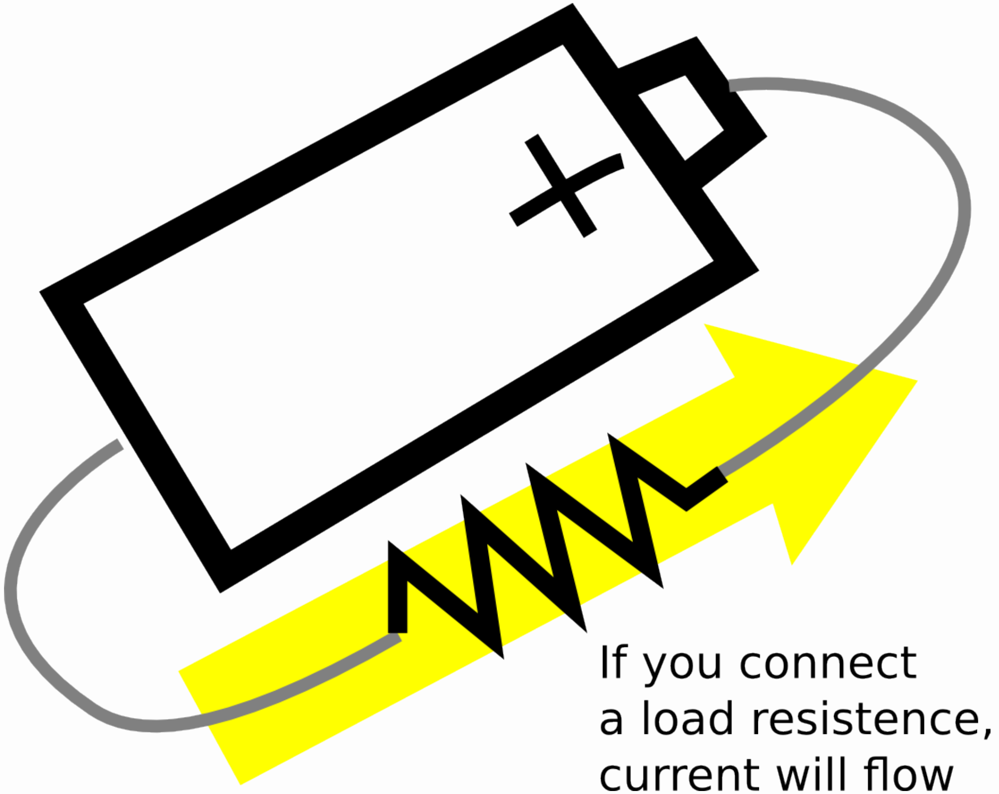
Load

- Load is a resistance (measured in Ohms or "R") you put between a voltage to make current flow



Current

- Current is a measure (in Ampere or A) of how much charge is moving through the circuit.



Power

- Power is the **voltage multiplied by the current** and is measured in Watts (W)
  - Even at low voltages a lot of power can be used if a lot of current is flowing
  - At high voltages, very little current needs to flow to use a lot of power
- Power is unique because it's the only way you can compare currents at different voltages

Some identities

- $I = V / R_{(load)}$
  - Into the same load, higher V makes more current flow
  - At the same voltage, higher load resistance makes less current flow
- $P = I \times V$
  - Lower V or I, less power
- $P = V/R \times V = V^2/R$
  - **Half voltage --> quarter power!**

Power is boss

- To talk about power, talking about voltage or current alone is useless
- P = IV so we need to talk about current AND voltage if we talk about either
  - Eg, “it takes 50mA”... 50mA at 1.2V == 60mW, 50mA at 5V == 250mW... which is it?
- Converting voltage and current measurements to power lets you compare measurements made at different voltages

However...

- If the voltage part of your measurement is constant, you can treat current part as a stand-in for being a scaled version of power
  - Shortcut is true if you are interested in relative changes in power local to same measured rail

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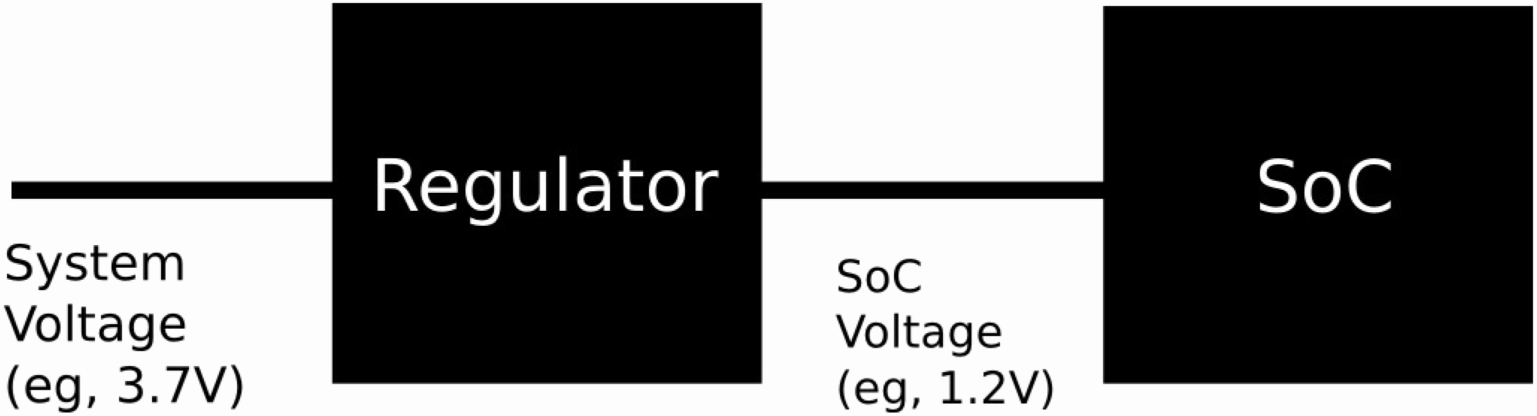
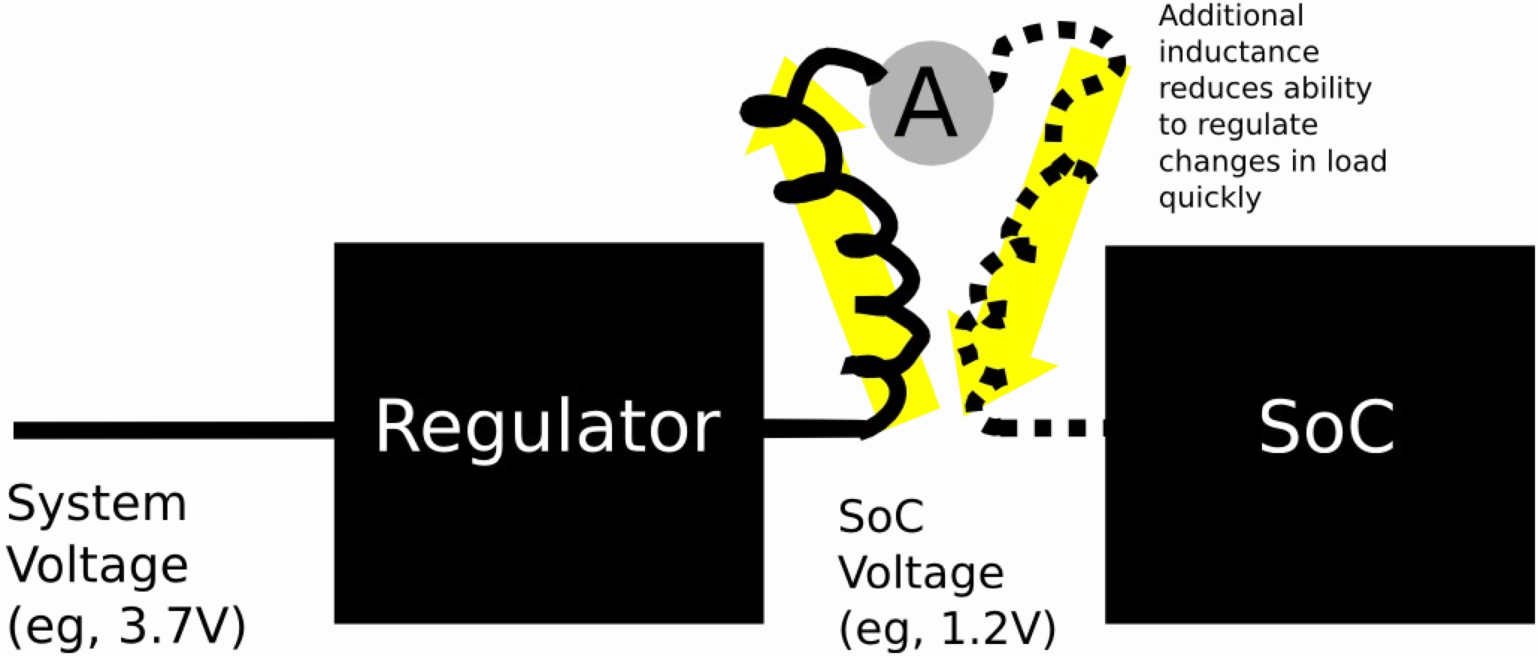
Regulator structure

- Regulators adapt a voltage source to provide a different voltage, even if the load is changing dynamically



Traditional current measurement

- Normally we would stick an ammeter in series with the load



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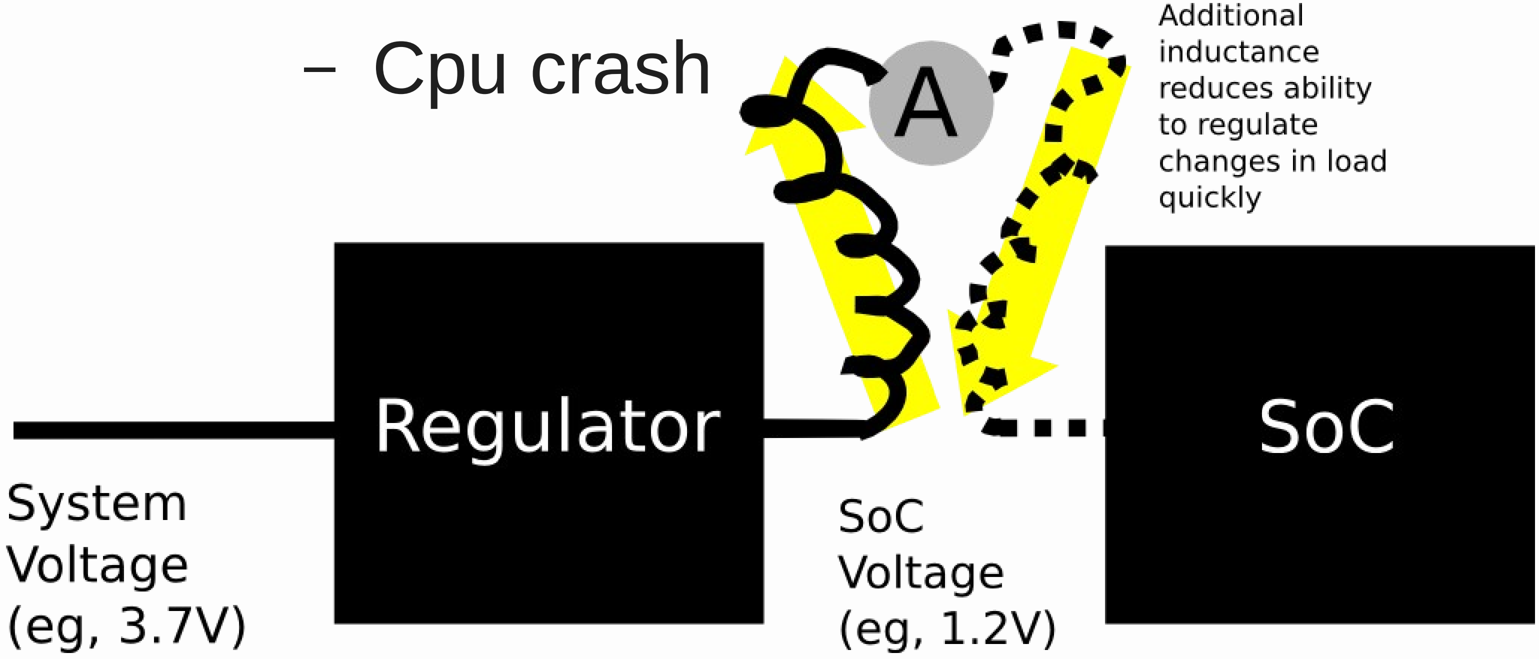
Traditional current measurement

- Regulator cannot “see” a fast-changing load clearly and fails to regulate
  - Cpu crash



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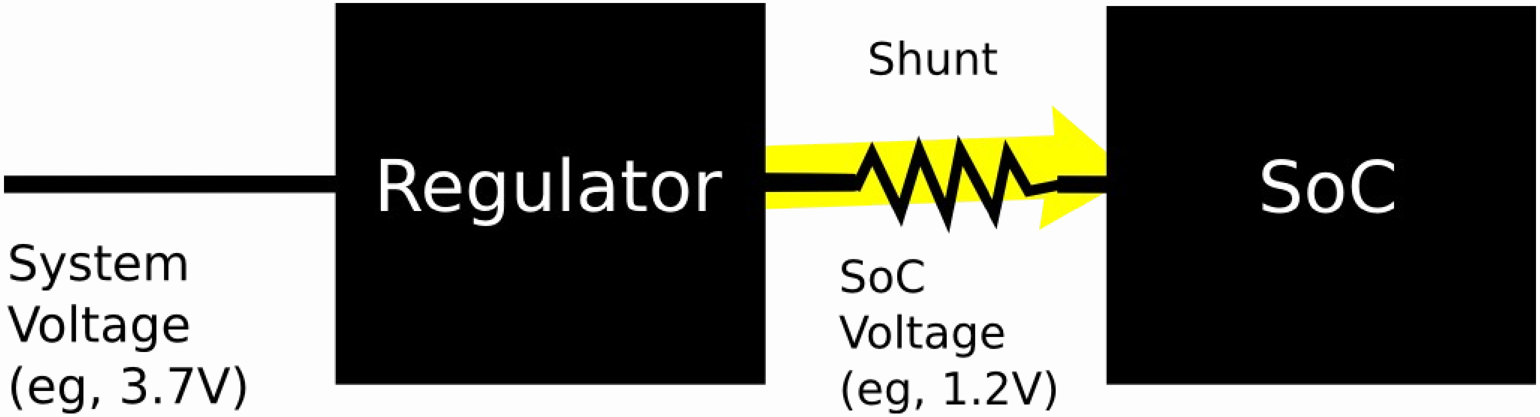
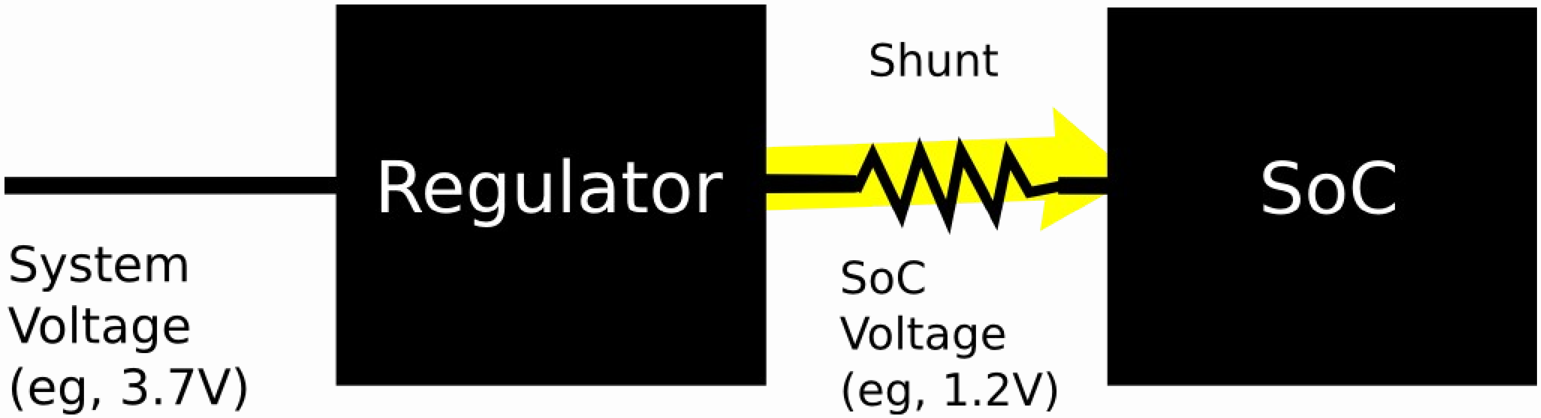
Shunt current measurement

- A shunt is a very small resistance (typ 33mR) placed in series with the load right on the PCB



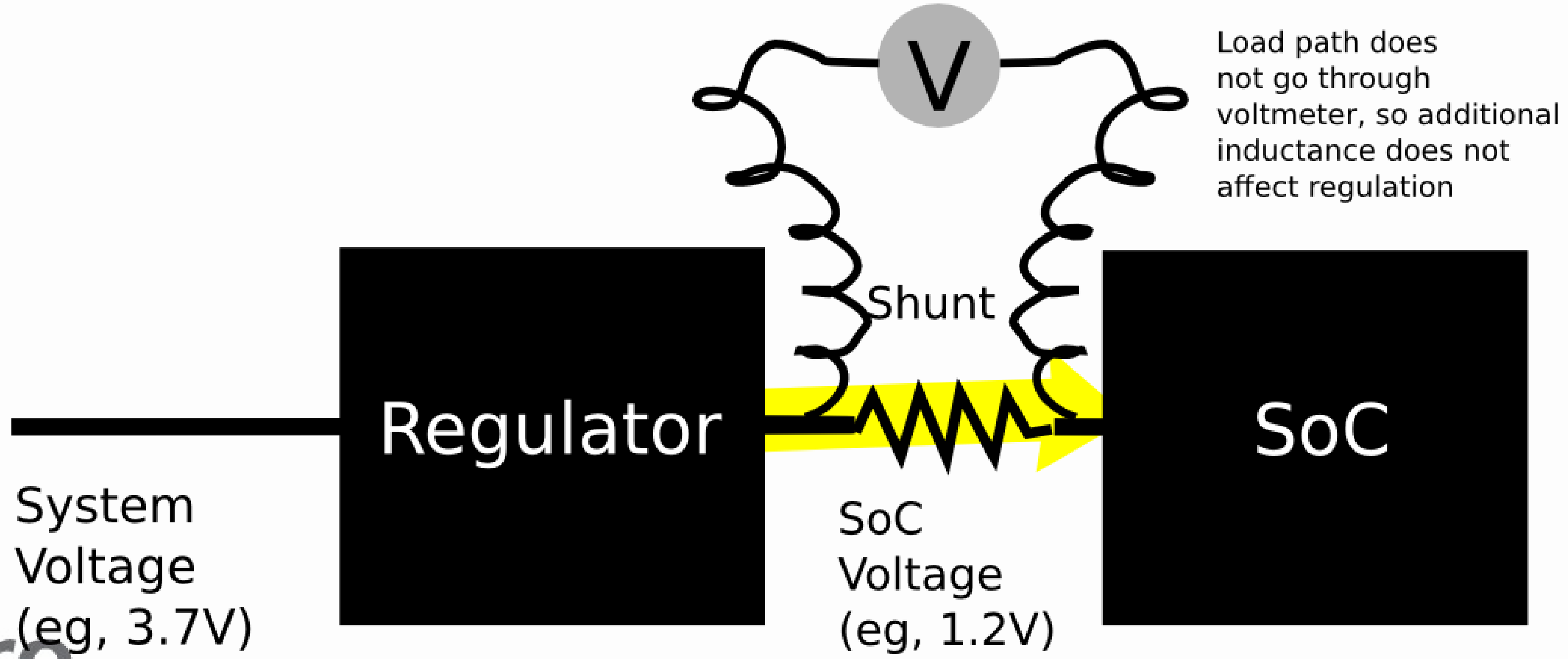
Shunt current measurement

- It introduces a very small reduction in voltage in proportion to current flowing



Shunt current measurement

- The energy probe adds an amplified voltmeter to measure the tiny voltage drop across the shunt



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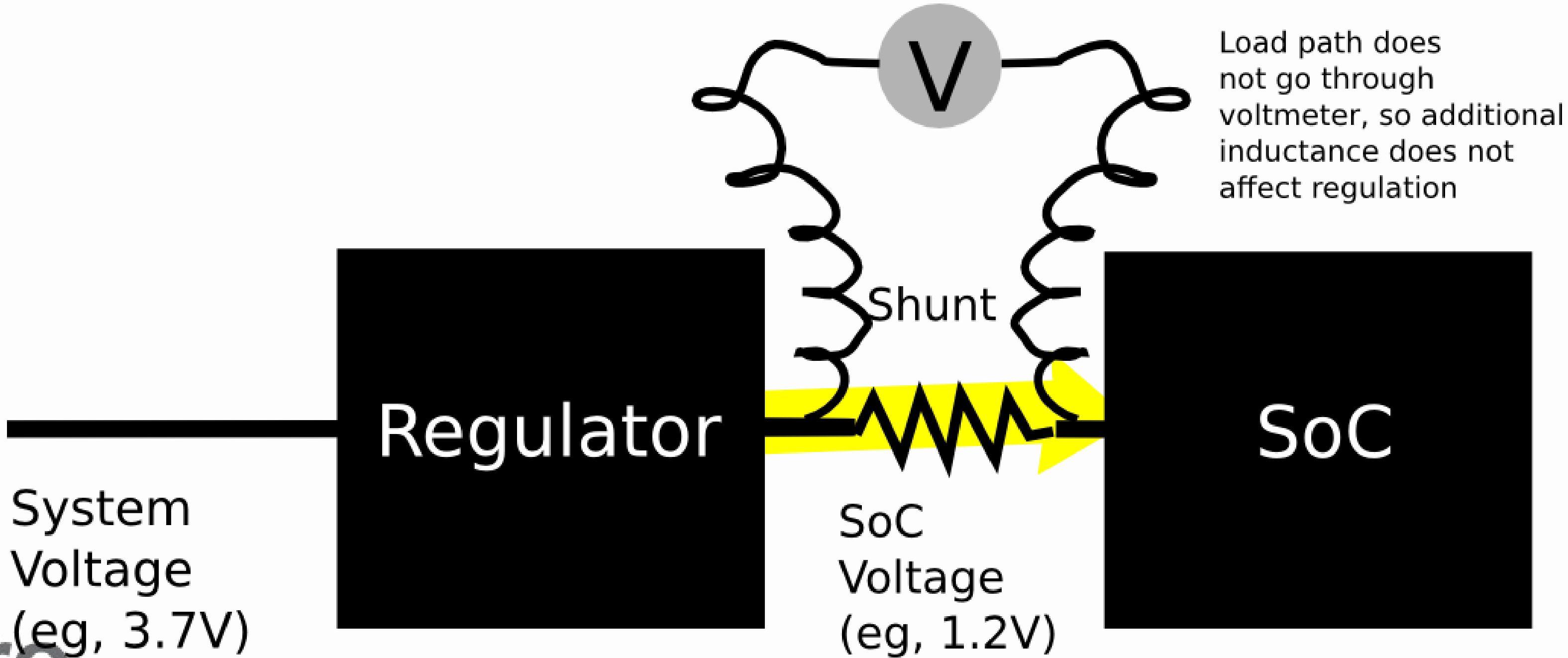
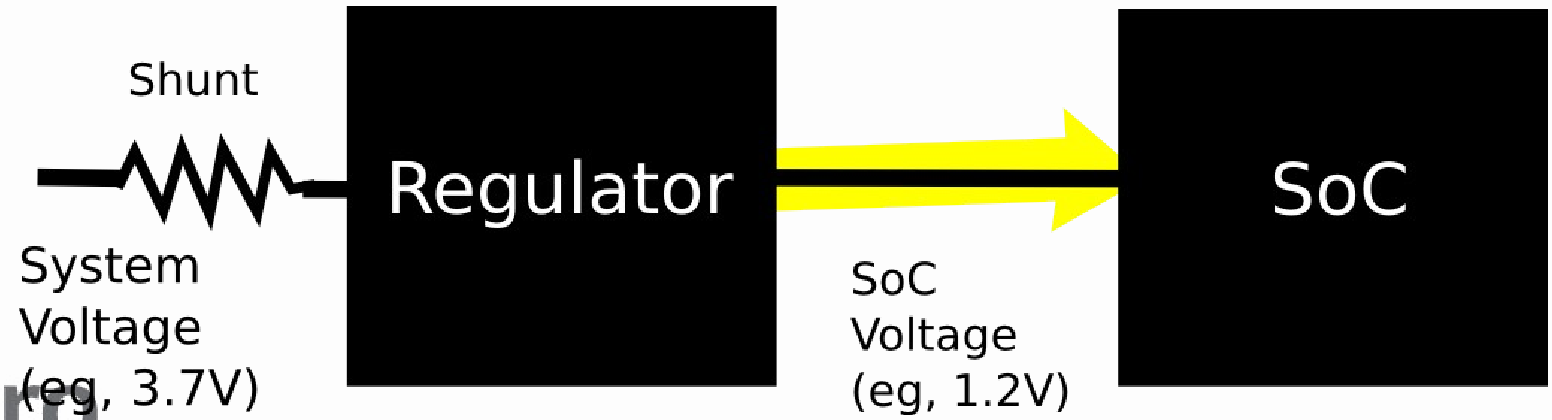
Shunt current measurement

- Because the shunt is a small resistor or metal staple, the regulator can usually “see through it”



Shunt current measurement

- Some regulators are only barely stable. You can measure the input side in those cases
  - Your measurement includes regulator efficiency losses



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- So the probe measures and reports **two voltages** on each channel
  - The voltage at one side of the shunt compared to 0V
  - An amplified version of the tiny voltage **across** the shunt

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ARM Energy Probe

- If we know the shunt resistance, $I = V_{(shunt)} / R_{(shunt)}$ tells us current flowing
  - Probe cannot deduce current without knowing $R_{(shunt)}$
- Since the probe also measures the shunt voltage compared to 0V, we can calculate **power** from P=IV

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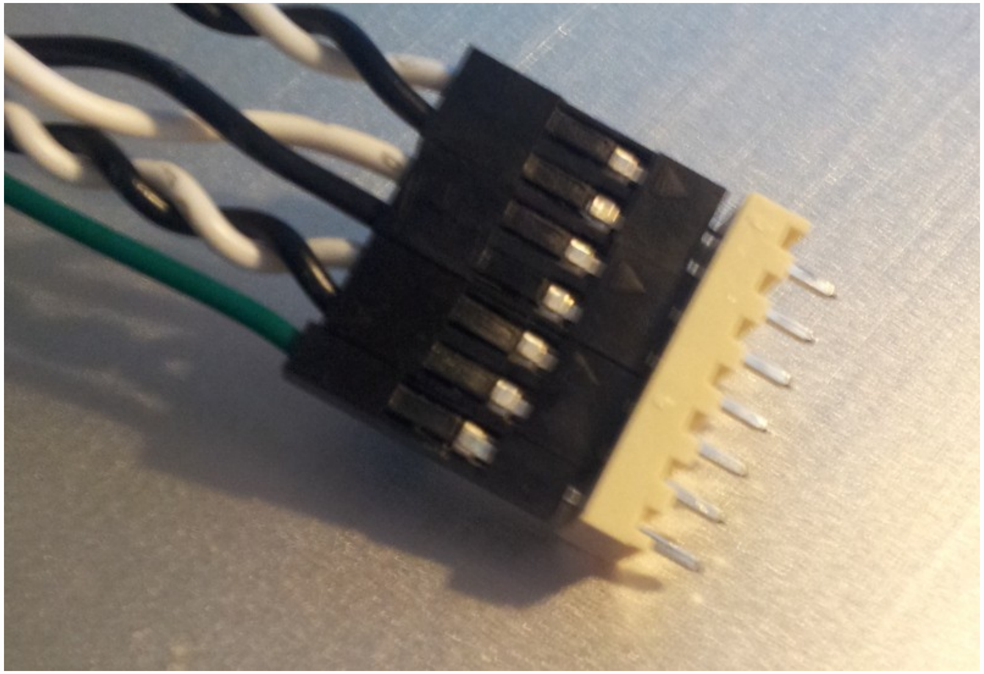
Wiring the probe

- You'll need a 7-pin 0.1” header to plug the probe on so you can detach it



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Wiring the probe

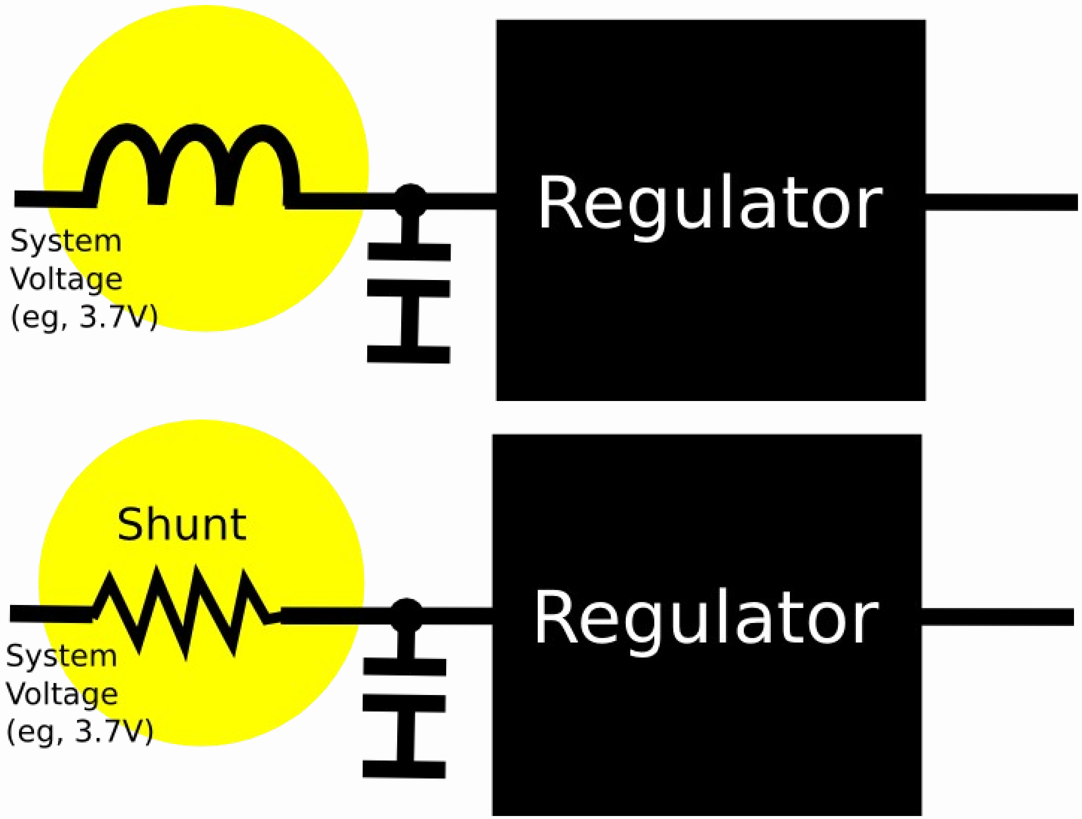
- Wire the green 0V lead to 0V on the PCB ideally near the regulators of interest
- Your board will work fine without the probe connected since current will flow through the shunt as usual

Choosing where to place shunt

- Most regulators have no convenient way to place shunt in series with output
- However there is almost always a convenient series inductor at the **input** designed to limit EMI going back up the power supply cable...

Choosing where to place shunt

- We can replace this inductor with the shunt

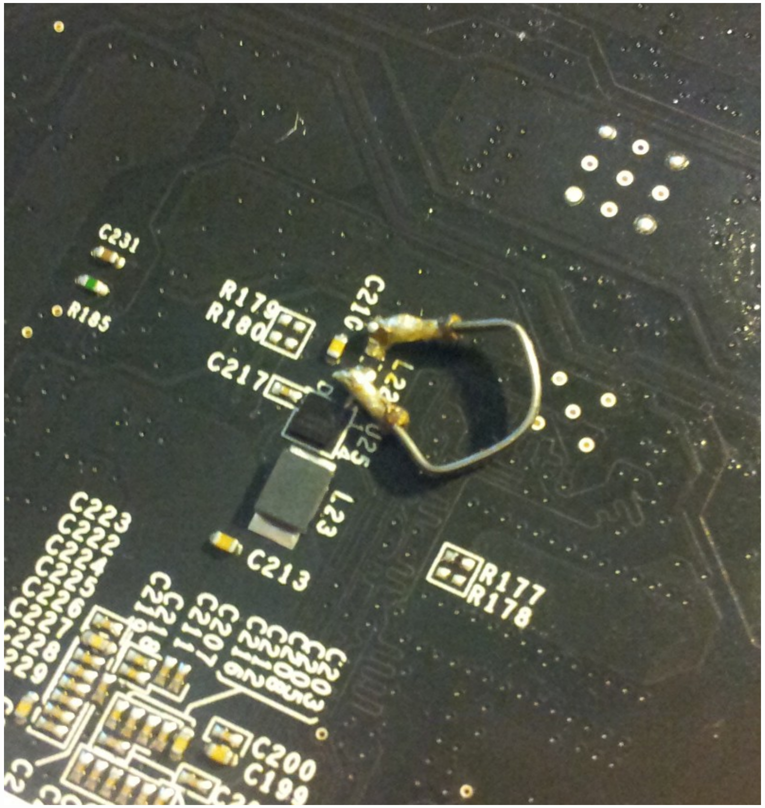


Choosing where to place shunt

- Measuring from regulator input side is fine but
  - You measure the input voltage, not the output
    - You cannot see regulator output DVFS voltage directly
  - Regulator efficiency overhead also measured
    - All real designs must include real regulators, so it's sane

Placing the shunt

- This is a metal precision shunt replacing L22 on 4460 Panda (VDDCORE)



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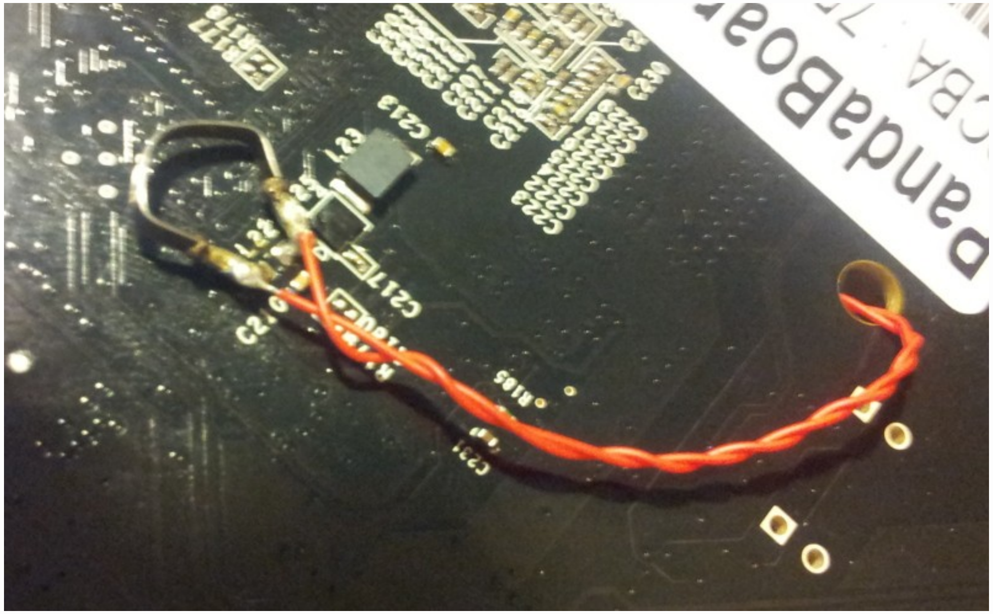
Wiring the shunt

- Twist two thin insulated wires together to wire the two sides of the shunt to the probe connector



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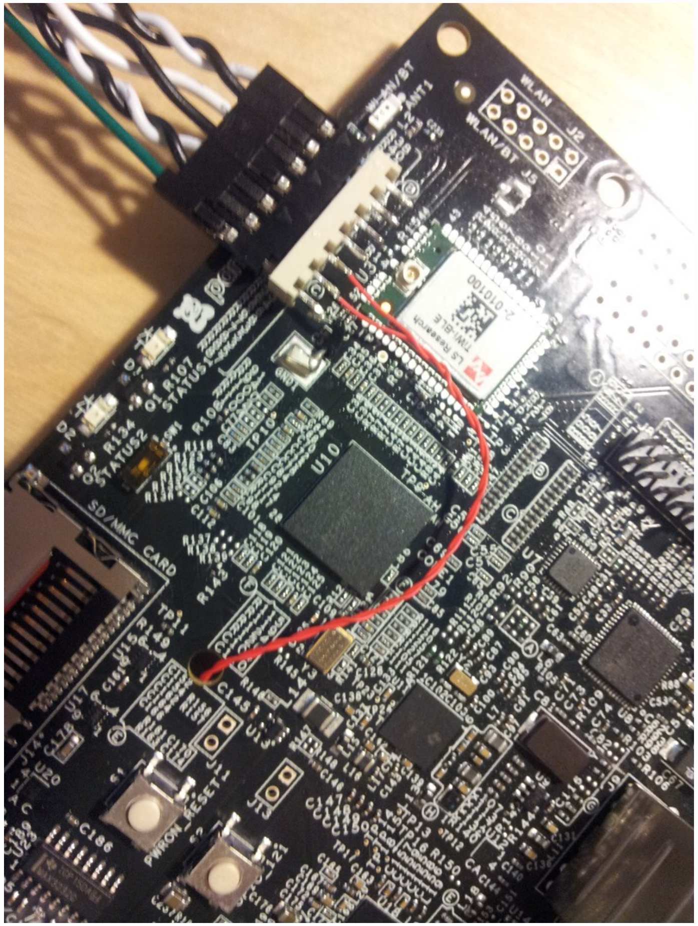
Choosing where to place shunt

- Glue the header to one edge of the PCB



Probe cares about sense leads

- The white side of the sense leads needs to go on the pre-shunt side of the shunt, black to post-shunt
- It won't damage the probe to get it wrong but current readings will always be near zero

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Shunt resistance selection

- Low resistance shunt is preferable to minimize regulation disruption
- Probe ADC resolution can be a problem then
  - With 33mR shunt, one ADC count == 4mA resolution
  - Considerable “noise” or aliasing

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Real measurement

- 4460 Panda VDDCORE
- Input side of regulator
- 33mR and 470mR shunt
- idle at U-Boot prompt
- 600MHz dynamic load
- Corrected for slope error
- Using linux commandline

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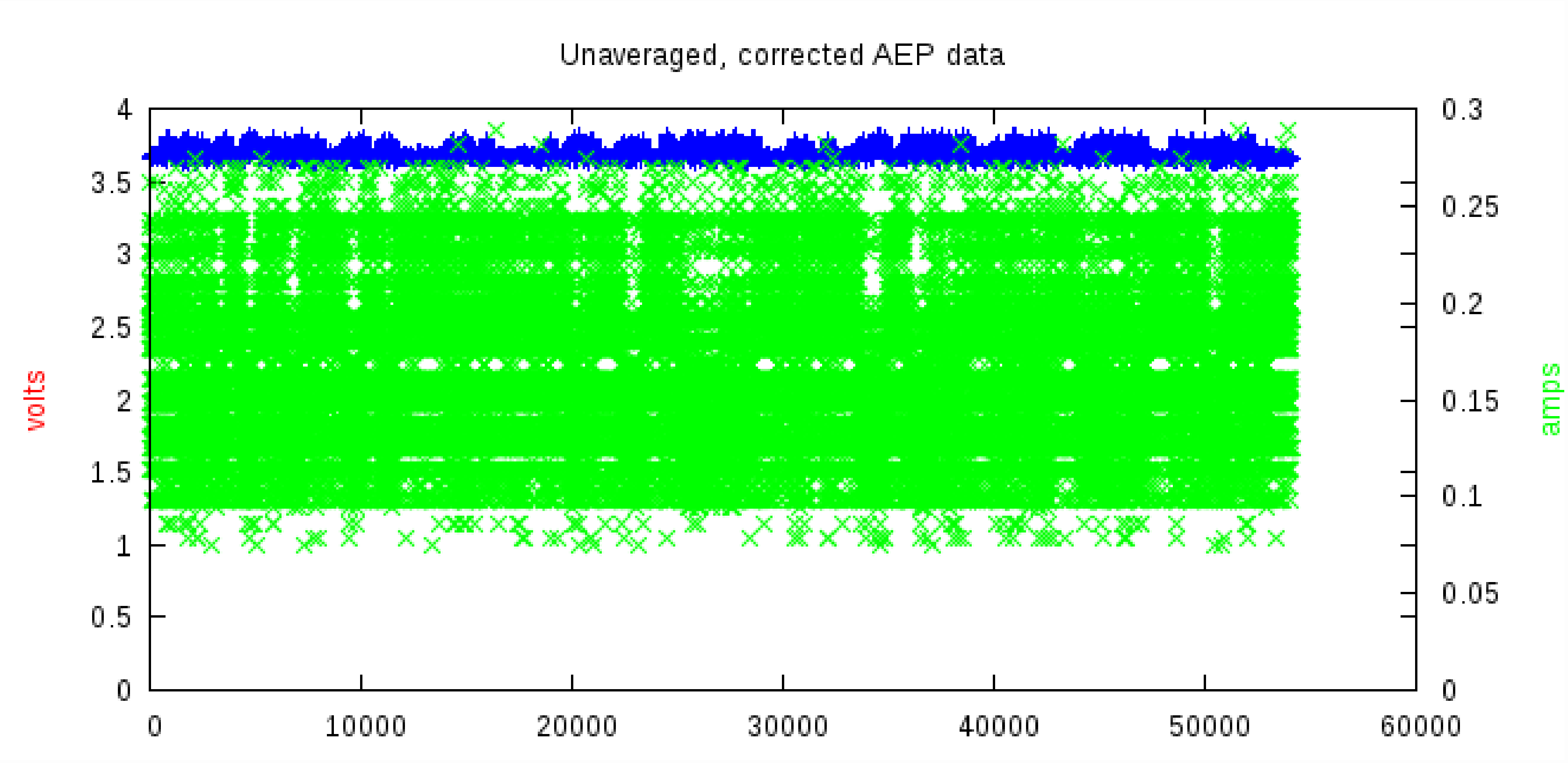
Unaveraged, 33mR shunt

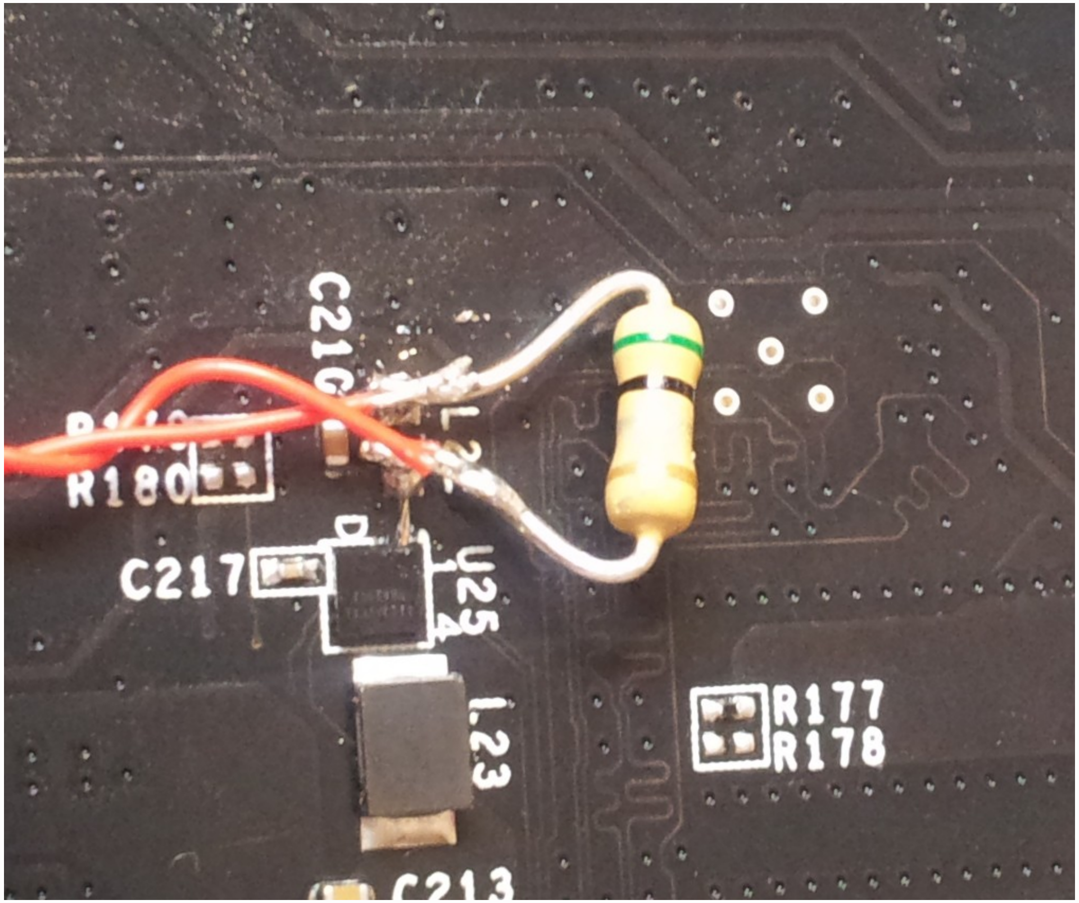


Interpretation

- 33mR is too low resistance shunt for the ARM probe
- limits the ADC count for the measurement to around 5% of ADC range
  - SNR reduced drastically
- Change to a higher resistance shunt so we have a bigger voltage to measure

Same tests with 470mR shunt

- “0.5R” resistor



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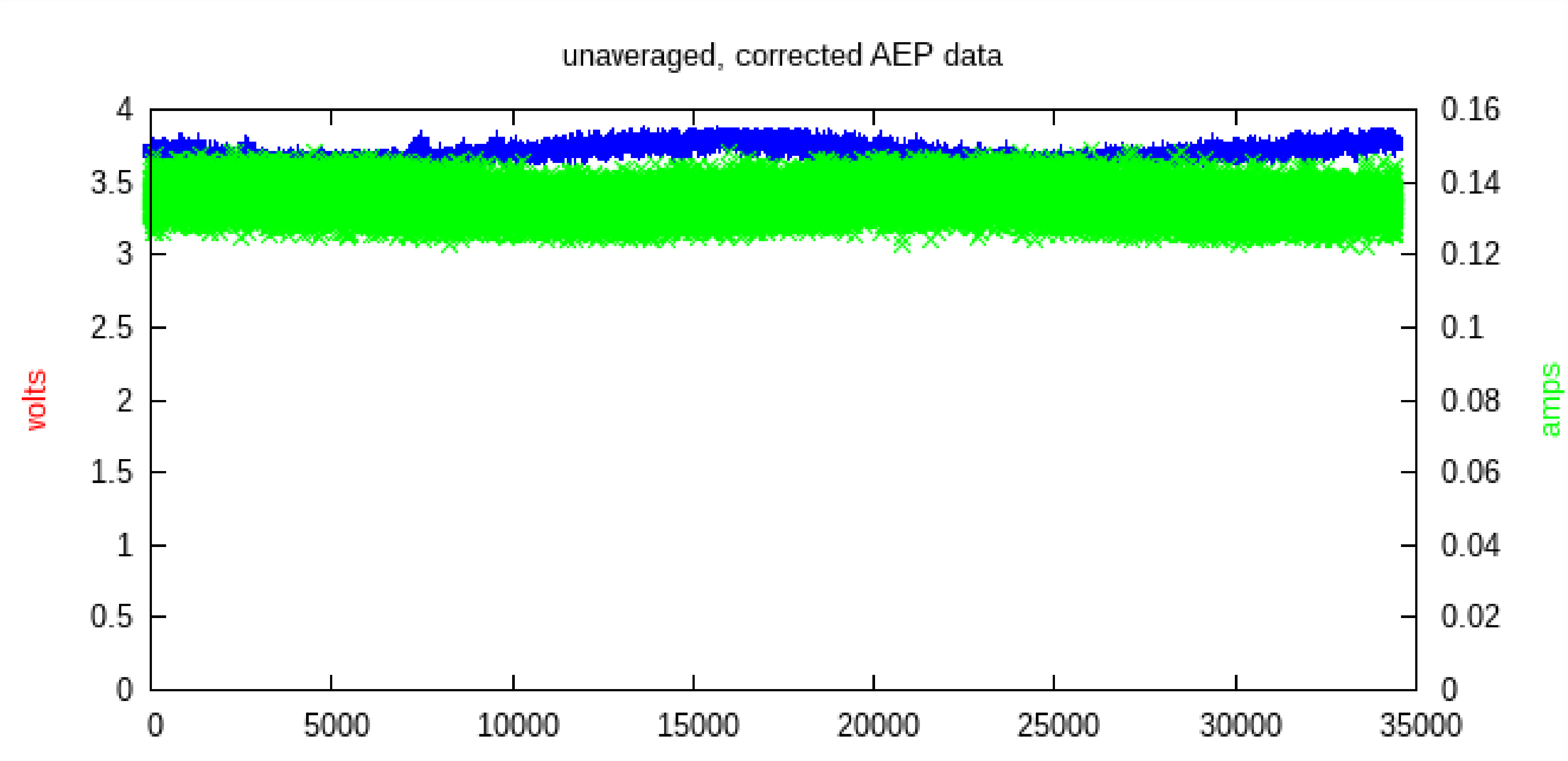
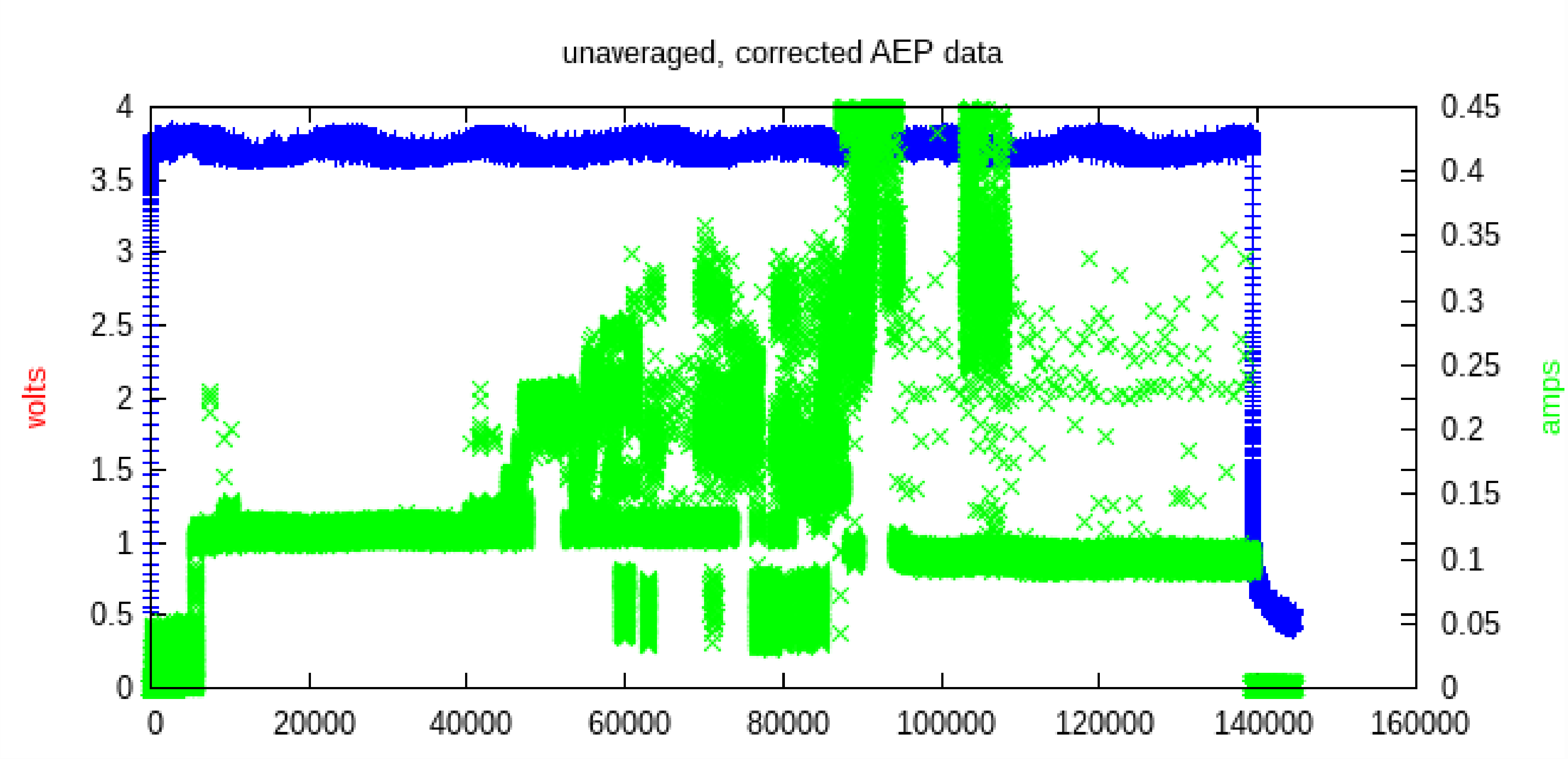
Unaveraged, 470mR shunt



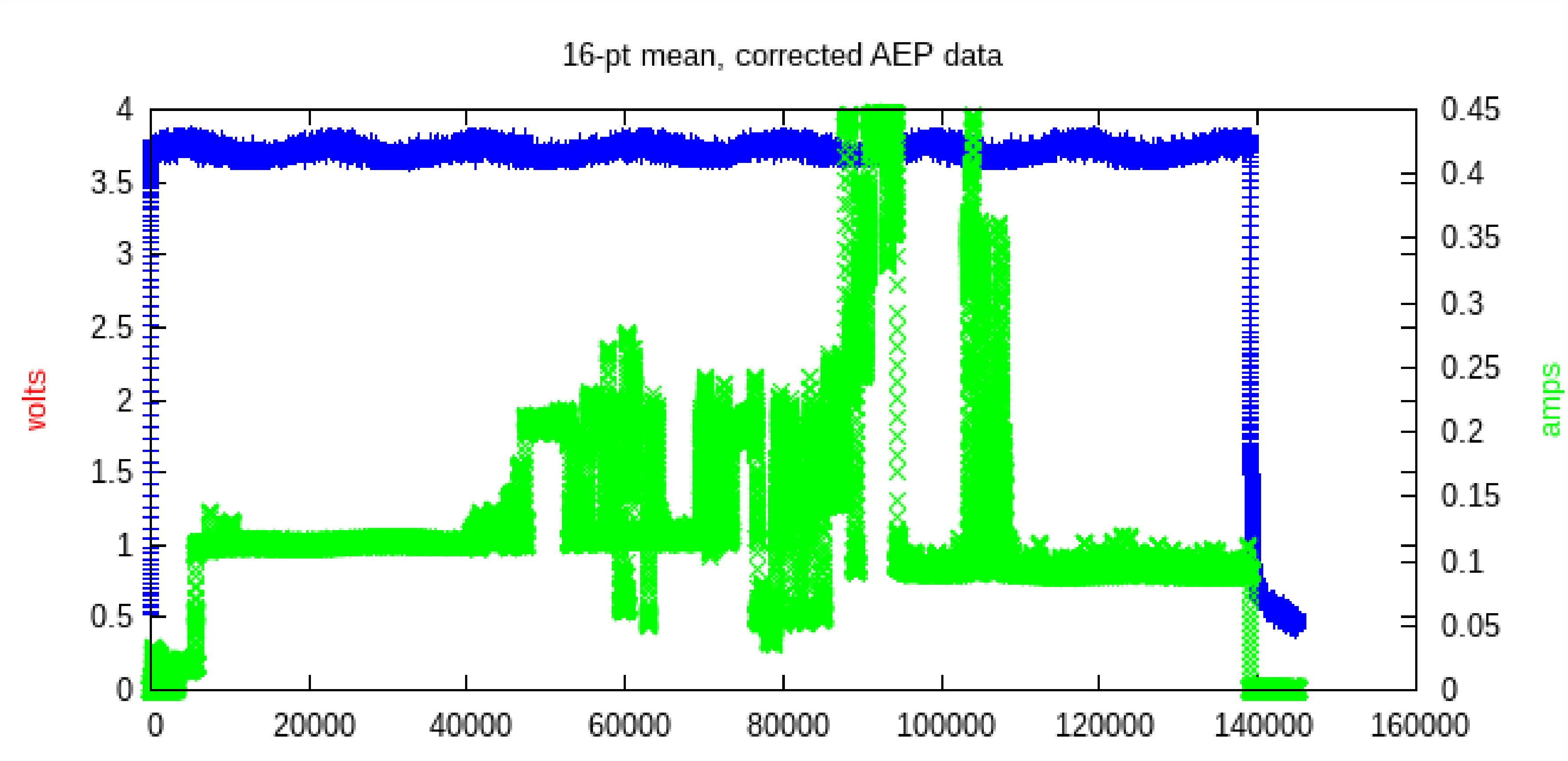
Interpretation

- Much better SNR
- Resolution improved to 280uA / ADC step
  - For static currents, high averaging will give even more precise results

Unaveraged, 470mR Linux



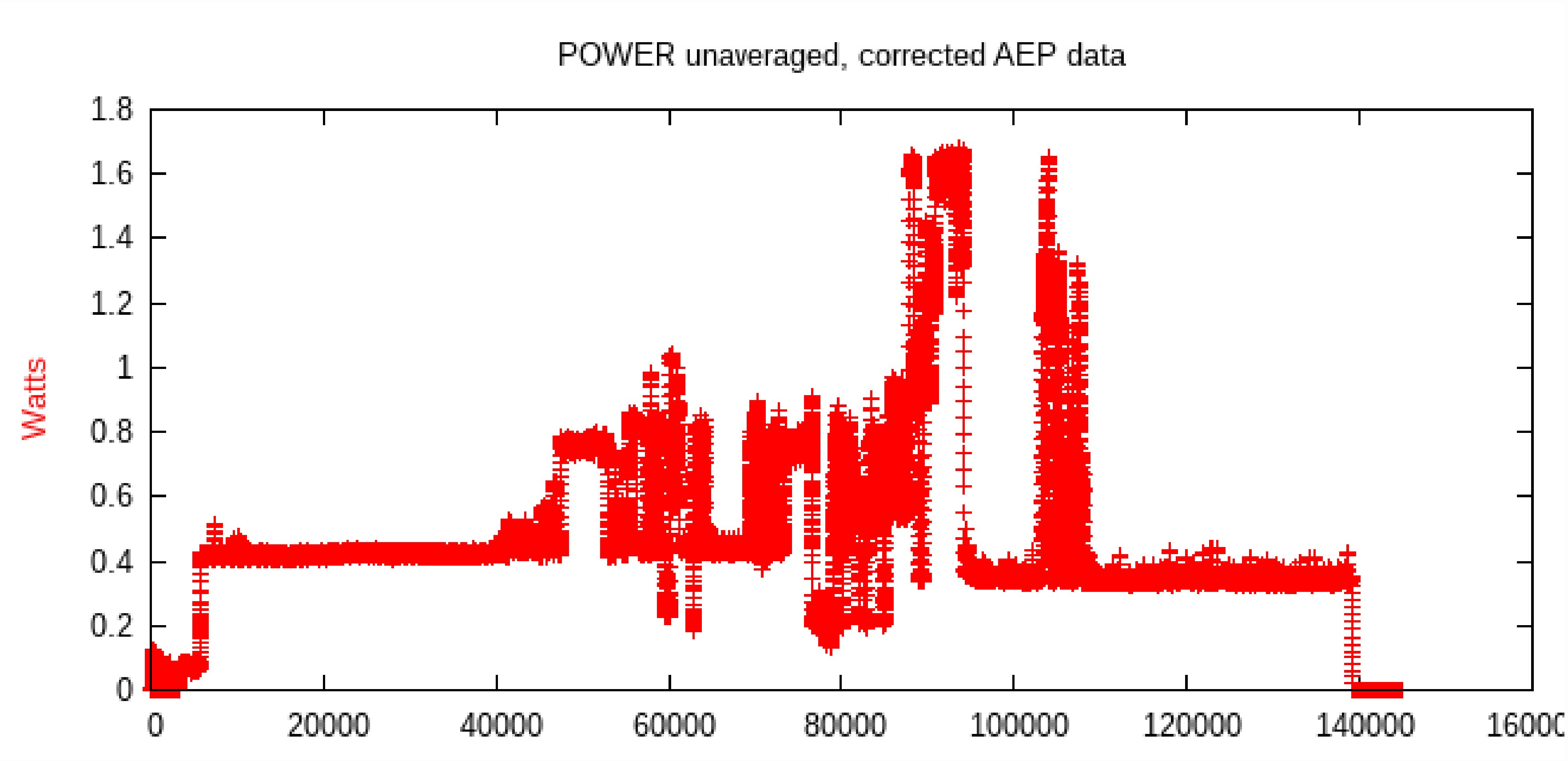
16-pt mean, 470mR Linux



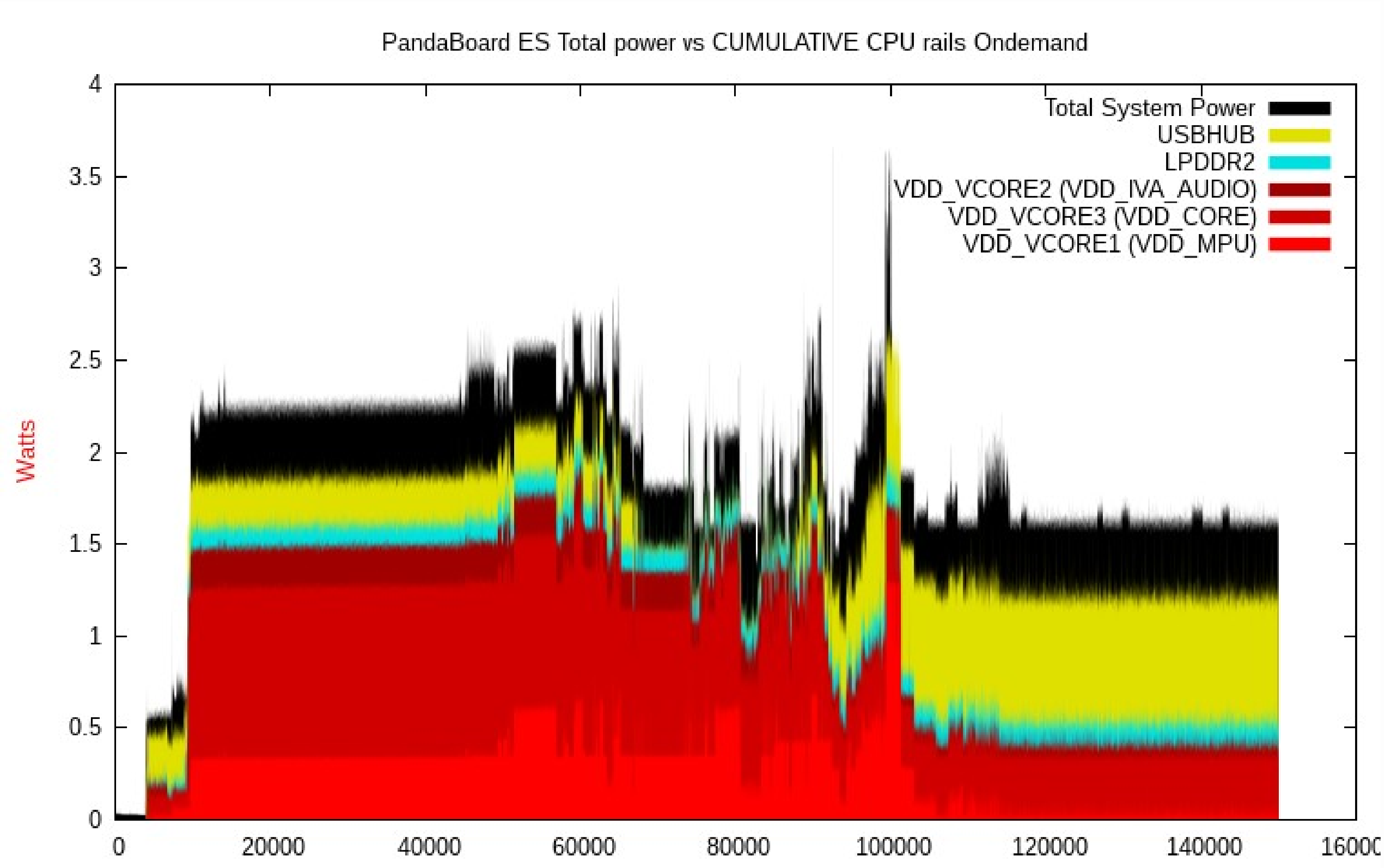
Interpretation

- 100us sample hides spikes
  - Short increases in current may be missed completely
  - Some rails dynamic load changes at 1GHz
  - 1 AEP sample covers 100,000 CPU clocks...
  - Any averaging makes it worse
- Rest of the graphs show power, not separate voltage and current

POWER, unaveraged, 470mR Linux



6 channel “cumulative” view



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Summary

- ARM probe optimized to measure high currents
- Unable to use small value shunts well with normal currents
- Try 470mR shunt first
- Use 0.1% or 1% tolerance resistor if available

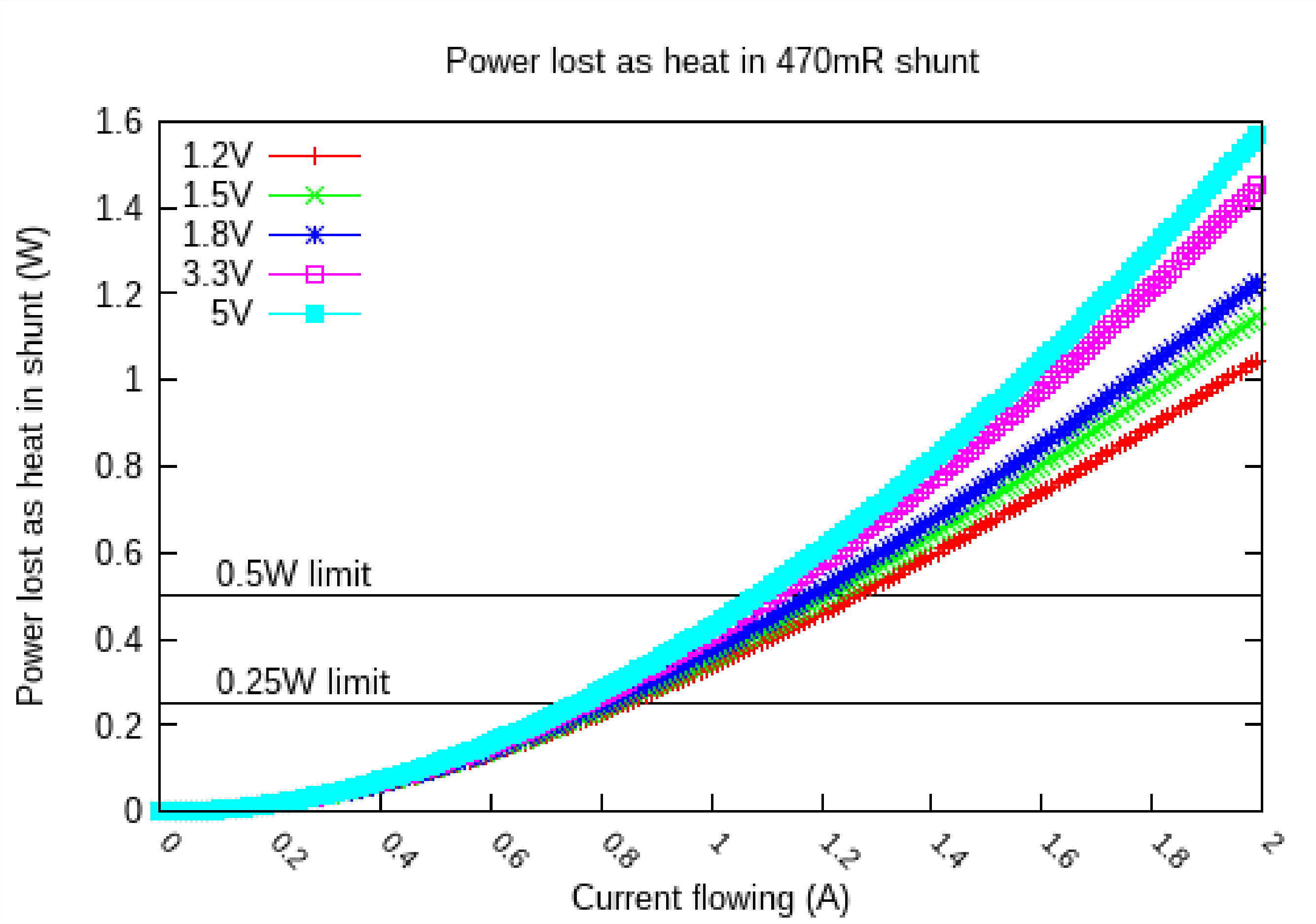
Caution

- Higher resistance shunt == more voltage drop... measured current flows through the voltage drop and P=IV for the shunt
- It has to dissipate the power as heat
- 470mR resistor used here rated 0.25W
- Only good for 0.7A at common voltages
- Higher power resistors available

Various power rating resistors

- 5W, 2W, 1W, 0.5W and 0.25W

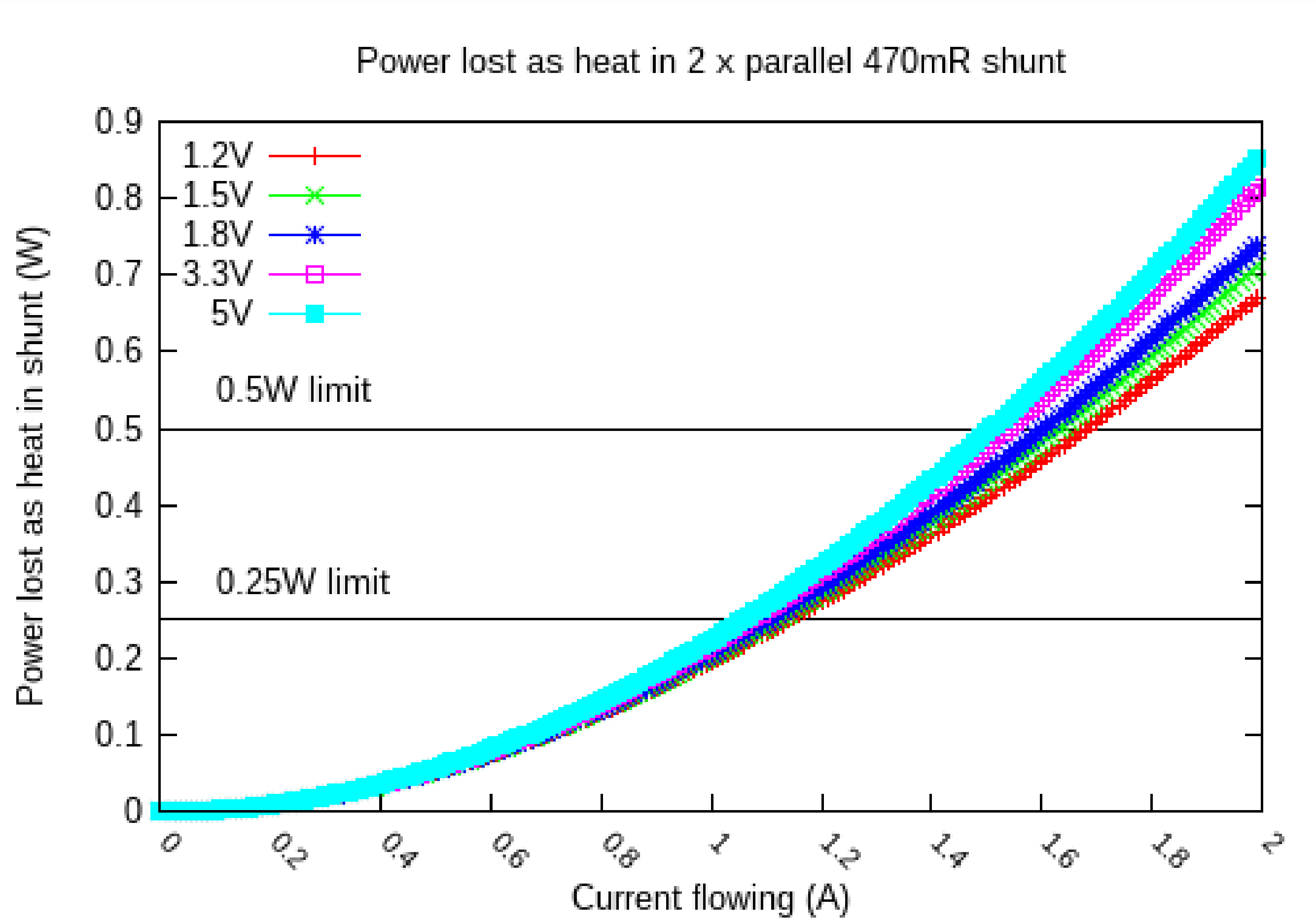
Power dropped in shunt



Parallel up shunts to cope

- 2 x 470mR, 0.25W shunts in parallel becomes 235mR, 0.5W capable
- The voltage drop is halved and the dissipation limit doubled (resolution /2...)
- Can cope with ~1.5A at the common voltages

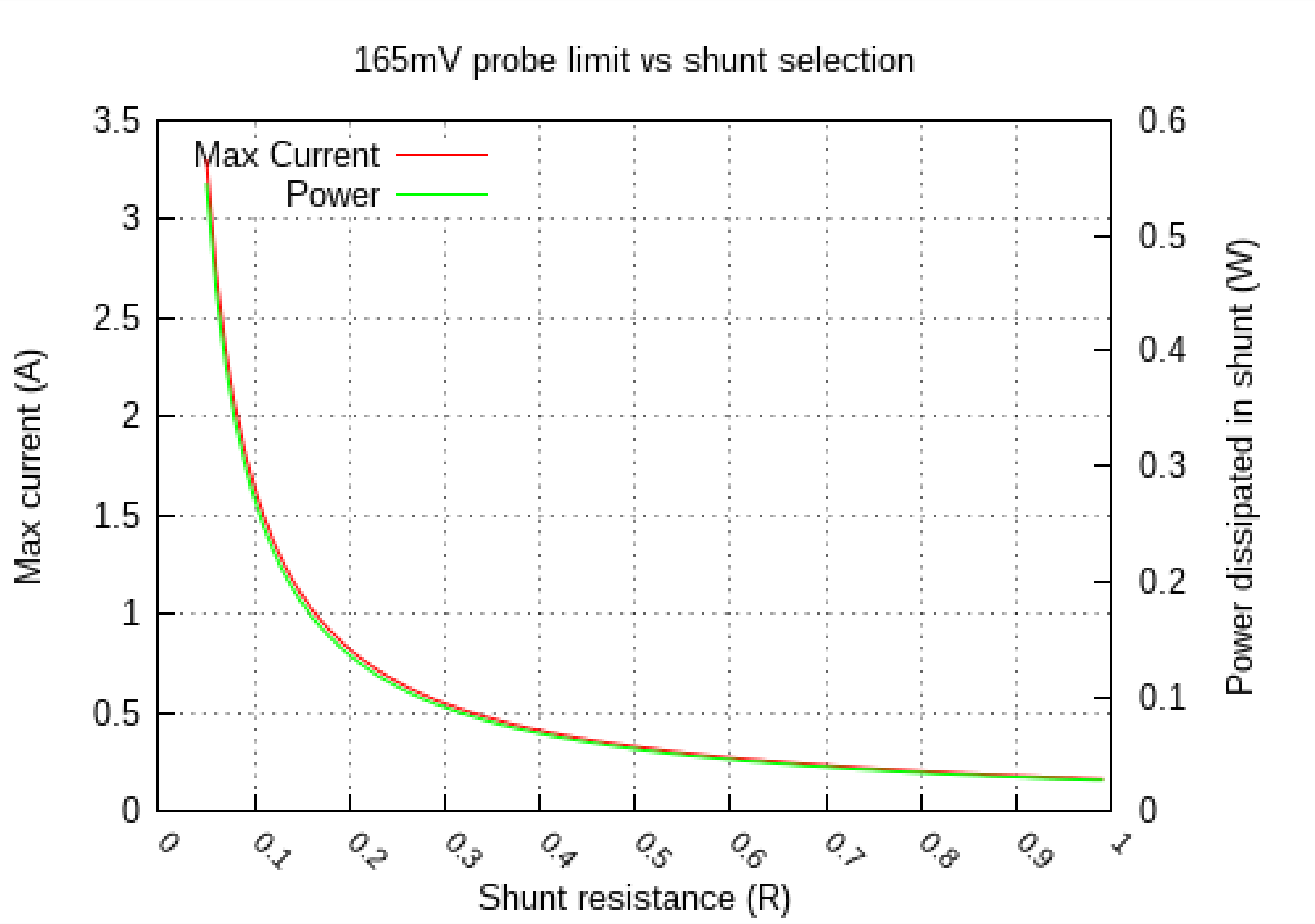
Power dropped in shunt



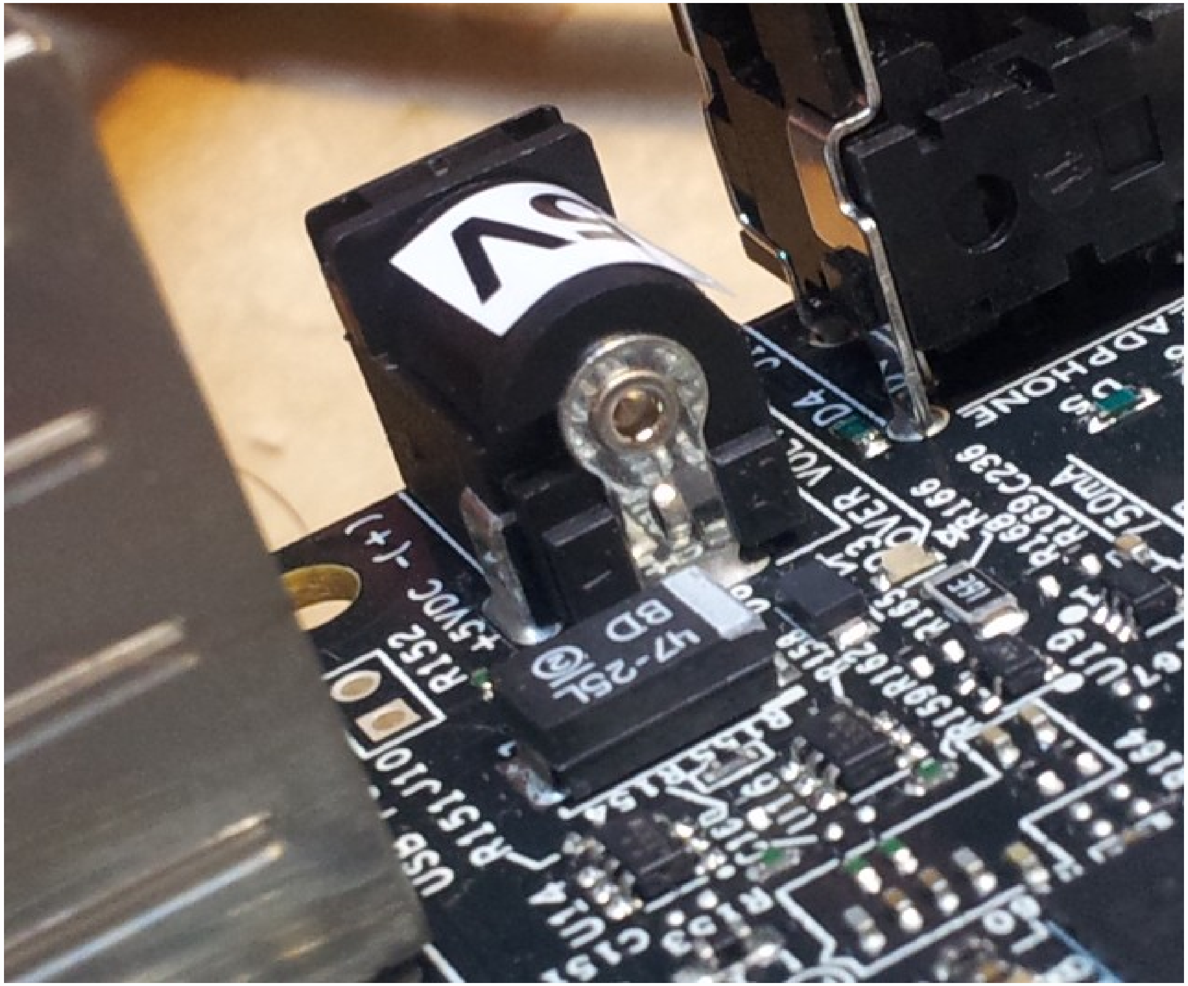
Shunt selection vs current range

- Probe can only measure up to 165mV across the shunt
- It means you have to select the shunt resistance according to the maximum current expected
- Following chart shows effect of common shunt values
  - Lower Rshunt --> high noise, low resolution

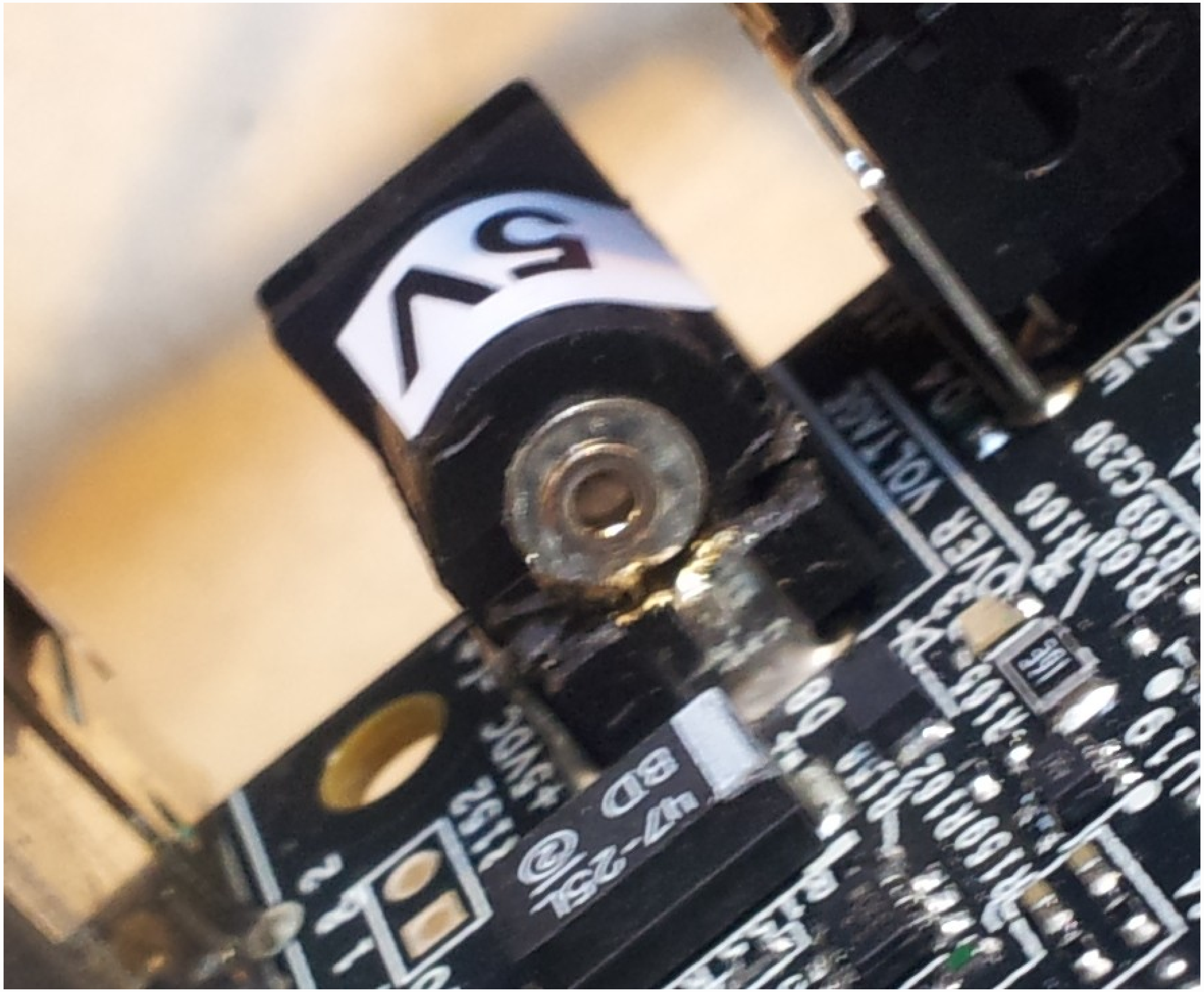
Shunts dropping max 165mV



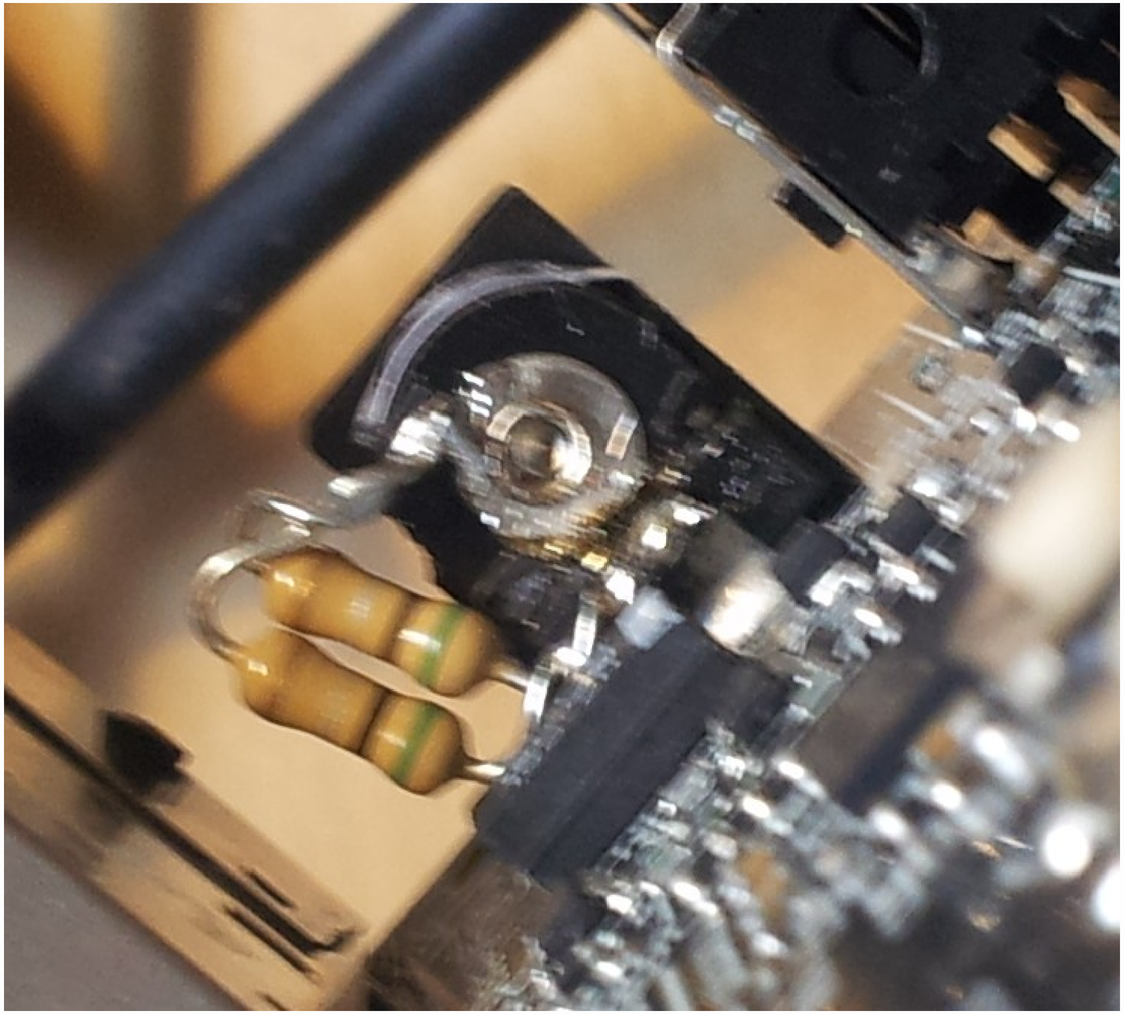
Attaching shunt to DC jack



Cut the + conductor



Apply shunts in parallel cf power



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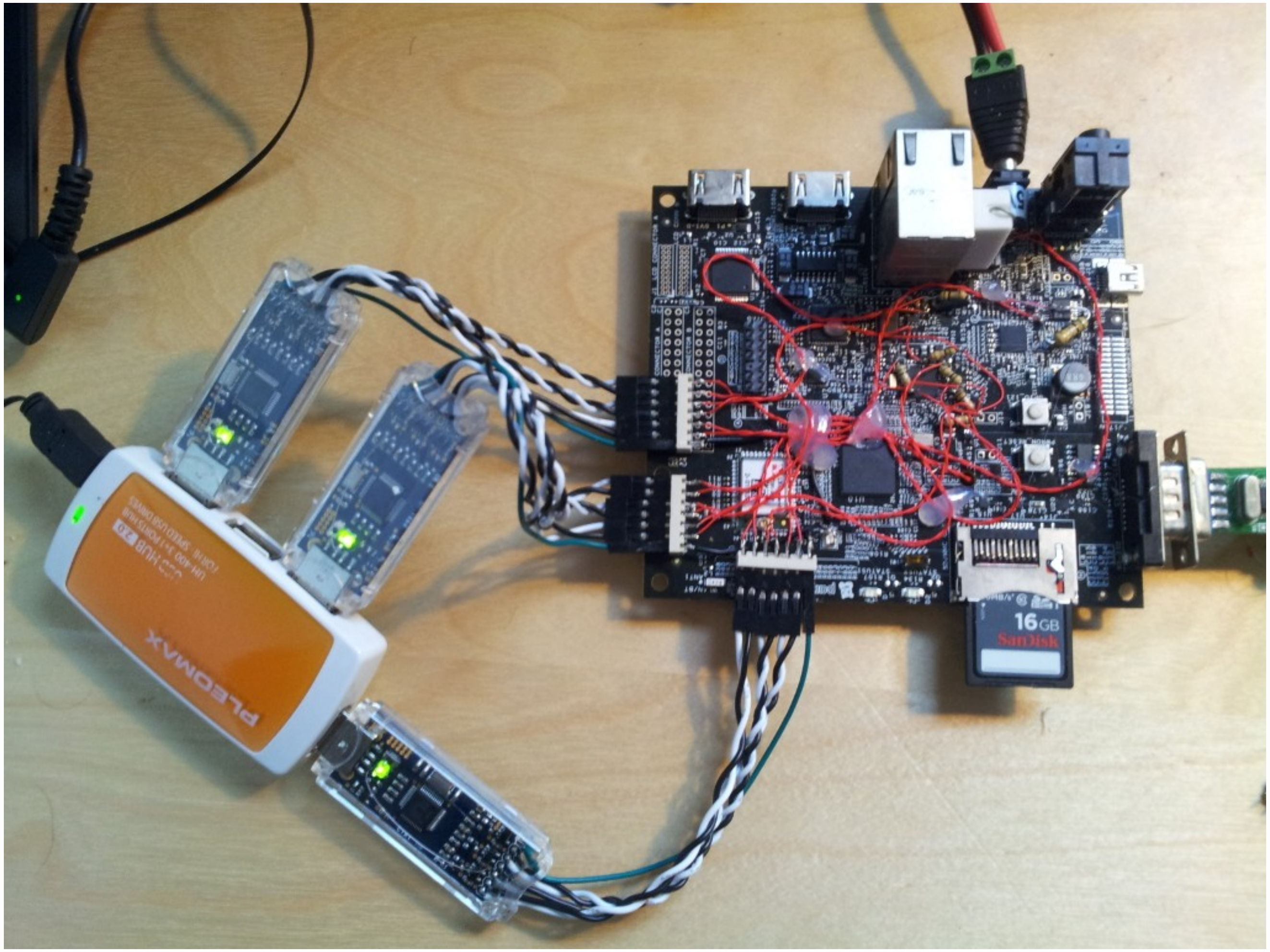
Panda ES wired for 9 rails



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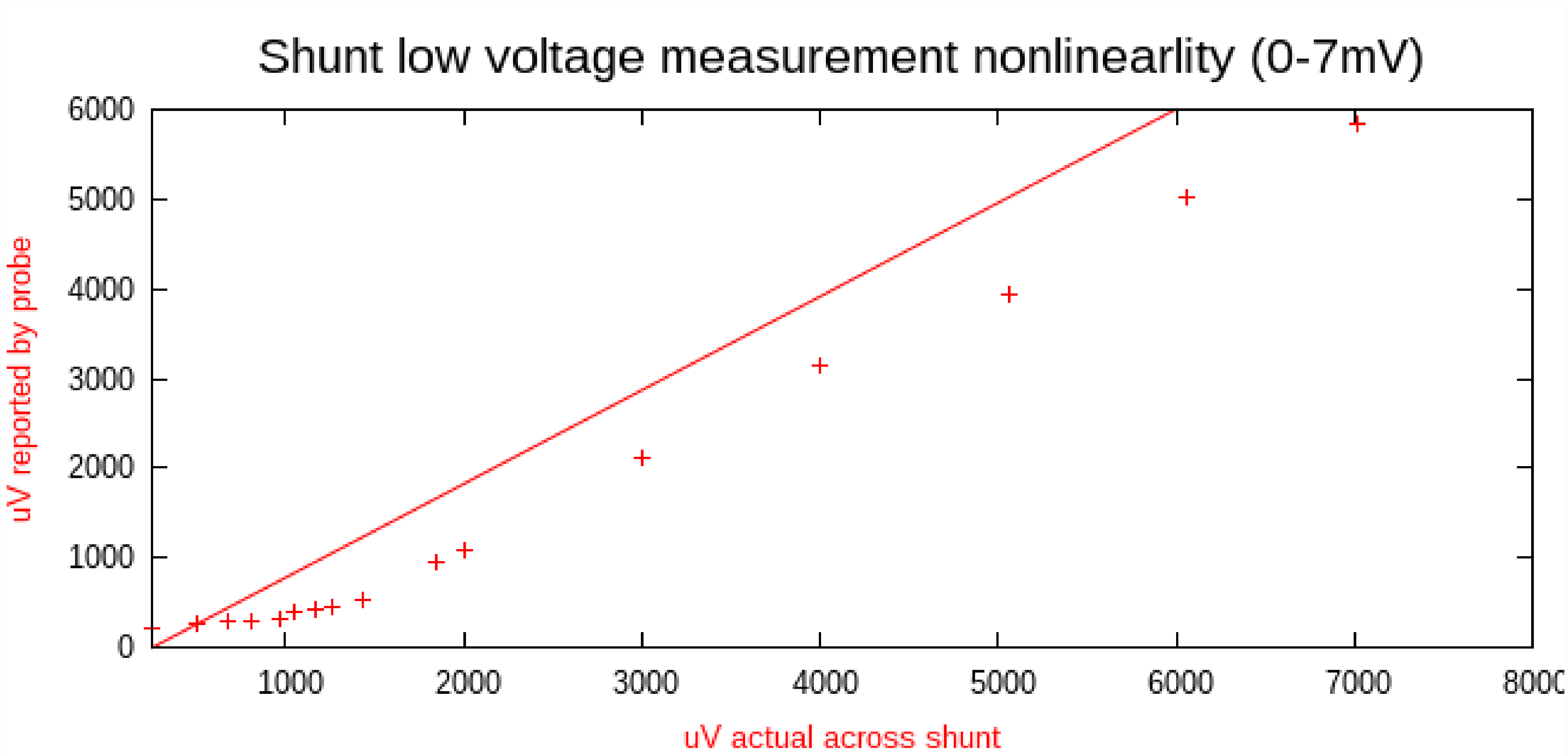
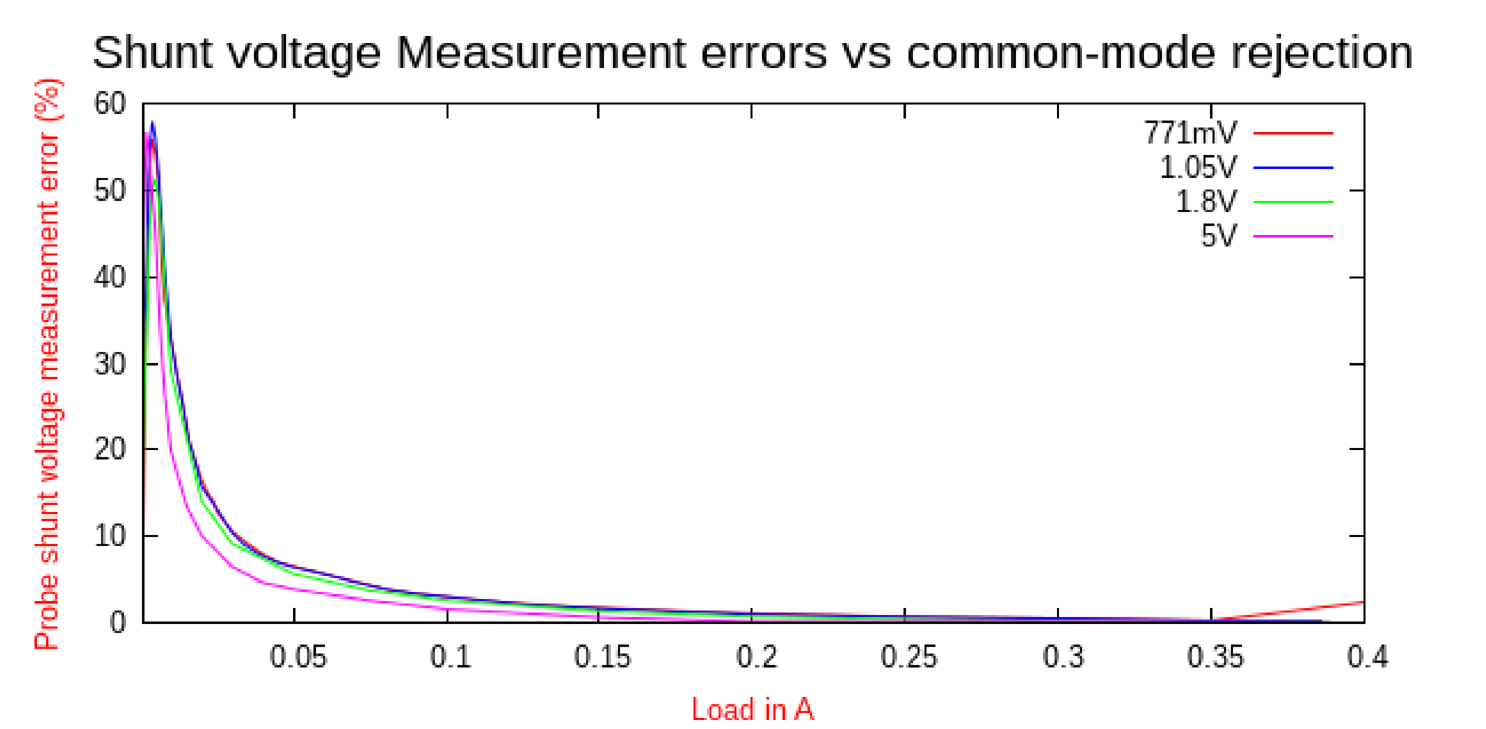
Performance characteristics

- Badly nonlinear at low cross-shunt voltages



Performance characteristics

- Raw results < 50mA (470mR shunt) **poor**
  - Very nonlinear, other errors mentioned next



Analysis

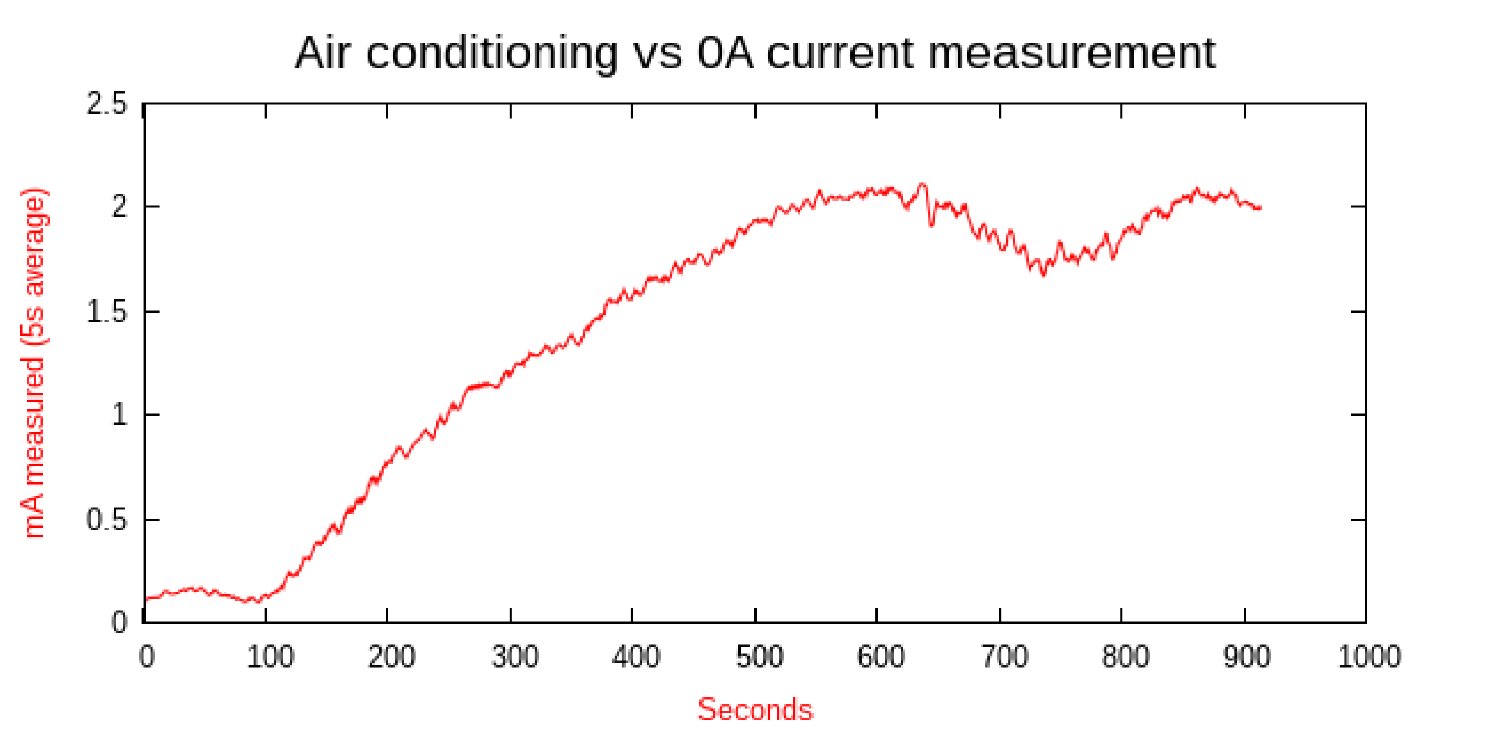
- Raw probe current numbers below ~50mA (470mR shunt) have significant error
  - Interpolation models and autozero mentioned next can reduce this error
- Below 2mV across shunt (~4mA with 470mR shunt) measurements unrepeatable
  - Due to shape of nonlinearity at low end, only 4uV meas. difference between 0mA and 1mA
  - Well below noise and temperature drift floor

Autozero setup

- Short all shunt inputs with wire to 0V
- Use autozero then monitor result over time

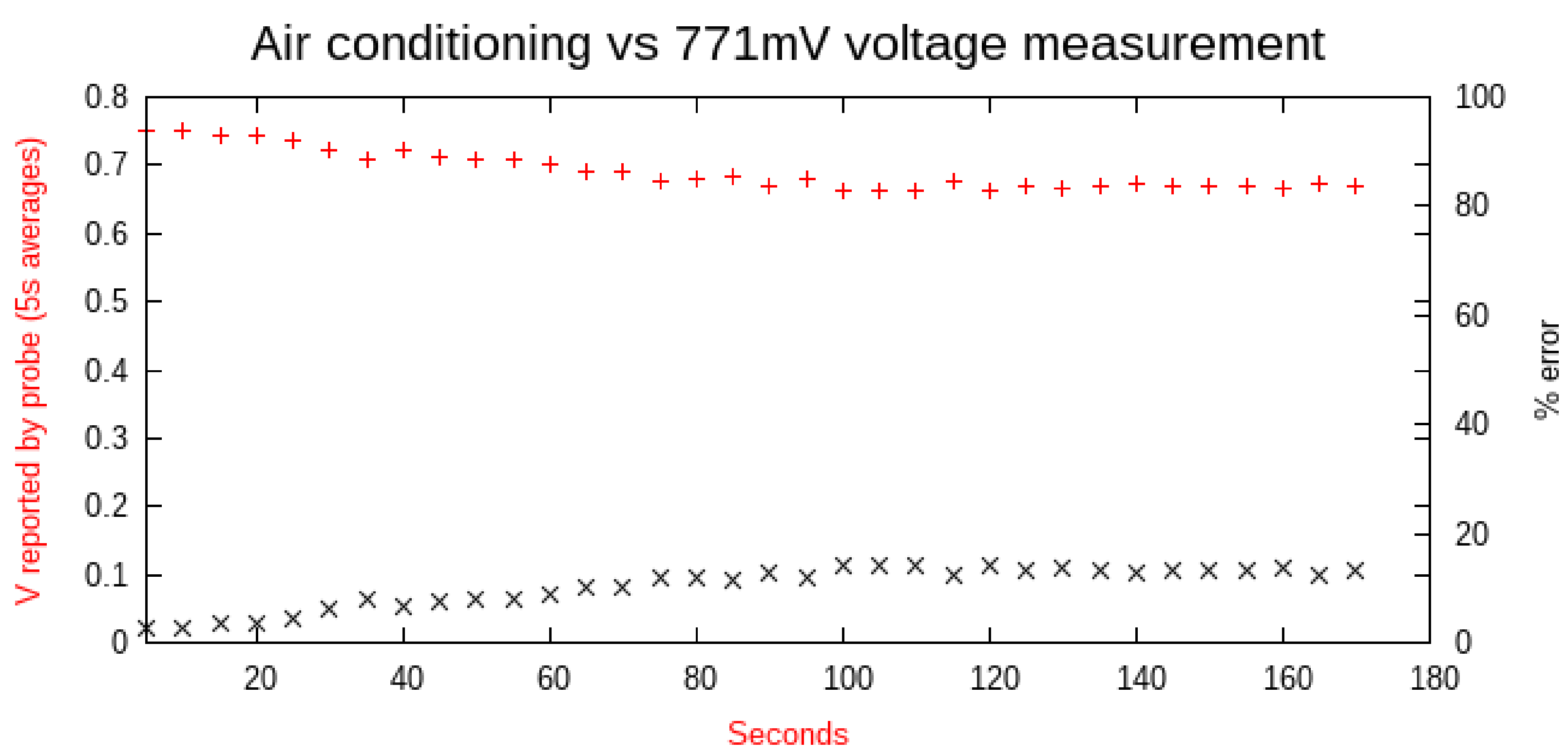
Temperature drift vs 0A current

- +1mV offset from 10°C drop in room temp
  - == “0A” error of +2.1mA with 470mR shunt !



Temperature vs voltage

- Same problem on voltage channel, air conditioning offsets by -15%

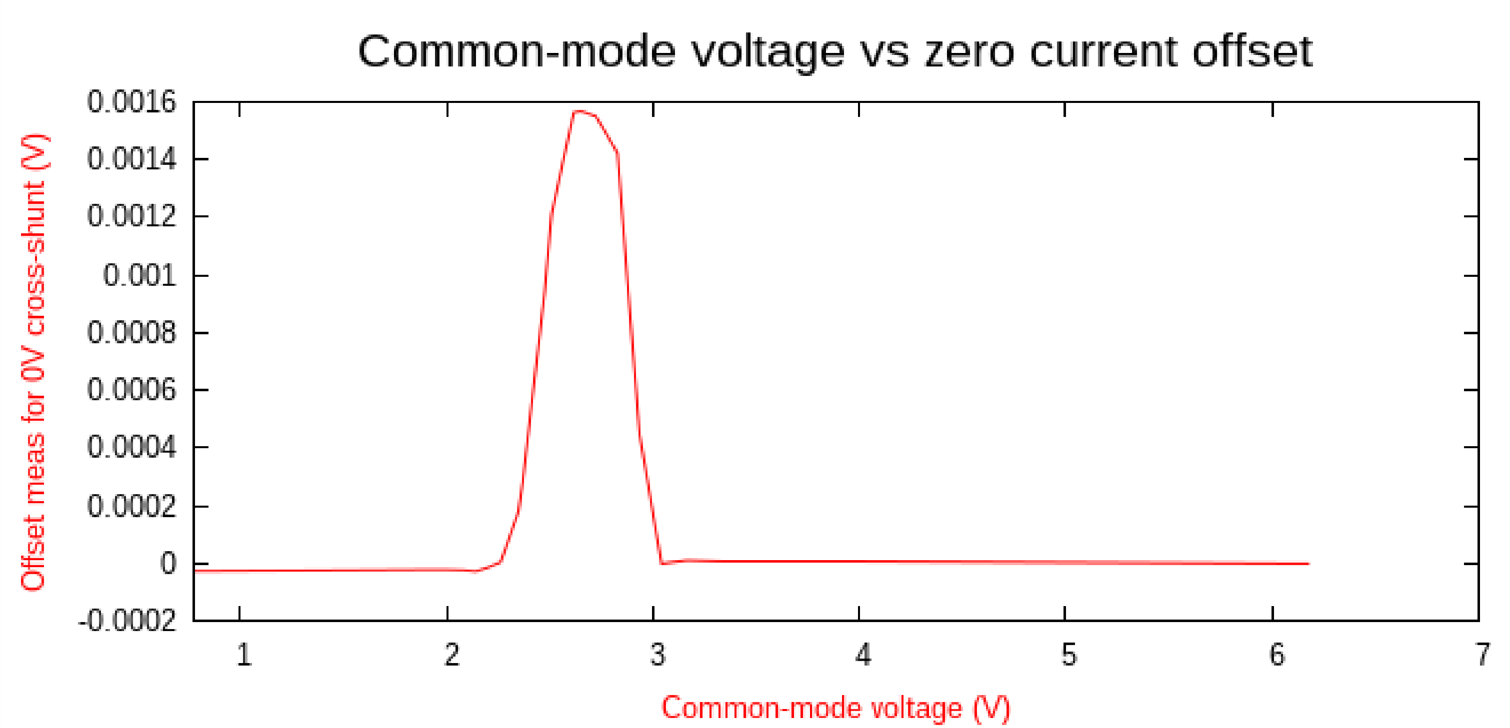


Analysis

- Shunt measurements have > 1mV (== >2mA with 470mR) offset uncertainty due to temp
- Can combat it a bit by keeping temperature as stable as possible and measuring offset before real measurements (**--autozero**)
- Currents below a few mA are going to give unrepeatable results and have high error, due to probe nonlinearity, air currents, sunlight on probe etc

Common-mode voltage error

- Shunt voltage measurement has extra error from common-mode (vs 0V) voltage at 2-3V
  - Equivalent to 3.2mA error with 470mR shunt



Correction model

- Software has table of “actual vs measured” cross-shunt voltages at different common-mode voltages
  - This calibrates against all the common-mode anomalies and nonlinearities
    - Common-mode related error is actually critical
- Checks table to find nearest known measurements either side of current measurement and interpolates

Ch2 Correction offsets (0-165mV)

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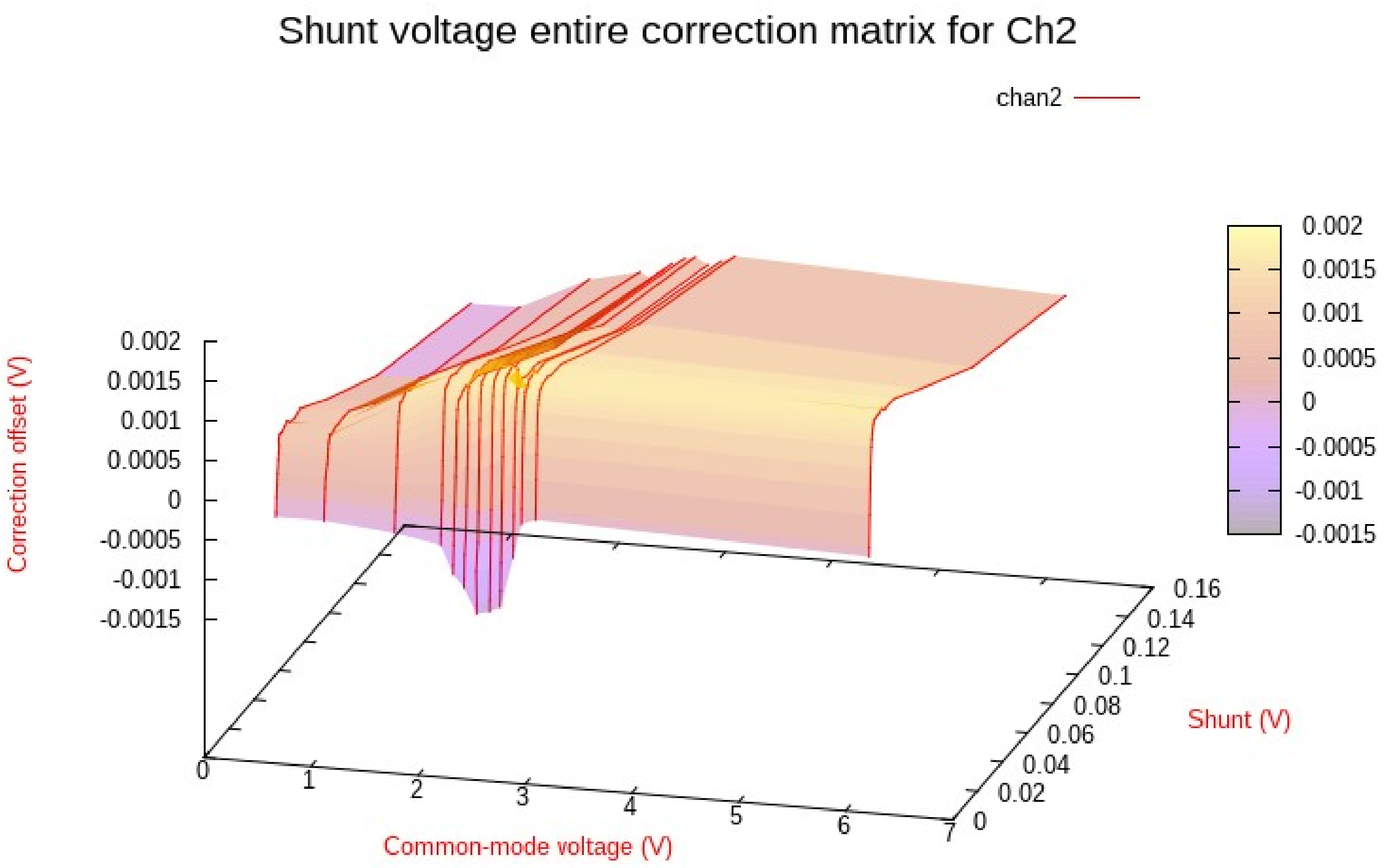

Correction offset map (0-15mV)

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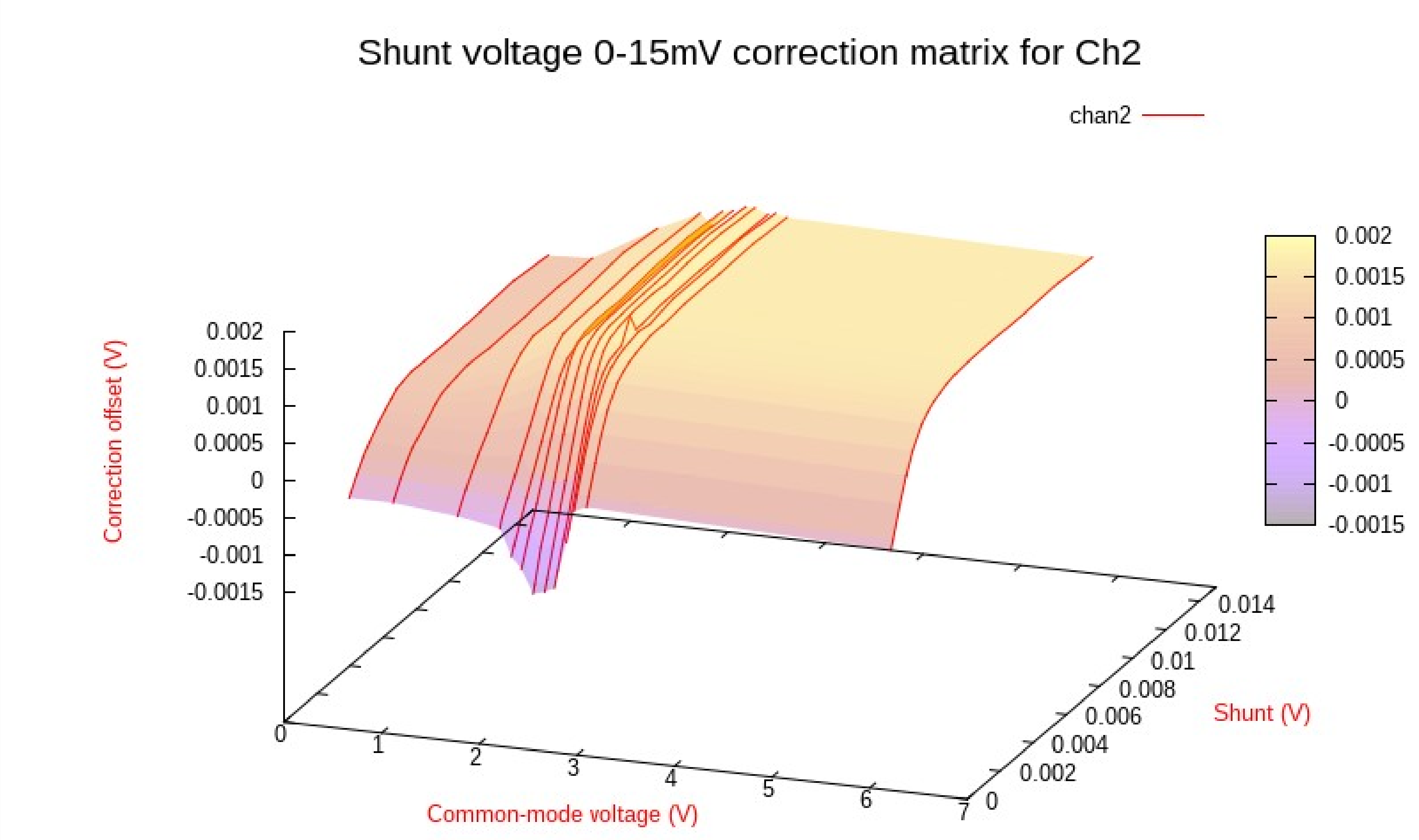

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Actual transfer functions (0-7.5mV)

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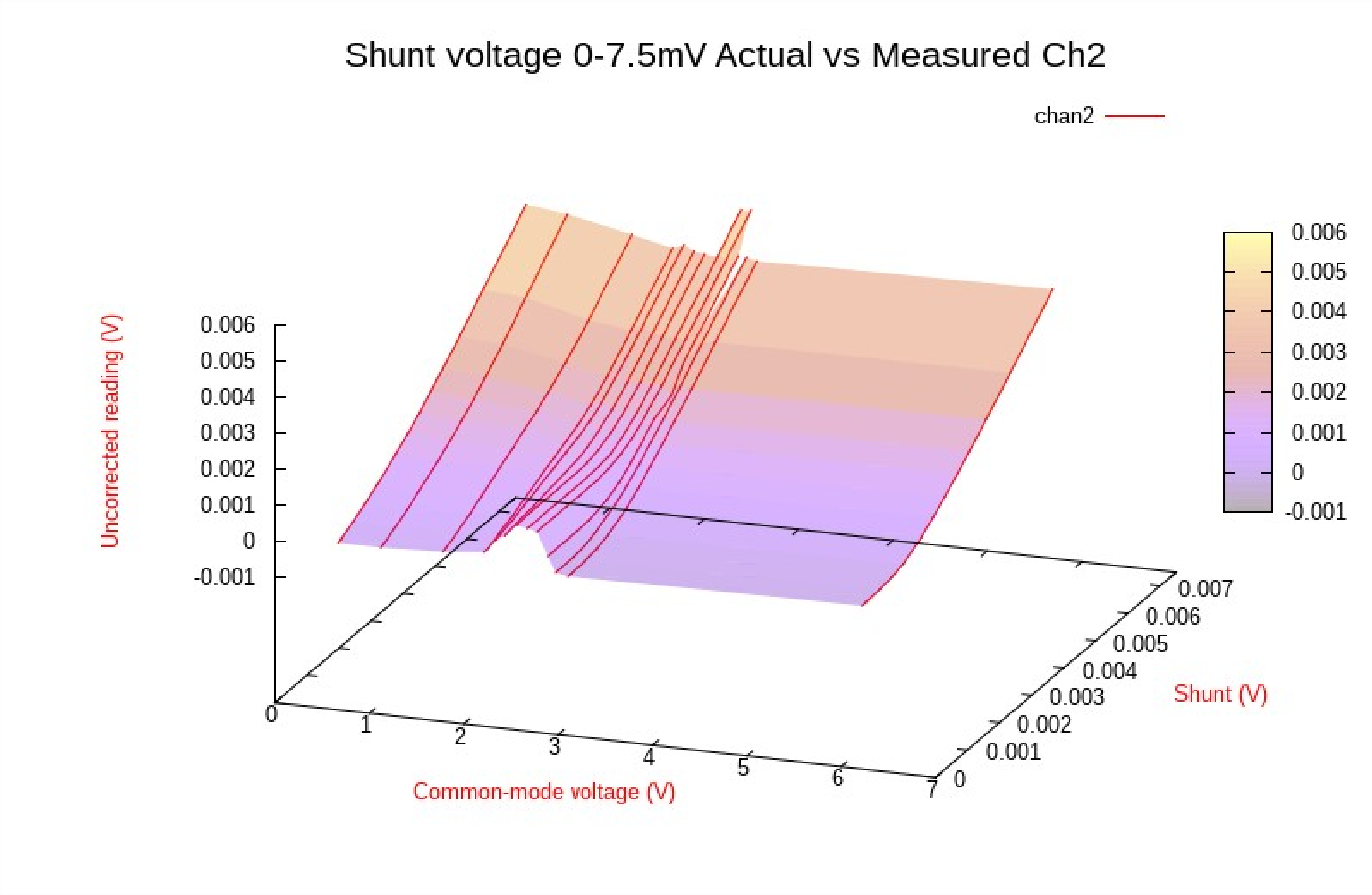

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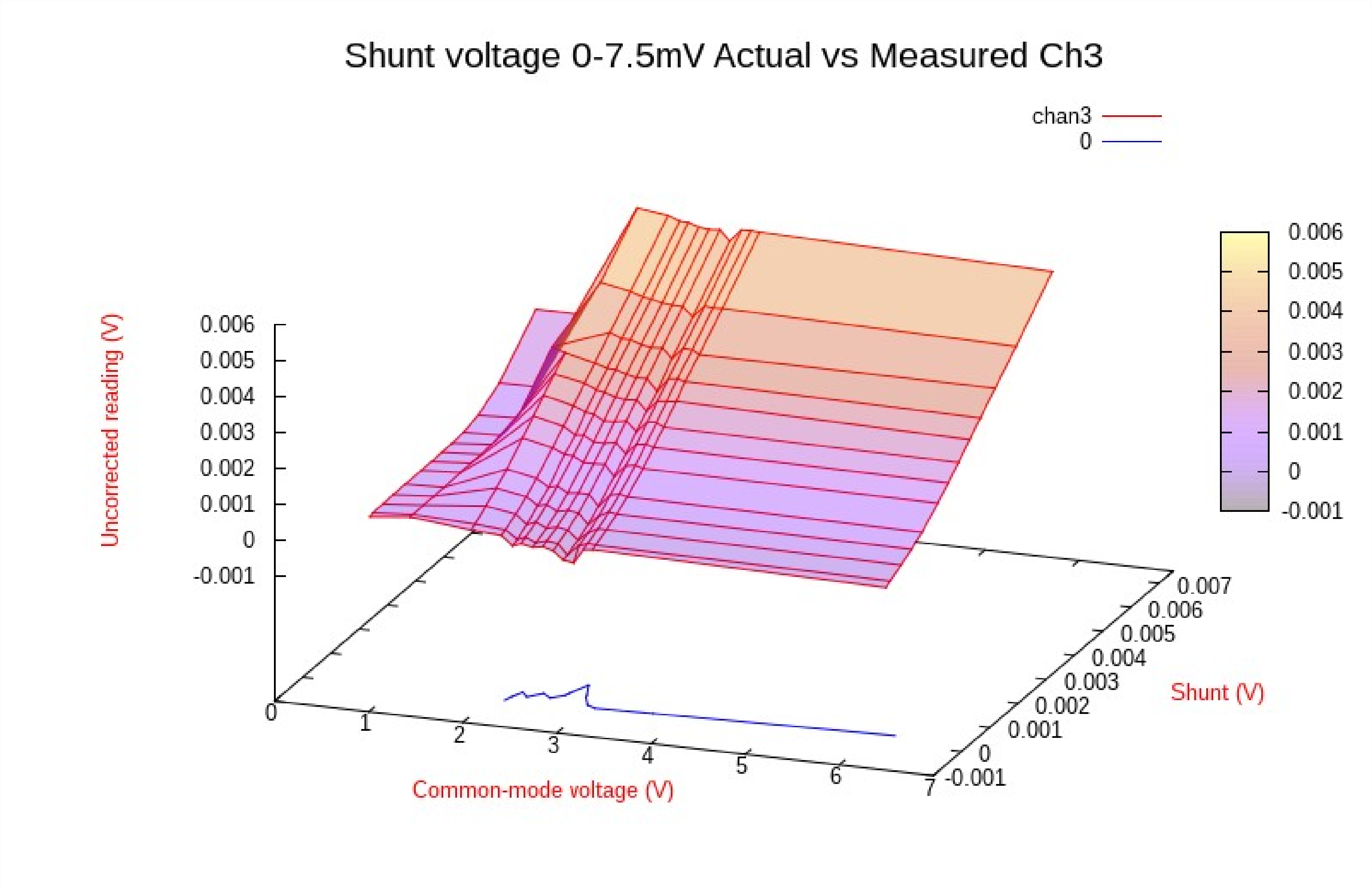
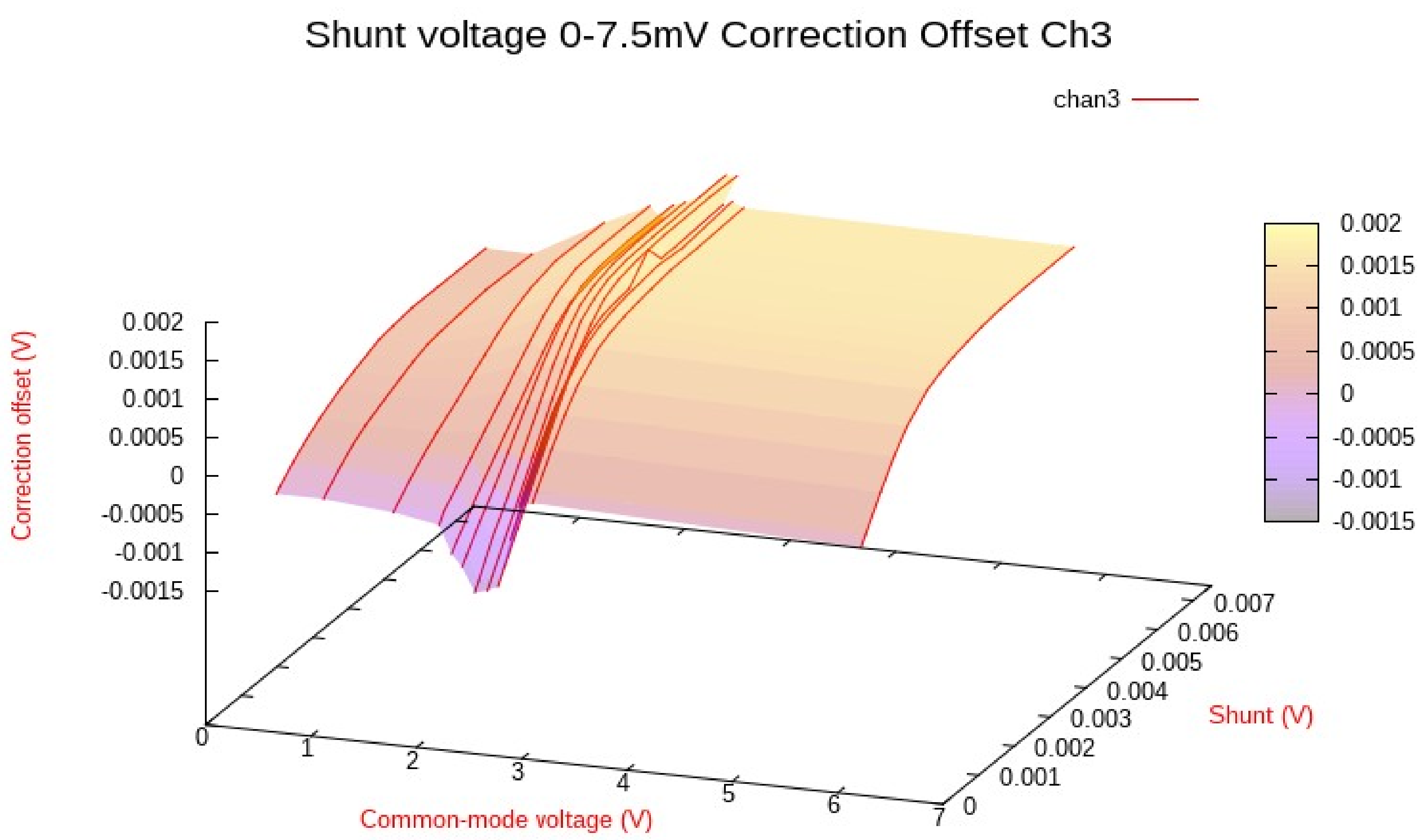


Actual transfer functions (0-7.5mV)

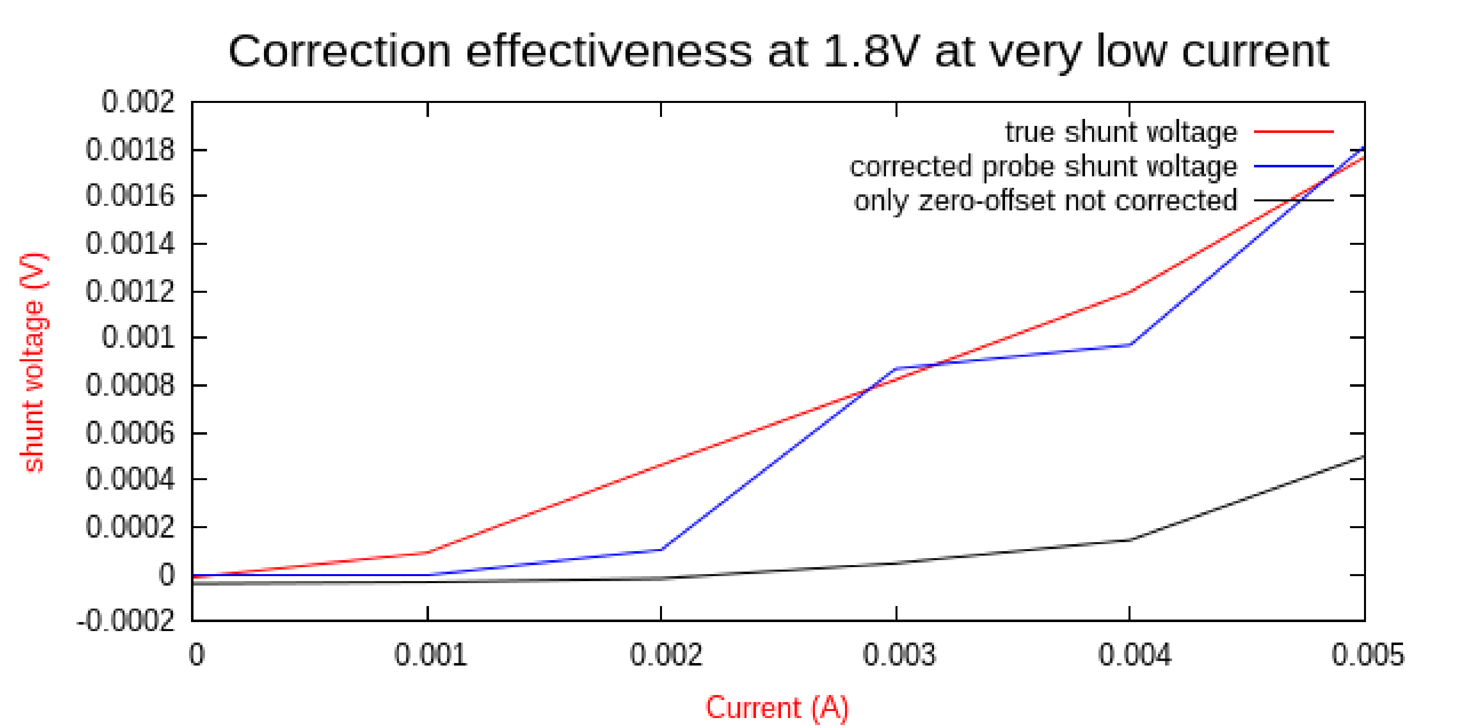
- 

Correction model

- Software can also measure channels when shorted to 0V, and store these autozero offsets and noise estimates for voltage and current measurements per channel stored in config file
  - Perform autozero with sense leads shorted to 0V before doing measurement series
  - Try to keep temperature stable during measurements

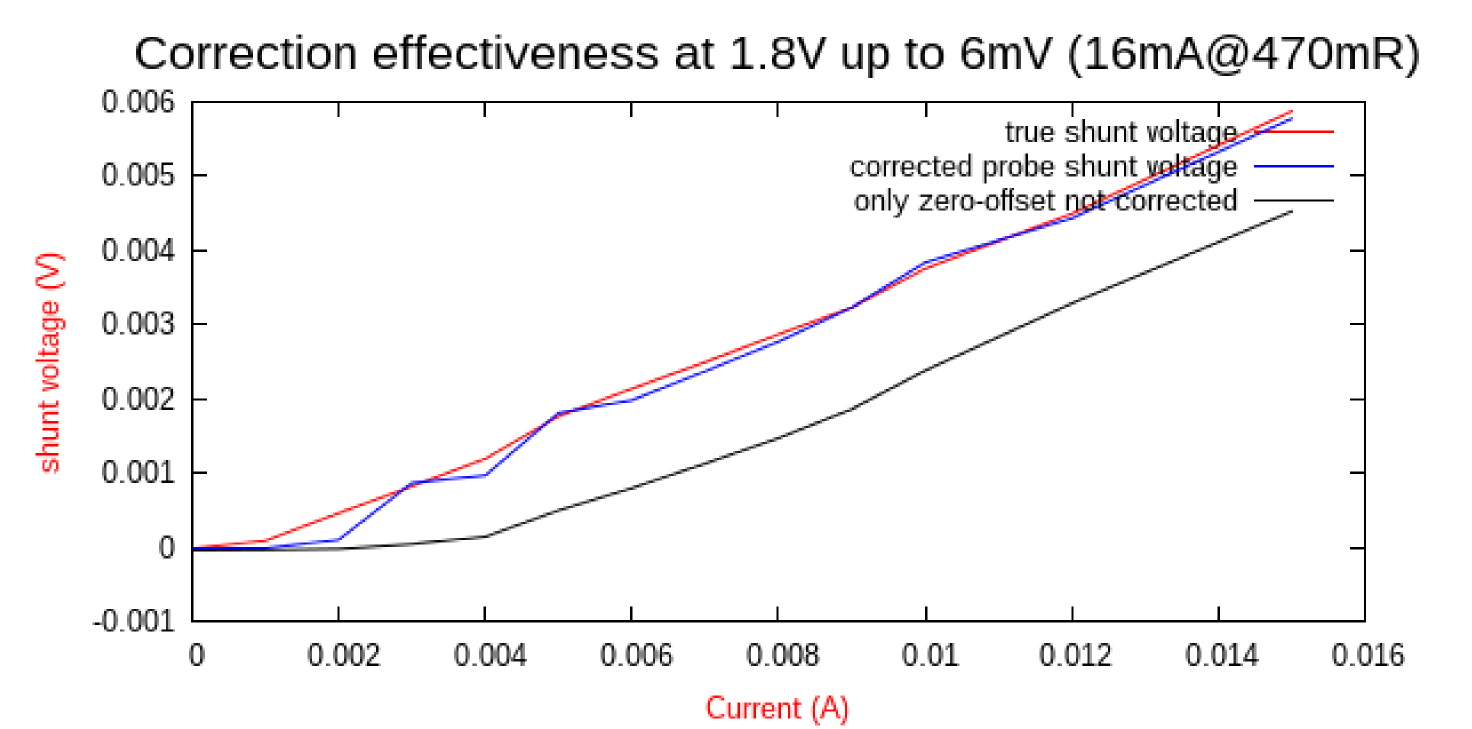
Correction Effectiveness (ch1)

- No data to repair at < 2mV across shunt
  - Uncorrected slope too flat near 0V to measure



Correction Effectiveness (ch1)

- At >2mV across shunt, correction effective
  - Flat nonlinearity exists only near 0V



Low current measurements

- Probe (ch1) unable to measure < 2mV across the shunt (<4mA @ 470mR shunt)
- 4uV measured difference in shunt voltage between 0mA and 1mA load with 470mR shunt (should be 470uV per mA)
  - Problem caused by flat, nonlinear response near 0V shunt voltage
  - 10°C temp change causes >1000uV drift by comparison, **4uV is lost in 0V offset drift**

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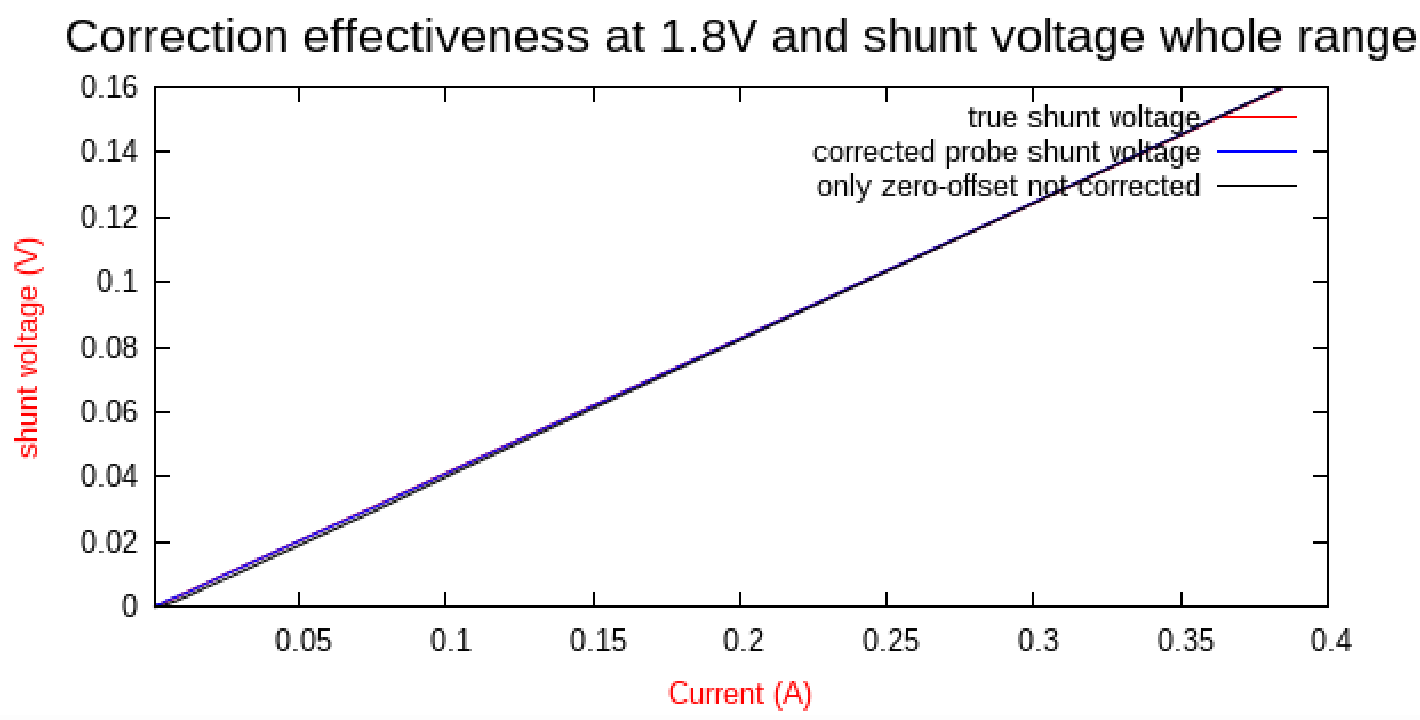
Low current measurements

- Increasing shunt value helps a bit
  - With 1R shunt, > 2mA OK, limited to 165mA; 2R shunt down to 1mA OK, limited to 82mA
  - High value shunts may cause difficulties at input side of switching regulators
    - Try adding 10uF+ ceramic cap after shunt if so
- Hard to get good numbers for suspend on normally high-current (low Rshunt) rails
  - Conflicting requirements on Rshunt selection

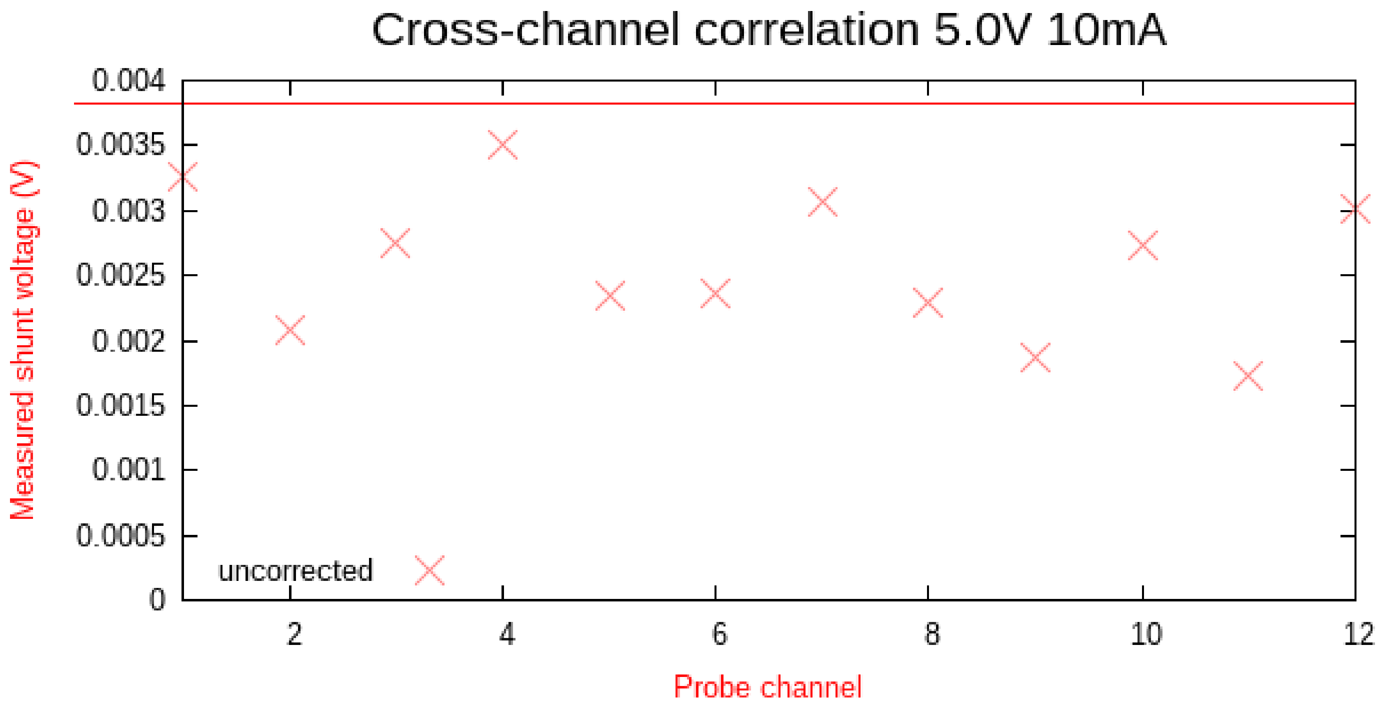
Correction Effectiveness

- Linearity and accuracy improve at higher shunt voltages up to 165mV maximum
  - Graph hides the mess down near 0 ☺



Differences between channels

- Uncorrected (except zero offset) measurement on 12 channels of 4 probes for same 3.829mV shunt voltage (red line)



Differences between channels

- 1.8mV spread of results for same 3.8mV measurement, just by using different channels... >47% error...
- Common-mode voltage detection was fine with spread of only 105mV (2%) for 5.0V measurement over 12 channels, just differential shunt voltage measurement affected

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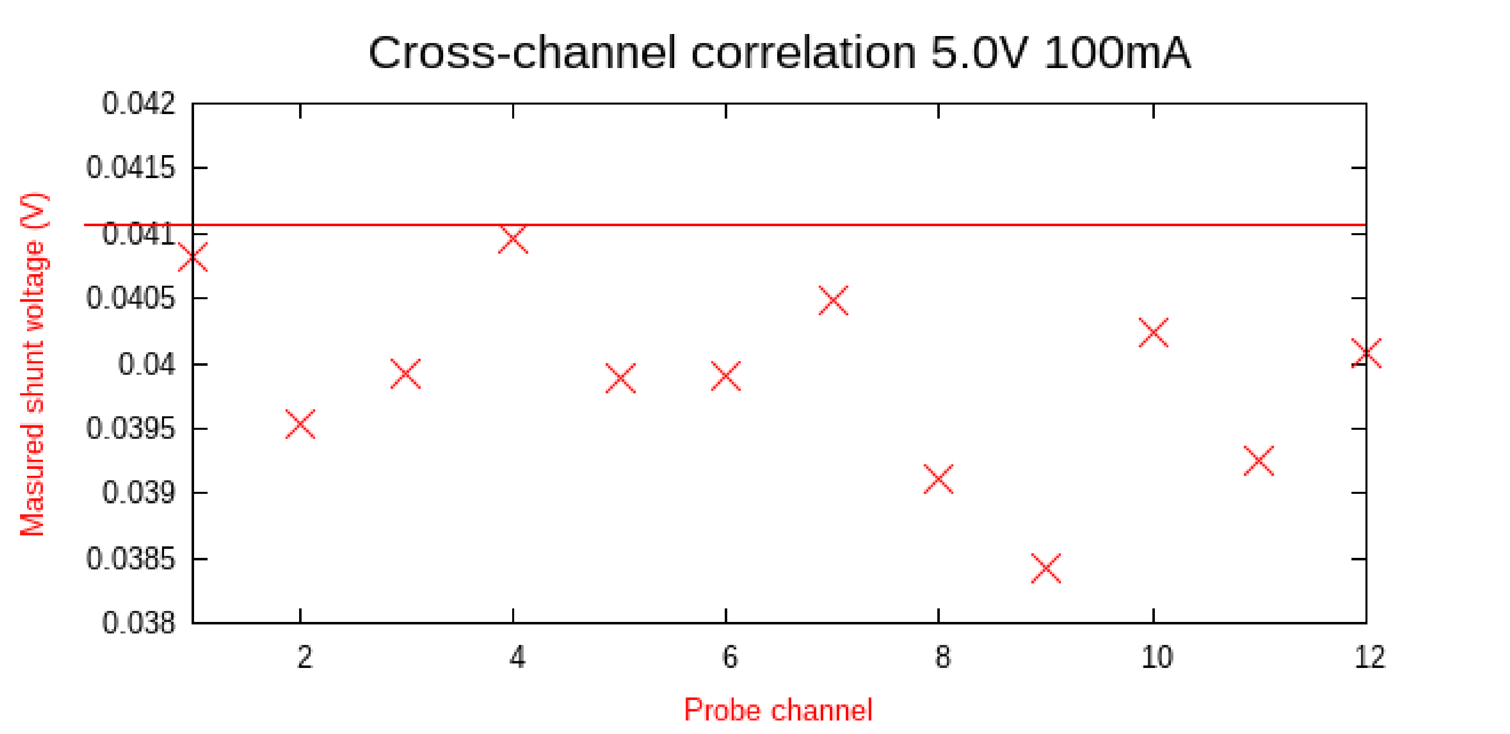
Differences between channels

- Spread at higher shunt voltage (41.05mV red line) narrows, worst error -5%

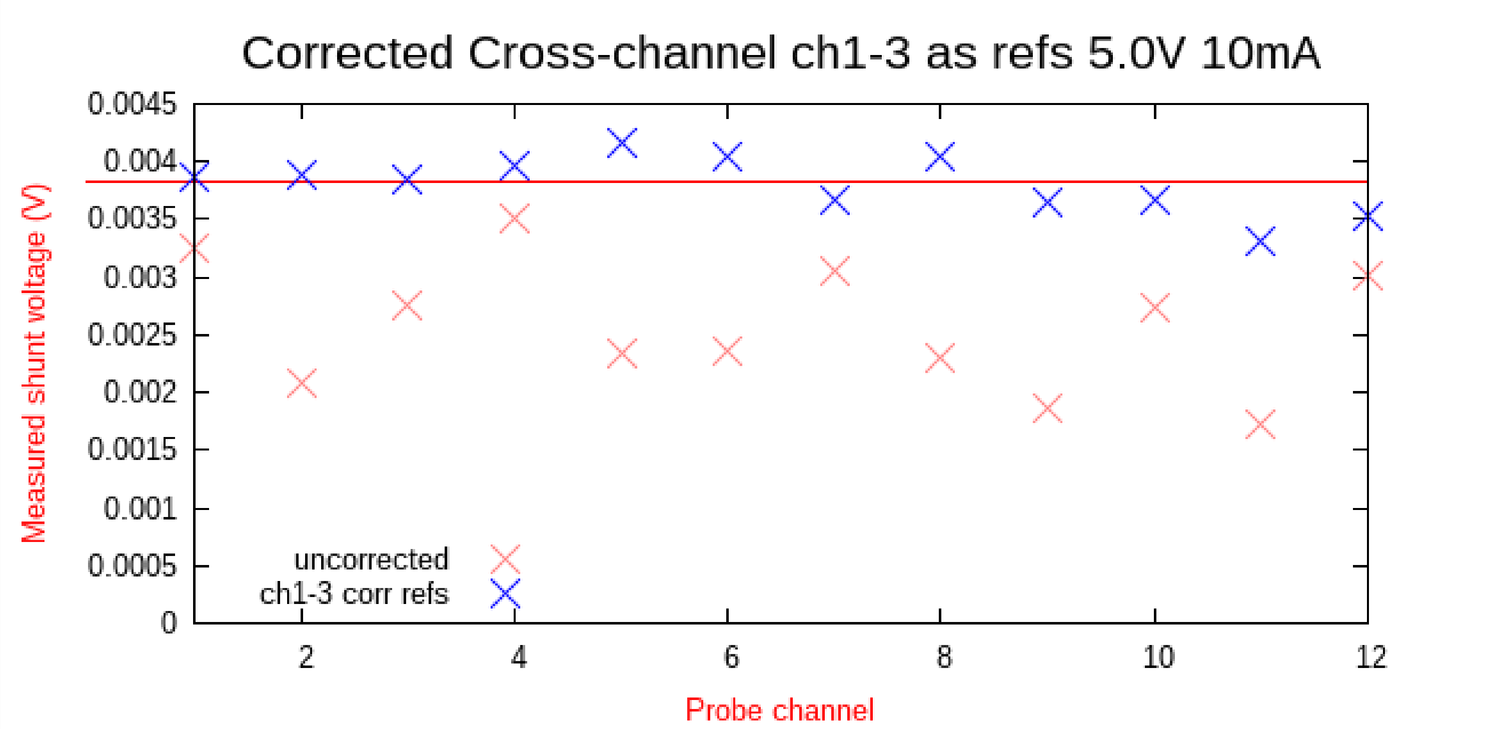


Channel correlation correction

- Detailed correction maps taken from channels 1 – 3 stored in software
- Channel config contains % uncorrected error at 3.8mV shunt voltage
  - User needs to measure it on each channel
- Software selects “nearest” correction map from ch1 (-14.5%), ch2 (-45%) or ch3 (-27.5%) for each channel.

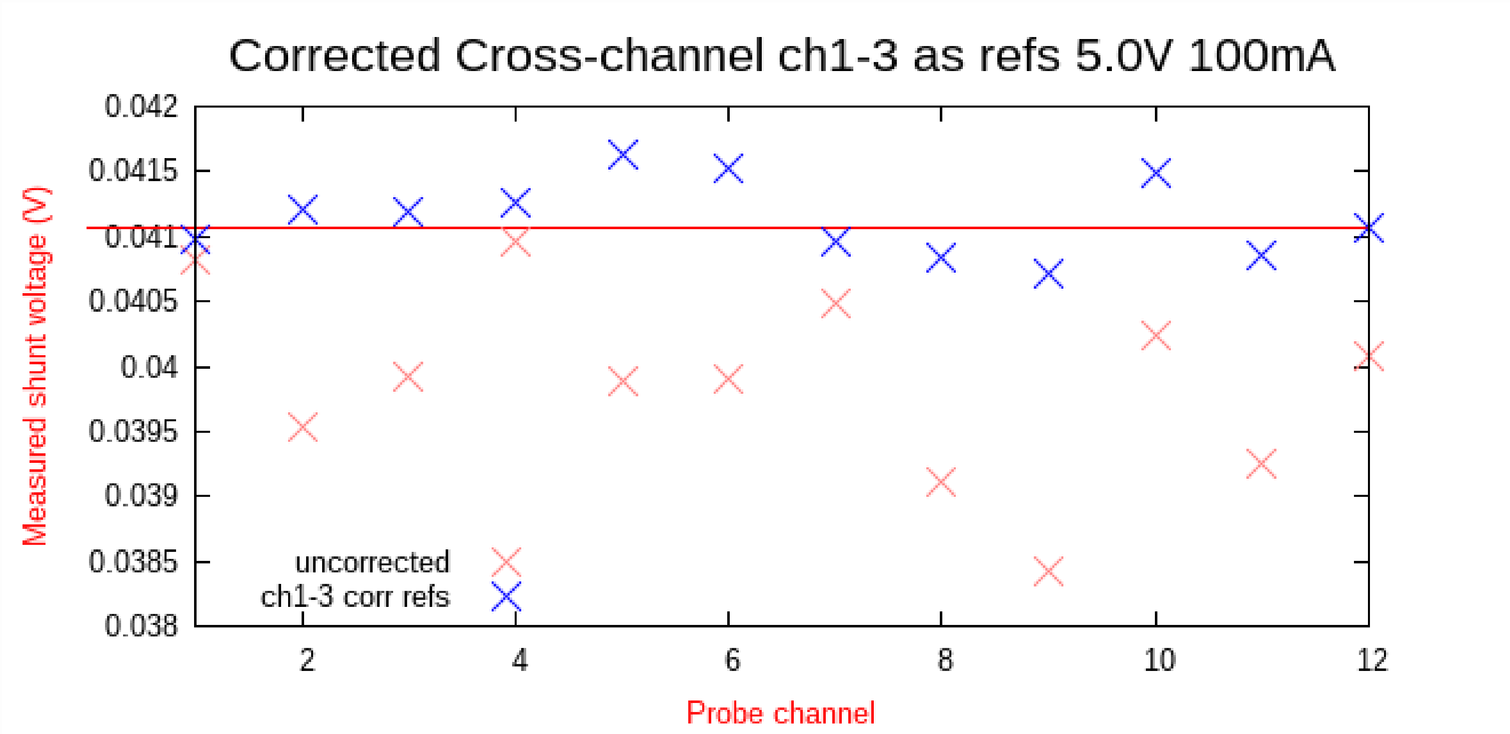
Channel correlation correction effectiveness

- Selected ch1-3 detailed correction maps
  - Error less than -13%/+9% at 3.8mV



Channel correlation correction effectiveness

- Selected ch1-3 detailed correction maps
  - Error less than +/- 1.2% at 41mV



Cross-channel calibration procedure

- For each channel, Autozero then
  - Use 470mR shunt in series with ~500R load (not mR!), and apply 5V: ~3.8mV should appear across the shunt
    - Measure the shunt voltage with a multimeter if possible to make error calculation more accurate
  - Measure channel using -r (raw) and note uncorrected shunt voltage measured
  - Add % error from real shunt voltage to config
    - If measurement is lower, use negative number

Shunt tolerance error

- All errors mentioned independent of shunt
- Also actual shunt resistance is not known precisely
  - Typically +/- 1% or 5% at room temp
  - Also varies with temperature
  - At high currents, may self-heat
    - Not typically a problem with our situation
  - Error here directly affects current and power calculations

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Summary

- Autozero before measurements
- Keep temperature stable
- Don't believe current measurements below a few mA, they are likely bogus
- Correction deals with most internal error sources, inter-channel correlation needs measurement and entry in config file
- Treat current measurements as +/- 10%

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Arm Energy Probe Basics

- What it is
- Quick electronics 101 recap
- Measuring around regulators
- Wiring your board for AEP usage
- Some actual measurements
- Major sources of measurement error
- Linux Commandline tool

Linux arm-probe commandline tool

- Scripting and gnuplot-friendly
- Output on stdout (info on stderr)
  - Gnuplot style ascii floating point
    - `Sample# volts amps watts` (default) or
    - `Sample# watts` (**--justpower / -j**)
- If previous output piped into stdin, adds column
  - Friendly for combining multiple runs
    - `Sample# watts1 watts2`

Config file

- By default, ./config, # for comments
- First non-comment line is name for setup the config represents, eg, PandaES-B1-ANDY
- Then device path like /dev/ttyACM0
  - Followed by 3 x channel setups indented by space
  - <space> <channel name> <Rshunt> <Vslope> <Voffset for current> <fixed pretrigger> <”pretty name”>

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Config file

- Example config file
  - PandaBoardES-B1-ANDY
  - /dev/ttyACM0
    - VDD_VCORE1 0.470 1 -0.000253 0 VCORE1/MPU
    - VDD_VCORE2 0.470 1 -0.000262 0 VCORE2/IVA_AUDIO
    - VDD_VCORE3 0.470 1 -0.000304 0 VCORE3/CORE
- Space indent at start of channel lines is critical!
- Can define multiple probes in one config

Channel Autozero

- **--autozero / -z** takes 5s average on selected channel and writes the voltage and current seen into config for that channel
  - `arm-probe -c VDD_VCORE1 -z`
- During this, short both channel sense lines to 0V line so you are measuring 0V, 0A offset
  - Unfortunately the offset varies by channel and temperature...

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Auto zero tracking

- **--autozero / -z** also estimates voltage noise
- During normal captures, after applying the zero offset correction, if samples below 0 are seen, it may adapt the offset
  - If the negative sample is outside the noise range
  - If we have been sampling for a little while
  - Zero level offset changed by 10% of the deltas
  - Cannot do same trick for offset decreases

Channel names

- Select the channel you will capture using the channel name from the first config column
  - **--channel / -c** <channel name>
  - If you have multiple probes, will find the correct probe according to /dev/ttyACM section in config
  - Take care to connect probes to USB in same order
  - “Pretty name” is used for channel in output
    - Gnuplot needs '_' to be '_' in pretty name

Channel names

- You can give -c multiple times
- You can simultaneously capture from one channel per probe
  - No matter how many probes you use, and how many channels, you can capture all channels in no more than 3 runs

Trigger threshold and filtering

- Specify “trigger” threshold in mV or mW
  - In volts (**--mvtrigger / -q** <mV>), and / or
  - In power (**--mwtrigger / -w** <mW>)
  - Default, 400mV, 0mW
- Specify how long trigger must remain true to be accepted (**--ustrigfilter / -f** <us>)
  - Default, 400us (four samples)
  - 200mV / mW hysteresis applied

Pretrigger

- Until trigger conditions seen, probe in “pretrigger” state
  - Nothing on stdout
  - Displays live volts / amps / watts on stderr
- Can capture to pretrigger buffer so you can see what led up to trigger event
  - (**--mspretrigger / -p** <ms to capture>)
  - Pretrigger buffer flushed on stdout first

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Trigger holdoff

- Amount of time to wait after trigger event seen before actually triggering
  - **--mstrighold / -t** <ms>
  - Default 0ms
  - Allows you to target events that occur a fixed period after, eg, power-on, without capturing everything before

Capture length and autoexit

- Can define how long to capture data
  - **--mslength / -l** <ms> (default: no limit)
    - Needed when combining captures on stdin
  - **--exitoncap / -x** exits the program when this capture limit is reached
  - **--offexit / -o** waits for trigger conditions to be false before exiting the program
    - Perfect to sync multiple scripted captures so next capture can trigger at power-on

Averaging

- Can apply mean averaging
  - **--mean / -m** <samples> (default: none)
    - Use with a large mean buffer to get single figure results instead of graph data
    - Ten samples per ms, so **-m 50000 -l 5000** gives perfectly mean-averaged 5s capture
    - Set your device to loop performing use-case
    - Choose a capture interval several times one loop period for best accuracy

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Averaging

- Append a simple average to results
  - **--average / -a** <secs (float)> (default: none)
    - This is separate from the mean averaging
    - Even if you are not averaging the actual results, you can use this to get two extra results added at the end
    - These start from the time given (eg, 5.2) in seconds, which should be at or after the end of samples
    - With gnuplot, provides averaged “bars” on right

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Decimation

- Reduces output to once per n samples
  - **--decimate / -d** <samples> (default: 1)
    - Allows long period monitoring of rails without being overwhelmed by data
    - Can be combined with mean averaging, eg **-m 50000 -d 50000** issues one new fully averaged sample every five seconds
    - Sample# in output still counts real input samples, so you can follow real time

Multicapture helper scripts

- Two common multichannel capture cases supported by scripts
  - **aep-capture.sh** - capturing on all channels during or after boot for fixed period
    - Manages observing power cycling of target for each channel and synchronzing captures
  - **aep-zero.sh** – autozeros every channel
    - Assumes no current across shunt and no voltage compared to 0V, eg, all short to 0V

Gnuplot scripts

- Gnuplot scripts will need customizing for your setup but have the basics
  - aeplot-average -
  - (continued next time...)