Avoiding Battery Brownout
Tips for Astronomers

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Introduction

In the last two decades, amateur astronomy has been revolutionized by modern developments in electronics: digital cameras, image processing, and the *GOTO* telescope mount. It's now possible to click on some astronomical target on a laptop screen, or choose a target from a menu, and cause the telescope to slew to that location.

Figure 1: IOptron MiniTower GOTO Mount
Photocredit: `https://www.altairastro.com/product.php?productid=16225`

The GOTO mount consists of motors, gears and shaft encoders that are controlled by a microprocessor. In the field, the mount is powered by a portable battery, usually a 12 volt rechargeable.

The battery must be large enough to operate the mount - and any other equipment, such as dew heaters - for the duration of the viewing session. On the other hand, a battery is large and heavy, so it should be no larger than necessary.

In this paper, we describe techniques for choosing a battery of appropriate size and then how to maintain and monitor the battery operation.

Battery Theory

An electrical battery is a device for storing energy, by some sort of chemical reaction.

The plates of a lead-acid battery obtain a covering of lead sulphate during discharge, which changes back to lead buring charge. In a lithium-ion battery, lithium migrates between the two plates of the battery.

We can model a battery as an electrical device, without regard to the details of the battery chemistry. In figure 2, E is the battery and R the load resistance. To a first approximation, the battery voltage remains constant as it supplies current I to the load resistance. Eventually the stored charge in the battery is depleted and the battery voltage drops.

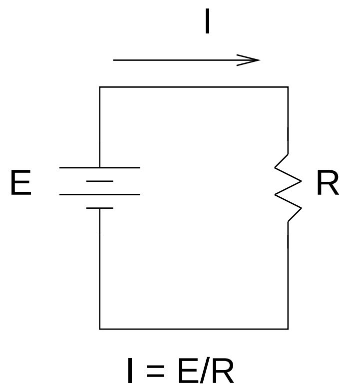
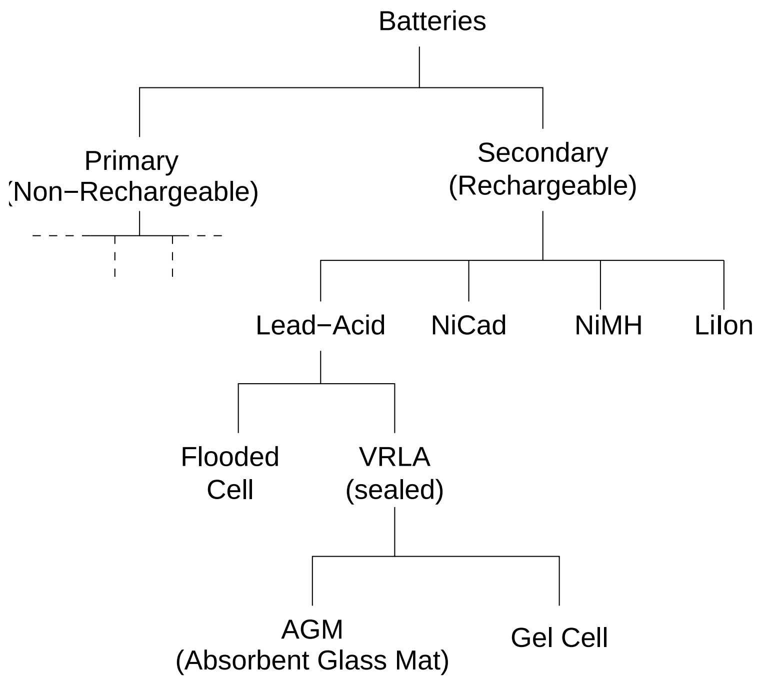


Figure 2: Modelling a Battery

Battery Types

There are two main categories of batteries: *primary* (non-rechargeable) cells and *secondary* (rechargeable) cells. Here we shall concern ourselves with the latter.

Wikipedia [1] lists 21 different types of rechargeable cells. A small subset of those are in active, practical use. We list those, and one speculative unit - the *sugar* battery, in the table shown below and in figure 3.



Type	Cell Voltage	Energy Density	E/$ WH/$	Self Discharge	Cycles	Notes
Lead-Acid	2.1	35	6.5	4%/mo	750	VRLA, AGM, Gel
NiCad	1.2	50	13	0.3%/mo	1500	
NiMH	1.2	65	36	30%/mo	750	
Li-Ion	3.6	200	29	7%/mo	800	
Sugar	0.3 to 0.6	2000				Future

Figure 3: Battery Types

Lead Acid

The lead-acid battery is historically the oldest type of battery, but it continues to be popular. As shown in the table, it has the lowest energy density, indicating that it will have the largest size (and, as it turns out, largest weight) of these batteries. Also, as indicated in the table, it has the highest cost per watt-hour of energy stored. However - not shown in the table - the lead-acid battery is relatively simple to charge and maintain, and so it continues to be the first choice for this application. Much infrastructure exists for this type of battery - for example, the battery *tender* - a device to charge and maintain a lead-acid battery - is readily available at reasonable cost.

NiCad

NiCad batteries were popular at one time because they are capable of substantial short circuit current. However, cadmium is very toxic so the battery creates a disposal problem and it is now banned in the European Union.

Nickel Metal-Hydride (NiMH)

These batteries are a replacement for Nicad, especially for small, rechargeable batteries. NiMH batteries have a substantial self-discharge, about 4% per day [2].

Lithium-Ion

Lithium Ion batteries are a *substantial* advance in battery technology, with a huge increase of energy for a given size and weight compared to lead-acid. Li-Ion has been an enabling technology for battery-operated power tools and electric cars, among others. However, Li-Ion requires a special charger: overcharging will damage the cells and can cause an explosion. Catastrophic fires caused by microscopic short circuit between plates are a concern and require stringent quality control, sending up the cost. Generally speaking, the battery and its charger should be purchased together, ensuring that they are properly matched. Also notice that the cell voltage is 3.6V compared to lead acid 2.1V, so Li-Ion is not a direct substitute for lead acid.

Li-Ion batteries will eventually show up as power for GOTO telescope mounts, integrated into the mount with the charging electronics. Celestron have just announced the NexStar Evolution 8, which has an integral Li-Ion battery. The mount is claimed to be capable of 10 hours operation[1].

Types of Lead-Acid Battery

Drilling further down in the battery heirarchy of figure 3, there are three variations on the Lead-Acid battery.

Flooded Cell

This is the historic design of lead acid battery, where the plates are submerged in a liquid electrolyte. Each cell is in a separate compartment, with a removeable cap. The battery produces oxygen and hydrogen gas when it is being charged, so it must be operated in a ventilated location.The battery must be maintained in an upright position and periodically refuelled with distilled water.

Flooded batteries cannot be shipped by air.

The state of charge of the battery can be determined with a *battery hydrometer*. A sample of the liquid electrolyte is sucked into a turkey-baster like syringe. The level of a float in the syringe shows the state of charge of the battery.

According to reference [3] flooded batteries are the best choice for renewable energy systems (such as a solar or wind power system).

Figure 4: Flooded Lead Acid Battery
Photo credit:
http://www.baebatteriesusa.com/products/opzs_block.shtml

Sealed Lead-Acid Battery

The generic term for a sealed lead-acid battery is *valve regulated lead-acid: VRLA*. These further subdivide into *absorbent glass mat: AGM* and *gel cell*.

Absorbent Gas Mat: AGM

AGM batteries have replaced flooded cells in automotive use, so they are readily available at reasonable cost. The battery is sealed and the electrolyte contained in a fiberglass matrix, so it does not vent gasses when charged. The capacity and maximum output current are slightly less than a flooded-cell battery.

Gel Cell

In a Gel Cell, the electrolyte is contained in silica gelatinous material. They are somewhat more acceptable in certain environments such as aircraft equipment. However, they are more expensive than an equivalent AGM battery, have higher internal resistance (limiting the maximum output current) and the capacity decreases at low temperature[2].

[1] Thanks to Dave Roberts for a pointer to this product.

[2] The author once constructed a 28 volt gel-cell battery pack to operate a helicopter-borne instrumentation system with a capacity of 40 amp-hours. The battery pack was massive: 39kg. A VRLA battery pack would have been smaller and lighter, but was not permitted by regulation [4].

The most common battery in use by amateur amateur astronomers for their goto telescope mount is a lead-acid cell, vrla (sealed), absorbent glass matt type.

Care and Feeding of the Lead-Acid Battery

Charging

With some care, a lead-acid battery will last through 200 to 300 charge-discharge cycles over a period of years [5].

The ideal lead-acid cell charger charges the battery in three stages:

1. **Bulk Charge** Charge the battery with constant current. The battery voltage increases as the battery charges. The rate of charging can be quite high as long as the charger transitions properly to the next stage (constant voltage) [6]. The battery is about 70% efficient in converting charge current into stored charge, so more charge must be supplied than is actually stored.
2. **Topping Charge** Hold the charging voltage at something between 2.3 and 2.4 volts per cell (13.8 to 14.4V for a 6 cell battery) until the charging current drops to a low value.
3. **Float** Reduce the voltage to the *float* voltage and hold it there. The float voltage is 2.2 volts per cell, or 13.4 volts for a 6 cell battery at 26°C. This voltage is critical, and should be temperature compensated at a rate of -3.9mV/°C.

Figure 5: Battery Tender
Photo credit:
`http://media.digikey.com/photos/Patco%20Electronics%20Photos/3201P,3202P,3202-750.JPG`

A charger that maintains a float charge can be left connected to the charger for long periods of time. The charger is then referred to as a *battery tender* (figure 5).

A simpler charger can be used to replentish the charge in the battery, but it then needs to be disconnected when the battery is fully charged. Failure to do that will damage the battery. Human beings tend to be distracted from watching over a battery, so simple chargers are usually a bad idea.

When purchasing a charger, look for the term *battery tender* and/or *temperature compensated float voltage*.

A Custom Charger

For those who are interested in the internal circuitry of a battery charger, there there are many descriptions on the web of constant-current constant-voltage supplies that can execute steps 1 and 2 of the charging protocol. However, it is rare to find a circuit that executes step 3, maintaining the float voltage. The UC3906 integrated circuit, described in [8] and [9] is specifically designed to implement a battery tender, and probably a good place to start a custom charger design.

Discharging

It is clear that one should not discharge the battery below its *cutoff voltage*. The value of the cutoff voltage varies from 12.5 to 10.5 volts among battery manufacturers and according to output current and duration of the discharge. Kendrick suggest 11.7 volts as a routine matter and certainly never below 11.0 volts [7]. A higher value limits the capacity of the battery and a lower one endangers it.

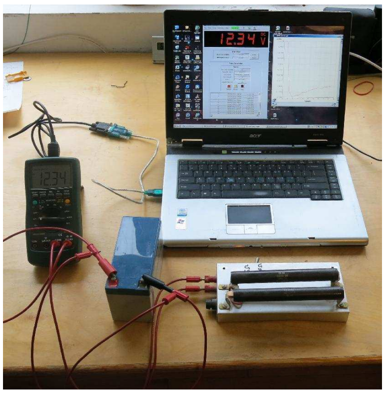
It is especially important that the battery not be left in the discharged state, that will lead to sulphation of the plates and destroy the battery. The battery will often recover from an excessive discharge if it is charged immediately.

Battery Capacity

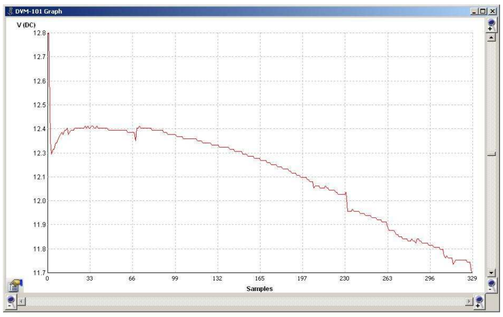
The *capacity* of the battery is given the letter C and is measured in amp-hours, that is, the product of the battery current and the time it can supply it[3]. For example, a 7 amp-hour battery should be able to supply 7 amps for one hour, or one amp for 7 hours, or 3.5 amps for 2 hours, and so on. This equation is *very* approximate: it depends on the history of the battery, the point at which the battery is deemed to be empty, on the rate of discharge, and on the ambient temperature. Consequently *the only way to be sure of battery capacity is to measure it.*

Battery charge and discharge currents are often given in terms of the battery capacity C. For example, a 7 amp-hour battery being discharged at 0.1C is supplying a current of 0.7 amps.

Measuring Battery Capacity



(a) Measurement Setup



(b) Test Result

Figure 6: Measuring Battery Capacity

To measure battery capacity, the battery is discharged through a resistor, just as shown in figure 2. The battery voltage is recorded over time. When the battery reaches minimum allowable voltage (11.7 in the case of a lead-acid battery) the test is stopped. The capacity is calculated from the recorded graph.

The measurement setup is shown in figure 6(a). A 12 volt, 7 amp-hour battery[4] (blue) is connected to a 10 ohm, 100 watt load resistor[5], the brown cylinders on the right.

The 10 ohm load gives an approximate load current of

$$I = \frac{E}{R} = \frac{12}{10} = 1.2 \text{ amperes}$$

This load current isn't terribly critical, but it should be in the ballpark of the load current that will be used in practice.

A recording digital voltmeter Syscomp DVM-101[6] monitors the battery voltage while communicating the measurements to a laptop. The laptop computer records and displays a graph of the voltage against time.

The load resistor must be chosen so that it is capable of dissipating the load power. For a 12 volt battery with a 10 ohm load, the power in the resistor is given by:

$$P = \frac{V^2}{R_l} = \frac{12^2}{10} = 14.4 \text{ watts}$$

The Ohmite L100J resistor is capable of dissipating 100 watts, so there is lots of safety margin with that resistor. It does, however, get quite warm so it is best to mount it in the open where air convection can occur.

[3] The amp-second is a measurement of electrical *charge*, 1 coulomb (6.2×10^{18} electrons). So an amp-hour is equal to 3600 coulombs.
[4] PowerSonic PS-1270 F1.
[5] Ohmite L100J10R, available from Digikey, $10.
[6] www.syscompdesign.com, $79.

The resultant recording of battery voltage vs time is shown in figure 6(b). The measurements are taking place every 30 seconds, so reading 329 corresponds to 2.74 hours.

There are various ways to obtain the capacity from the graph. Very approximately, the average output voltage during the test interval was

$$V_{av} = \frac{V_{max} + V_{min}}{2} = \frac{12.4 + 11.7}{2} = 12.05 \text{ Volts}$$

Then the average current was:

$$I_{av} = \frac{V_{av}}{R} = \frac{12.05}{10} = 1.205 \text{ Amps}$$

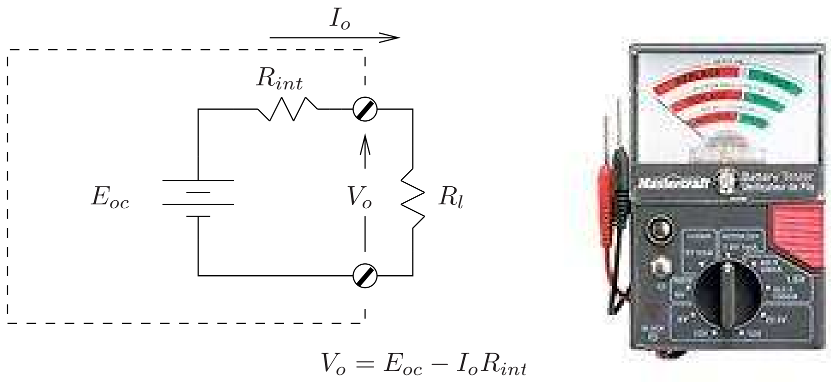
The time interval T was 2.74 hours, so the battery capacity is:

$$C = I_{av} \times T = 1.205 \times 2.74 = 3.3 \text{ amp-hours}$$

For example, if the telescope mount draws 0.5 amps when operating, then the operating time would be about 6.6 hours.

Notice that the measured capacity is only 47% of the battery nameplate capacity.

Internal Resistance



(a) Equation

(b) Tester

Figure 7: Internal Resistance

When the battery is open-circuited, there is no output current, and the terminal voltage V_o is called E_{oc} for *voltage, open circuit*. When current flows out of the same battery, the terminal voltage decreases. We model that effect by an *internal resistance* in series with the output, as shown in figure 7(a).

For example, suppose the open circuit voltage E_{oc} is 12.4 volts, the internal resistance R_{int} is 0.04 ohms and the output current I_o is 1.5 amperes. Then output voltage is given by:

$$V_o = E_{oc} - I_o R_{int} = 12.4 - 1.5 \times 0.04 = 12.34 \text{ volts}$$

This internal resistance is representative of a healthy battery [10], so the output voltage is not much different than the open circuit voltage. However, as the battery discharges or deteriorates, the internal resistance increases. The internal resistance is an important indicator of the state of the battery, so a proper test of battery condition should be done with a load attached. The open circuit voltage, by itself, can be very misleading.

The tester for small batteries[7] of figure 7(b) shows battery voltage under an appropriate load. This is much more useful than simply measuring the open circuit voltage.

[7] Canadian Tire #52-0057-2, $10.

For the internal resistance of a lead-acid battery is very low, so a substantial output current is required to indicate the state of the internal resistance. Furthermore, if the battery is connected to a short circuit, the output current is limited almost entirely by the internal resistance. For our example of a 12.4 volt battery with 0.04 ohms internal resistance, the short circuit current is theoretically 310 amps! In practice, the internal resistance of the battery will increase under these conditions, but there can still be a very large short circuit condition. For this reason, lead-acid batteries should have a fuse in the circuit.

It's useful to monitor the battery voltage under actual load conditions. If the battery voltage decreases significantly when supplying current, then the internal resistance may be a problem.

Deep Cycle (Marine) Batteries

These batteries are generally large and heavy, comparable in size and weight to an automotive battery.

An automotive battery is constructed to have low internal resistance and consequently have a large *cranking amperes* available for starting a car engine. To accomplish this, the plates are relatively thin. In use, a car battery is usually only partially discharged when starting the car engine. The car charging system supplies the necessary current for the automotive accessories.

A Deep Cycle battery is constructed to be charged and discharged over a larger range. To accomplish this, the plates are heavier than a car battery. The *cranking amperes* are lower, but the number of charge-discharge cycles to battery failure is higher. A deep cycle battery is appropriate for applications such as electric vehicles.

How does this apply to powering telescopes and laptop computers?

- If you need a large, heavy battery to operate your system a deep cycle battery is a better choice than a standard car battery. The deep cycle battery can be repeatedly recharged and is likely to last longer.
- Smaller AGM and Gel Cell batteries are generally designed for repetitive charge-discharge cycles, so there is no advantage to deep cycle batteries in smaller sizes.
- A deep cycle battery should not be discharged any further than any other lead-acid battery: in the order of 11.7 volts [11].

The Effect of Temperature

Lower temperature reduces battery performance in two respects: the battery capacity is lower (meaning it will discharge sooner for the same load) and the internal resistance is higher (meaning the output voltage will decrease more when a load is connected.) The internal resistance of a healthy lead-acid battery is extremely low, however, so it's mainly the battery capacity that is affected.

Battery capacity falls by about 1% per degree below about 20°C. [12]. For example, at -20°C, the capacity of the battery is 60% of its value at 20°C. Very approximately, the internal resistance will increase by 50% as the temperature drops from +20°C to -20°C [13].

Blake Nancarrow of the Toronto Chapter of the RASC[8] has a suggestion for cold-weather operation from a battery: place the battery in a food cooler[9], optionally adding a chemical hand-warmer.

Avoiding Battery Brownout: Summary

1. Choose a battery with enough capacity for the total current multiplied by the running time. Be conservative, use a safety factor of 2.
2. Charge and maintain the battery using a lead-acid *battery tender*.
3. Avoid discharging the battery below 11.7 volts.
4. Recharge the battery immediately after use. Do not allow it to sit in the discharged condition.
5. Periodically load test the battery to check its capacity.

[8] Royal Astronomical Society of Canada
[9] For example, Canadian Tire #85-3469-6

6. Monitor the battery voltage during operation, using a digital voltmeter or expanded scale voltmeter.
7. Watch for the drop in voltage under load that signals increased internal resistance.

Appendix: Expanded Scale Voltmeter

A digital voltmeter is an excellent instrument for monitoring the state of a battery, but it's not the most convenient device to use in the dark. Some digital voltmeters have a backlight, but it drains the meter battery rather quickly. Furthermore, the battery voltage changes under a transient load are not easy to view on a digital readout.

One possible alternative is the *expanded scale voltmeter* shown in figure 8. The schematic is in figure 9. This is a thermometer-type display of battery voltage on a special voltmeter scale expanded to show the range of voltages of interest. The readout is a row of LEDs, which are easy to view and interpret in the dark.

The design is based on the LM3914 Dot-Bar display integrated circuit [14], and one single-supply quad operational amplifier LM324. On the schematic of figure 9 the range is shown as 11.0V to 12.8V. The upper and lower limits are adjusted independently by two potentiometers. The LED intensity is adjusted by a third potentiometer.

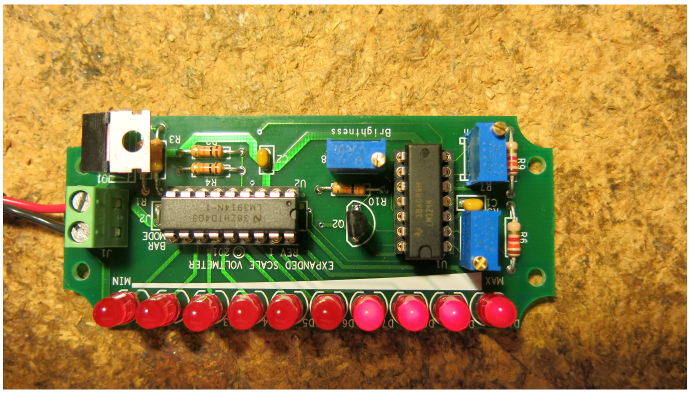


Figure 8: Expanded Voltmeter Circuit Board

The display can be configured by means of a jumper to show a thermometer-type bar, or as a single moving dot. For monitoring the voltage supply of a telescope, red LEDs are most suitable since these do not affect night vision. However, other LED colours could be used instead.

Adjustment and Calibration

You will need a voltmeter for this calibration.

- You can operate the expanded scale voltmeter circuit from any source of 12 volts, such as a 12 volt battery. The exact voltage is not critical. Connect the circuit to the power source, with extreme care to make sure the polarity is correct. The circuit is not diode protected and will be destroyed by a reversed power connection.
- Check the reference voltage, at pin 7 of the LM3914. It should be 1.25V.
- Check that pin 9 of the LM3914 is at +12V, in order to select `Bar` display mode. If it's not at +12V, check that the jumper J2 is shorted together.
- Adjust the `Intensity` potentiometer R8 so that it is at maximum, ie, pin 12 of the LM324 is at 1.25V.
- Adjust the Maximum potentiometer R5 so that pin 6 of the LM3914 is at half the maximum indicated voltage. For example, if the maximum indicated voltage is 12.8V, pin 6 should be at 6.4V.
- Adjust the Minimum potentiometer R7 so that pin 4 of the LM3914 is at half the minimum indicated voltage. For example, if the minimum displayed voltage is 11V, pin 6 should be at 5.5V.
- If you have access to an adjustable voltage supply, connect the expanded voltmeter to that. Vary the voltage between minimum and maximum (11 to 12.8V, for example) and the LEDs should display a column with no LEDs illuminated below 11V and all LEDs ON above 12.8V.
- Adjust the `Intensity` potentiometer R8 to give the desired LED brightness.

In particular, watch for a drop in voltage whenever the telescope mount is slewing – and therefore drawing significant current from the battery. A significant drop indicates an increase in internal resistance, which suggests the battery needs charging or replacement.

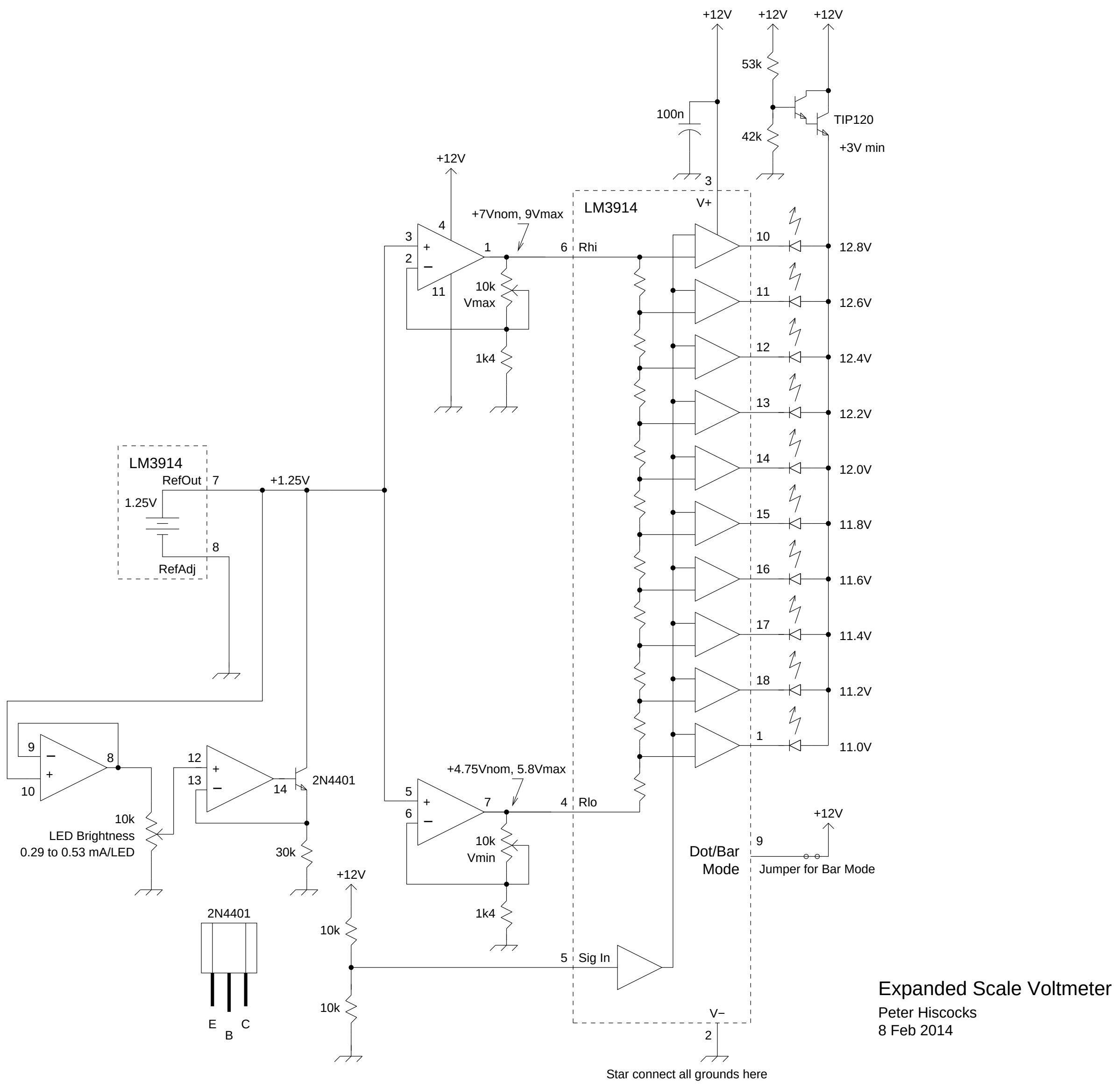


Figure 9: Expanded Scale Voltmeter

Parts List

Quantity	Reference	Description	Value	Manufacturer	Part Number
2	C1, C2	CAP CER 0.1UF 50V 10% RADIAL	100n	Vishay	K104K15X7RF5TL2
10	D1..D10	LED SS 5MM 625NM RED DIFF	Red	Kingbright	WP7113LID
1	J1	CONN TERM BLOCK 2POS 5.08MM PCB	Terminal Block	Phoenix Contact	1729128
1	J2	SIL VERTICAL PC TAIL PIN HEADER	JUMPER	Harwin Inc	M20-9990245
1	Q1	TRANS NPN DARL 60V 5A TO-220	TIP120	Fairchild	TIP120
1	Q2	IC TRANS NPN SS GP 600MA TO-92	2N4401	Fairchild	2N4401BU
1	R1	RES 51K OHM 1/4W 5% AXIAL	51k	Yageo	CFR-25JB-52-51K
2	R2, R4	RES 10K OHM 1/4W 5% AXIAL	10k	Yageo	CFR-25JB-52-10K
1	R3	RES 43K OHM 1/4W 5% AXIAL	43k	Yageo	CFR-25JB-52-43K
3	R5, R7, R8	TRIMMER 10K OHM, 25T	10K	Bourns	3296W-1-103LF
1	R6	RES 1.6K OHM 1/4W 5% AXIAL	1k6	Yageo	CFR-25JB-52-1K6
1	R9	RES 2.7K OHM 1/4W 5% AXIAL	2k7	Yageo	CFR-25JB-52-2K7
1	R10	RES 30K OHM 1/4W 5% AXIAL	30k	Yageo	CFR-25JB-52-30K
1	U1	IC OPAMP GP 1.2MHZ 14DIP	LM324	Texas Instruments	LM324N
1	U2	IC DRIVER DOT BAR DISPLAY 18-DIP	LM3914	Texas Instruments	LM3914N-1/NOPB
1	n/a	IC Socket 18 DIP		Assmann WSW	AR18-HZL-TT-R
1	n/a	IC Socket 14 DIP		Assmann WSW	AR14-HZL-TT-R
1	n/a	Plastic Case		Hammond	1591ATCL

References

[1] *Rechargeable battery*
http://en.wikipedia.org/wiki/Rechargeable_battery

[2] *NickelâĂŞmetal hydride battery* http://en.wikipedia.org/wiki/Nickel-metal_hydride_battery

[3] *Deep-Cycle Flooded Lead-Acid Batteries (FLA)*
http://www.trojanbatteryre.com/Tech_Support/ComparingFlood2VRLA.html

[4] *A Microcomputer-Based Camera Control System*
R.J.Hall, P.Hiscocks
Photogrammetric Engineering and Remote Sensing, Vol 56, No. 5, April 1990, pp 443-446

[5] *Can the Lead-acid Battery Compete in Modern Times?*
http://batteryuniversity.com/learn/article/can_the_lead_acid_battery_compete_in_modern_times

[6] *Sealed Lead Acid Battery Charging Basics*
http://www.powerstream.com/SLA.htm

[7] *Power Pack FAQ*
Kendrick Astro Instruments
http://www.kendrickastro.com/powerpackfaq.html

[8] *Improved Charging Methods for Lead-Acid Batteries using the UC3906*
Unitrode Application Note U-104
http://www.ti.com/lit/an/slua115/slua115.pdf

[9] *Simple Switchmode Lead-Acid Battery Charger*
John A. O'Connor
Unitrode Application Note U-131
http://www.ti.com/lit/an/slua055/slua055.pdf

[10] *Powerstream: Internal Resistance*
http://www.powerstream.com/1922/battery_1922_WITTE/batteryfiles/chapter08.htm

[11] *What happens to the voltage of a deep cycle battery during use?*
http://www.knowyourplanet.org/off-grid/batteries/deep-cycle-battery-voltage-and-discharge

[12] *Photovoltaic Education Network*
http://pvcdrom.pveducation.org/BATTERY/charlead.htm

[13] *Battery Performance Characteristics*
Electropaedia
http://www.mpoweruk.com/performance.htm

[14] *LM3914 Dot/Bar Display Driver*
Texas Instruments
http://www.ti.com/lit/ds/symlink/lm3914.pdf