

Solar Panels

Applications of solar cells on Cricket beacons

I. Purpose

We would like the Cricket beacons to evolve into a self-contained and self-sustained unit, which can drop in and out of intricate location support networks easily. In terms of power, solar power is the only alternative that accomplishes this. Solar power is a cost efficient, convenient alternative power source for the Cricket beacons. Not only do they make installation much easier through their lack of cables and complicated wiring, they also save much time on maintenance, as they are self-sustained units – no parts need to be replaced regularly (such as batteries). In this paper, I document my investigations on solar power in general, and on its application for beacons.

II. About the Panels

The panels I have chosen to use are small 60mm square solar cells¹. I was presented with four of these units when I began this project. Neither the manufacturer nor retail seller is known about these cells. However, I was able to find a product that seemed to be identical to this in every respect, appearance and performance. I subsequently ordered ten more of these solar cells. Specifically, they are the OK-60 model solar cells at OKSolar.com (http://www.oksolar.com/pv/pv_cells.htm, sold at allelectronics.com CAT# SPL-60), rated 3 Volts at 40 mA. Yet, still not much information was provided on these cells at this web site, and no data sheets could be found online.

Unlike batteries, solar cells do not provide a constant voltage, nor do they provide a constant current either. Depending on the wavelength of light, intensity of light, temperature of the cells, and the load connected to it, voltage and current may vary. The cells that I have in possession produce approximately 3.5V (their max output possible) outside on a sunny day, with or without a beacon load connected. However, when indoors, their behavior is much more interesting and calls for much investigation. On a desk under simple office lighting, a solar cell produces an open circuit voltage of about 1.4 V and a 0.2 mA short circuit current. But if held up against the light fixture, it produces 3.2V at 1.7mA. However, this is just OC voltage, and it does not provide much information about how the cells will perform when connected to a load such as a Cricket beacon. After a few simple tests, it was noted that these cells are not very capable of producing current indoors. When any load is connected, the voltage and current both drop tremendously (see solardata.xls for more comprehensive data).

I must also note that no two cells are the same; each one is unique in its own way. In other words, each will output a different voltage and current even if under the same lighting conditions and connected to the same load. Of the 14 cells I now have in total, I have classified them into 3 groups. Group 1 (named the 0.3V group) cells produce some OC voltage and some SC current (0.3V @ 45mA) under a specific lighting condition.

¹ Throughout the process, another solar cell was also being tested. It was the SS-SC-250T rated 250mA @ .58V by SiliconSolar (www.siliconsolar.com). However, due to the fragile nature of these cells (and they also required a lot more work before they could be used efficiently), these cells were quickly abandoned and the OK-60 cells became the mainstream cells used in all other tests, experiments, and explorations. For more information on these cells, see Appendix B.

Group 2 cells (the 0.45V group), under the same conditions, provided more voltage and current (0.45V @ 0.52mA). And finally, Group 3 (the 0.6V group) cells produced the most voltage and current under the same lighting (0.6V 0.6mA). I have labeled each cell according to its group, as it is imperative that one must not connect two cells from different groups together, whether it is in series or parallel. In a series of 0.45V(0.52mA) cells, a 0.3V(0.45mA) cell would drive the current down to 45mA. In a parallel connection of 0.6V groups, a 0.45V cell would drive the voltage down to 0.45V. The current through a series is equal to the current produced by the lowest current cell; and the voltage across a parallel connection is equal to the voltage of the lowest voltage cell.

I continued to perform more tests with solar cells, connecting them up in series and parallel and combinations of both. To understand the performance of these cells, I measured their OC voltage as well as their voltage when connected up to some load (in this case, the Cricket beacon). Likewise, I measured their SC current and output current. The settings under which these tests were conducted are as follows: office light, office light and spotlight, and intense office light (by placing the panels in the light fixture). The following two graphs summarize my findings (see solardata.xls for more comprehensive data).

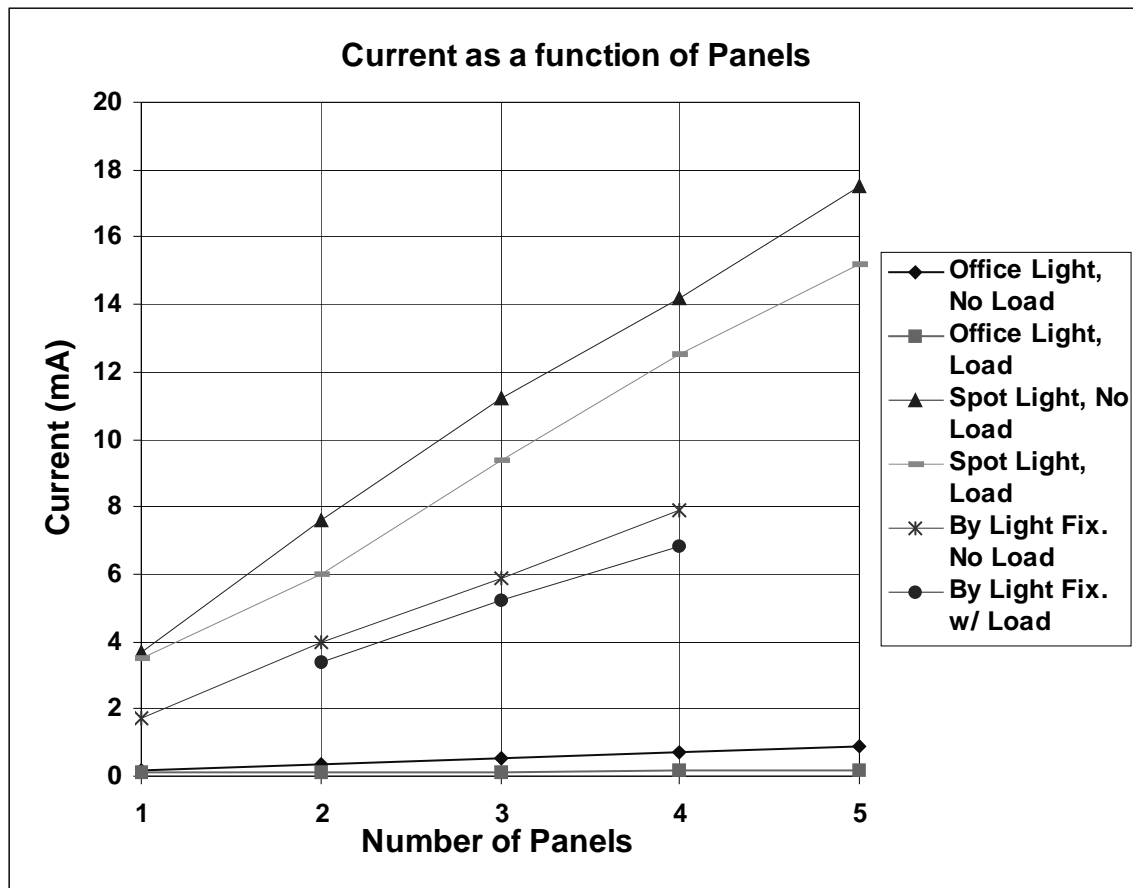


Chart 1. Current as a Function of the Number of Solar Panels

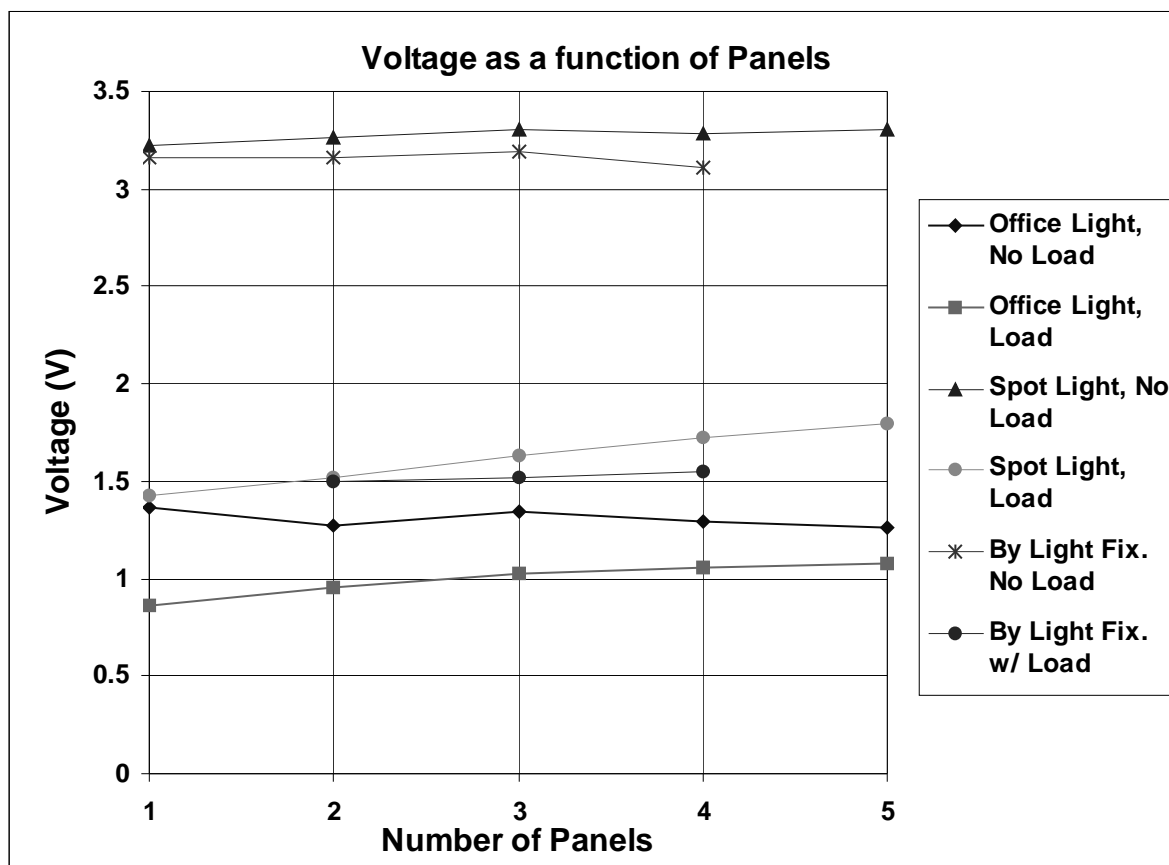


Chart 2. Voltage as a Function of the Number of Solar Panels

Note: The Load used here is the Cricket beacon, with the power switched to “On”. Also, the panels were of the 0.3V group and all were connected in parallel.

In the charts above, all the panels were connected in parallel, from one panel up to 5 panels (6 for some experiments). Not all 14 panels were used in the test, and there are several reasons for this: 1. It became increasingly difficult to connect more panels together without breaking or risking the breaking of cells. In my many experiments and setups, I have found that the weakest part of these solar cells are the solder points. They can tear right off the cell if too much stress is placed on the wire connected to it. 2. As this test was set out just to obtain a rough understanding of the trends of the solar cell voltages and currents, there was no apparent need to extend the tests beyond 6 panels. 3. Lastly, abiding by the rule set forth in one of the paragraphs above, no panels from different groups were mixed. As no group contained more than 6 of its kind, the test did not continue any further than 6 panels.

It seems that due to the lack of short wavelength, high frequency light in indoor office lighting, these solar power cells are unable to generate a substantial amount of

current. Under sunlight, even on a cloudy day (define a cloudy day as a day without shadows), the current produced outdoors is an order of magnitude greater than it could ever be indoors. Perhaps using solar panels indoors to power the Cricket beacons just isn't feasible or practical at all. Luckily, that isn't the case; solar powered beacons just lie barely on this side of that fine line – the “barely feasible but worth pursuing” side.

III. Application

III.1 Purpose

The goal is to power the Cricket beacons using solar, or rather optical, energy. Currently, they run on NiMH 1700mAh rechargeable batteries with a lifetime of approximately two weeks. Theoretically, a solar panel and rechargeable battery combination would ensure that the beacon runs forever – solar by day, battery by night, with the solar panels recharging the batteries when excessive energy was harvested.

III.2 First Attempt

At first, only one solar cell was connected to the beacon. Three intense spotlights in the lab were used in addition to the fluorescent office lights. It was noted that as the beacon and solar cell was raised closer and closer to the lights, the voltage across the cell increased. At about 3.7 volts (around 1 meter from the lights – the 1M-point), the beacon would start beaoning. What intrigued me the most, was that the second the beacon started to chirp, the voltage jumped up to about 4.2 volts; and, as the beacon and solar cell were lowered, everything would continue to operate, even if the beacon was lowered below the 1M-point.

A couple other phenomena were observed. For example, if the beacon were raised from tabletop to the 1M-point too fast, both indicator lights would go on and shine steadily (with debug switch turned on). And as the beacon was brought down again, the lights would remain on but get progressively dimmer. Only when the solar cell was brought considerably far away from the light source did the lights go off completely. In addition, if the beacon were brought to the 1M-point too slowly, sometimes the red indicator light would blink at an unusually fast rate. Only when the beacon was shut off and restarted did the situation cease. In conclusion, from the three phenomena observed in this experiment, there seems to be some asymmetry to these beacons – they don't stop functioning where they start, and problems don't resolve where they arise.

In any case, the beacons succeeded in beaoning completely healthily under these circumstances. Even though a spotlight was required, only one solar cell was necessary. If a beacon could work under intense light with only one cell, perhaps it'll work under office light with more cells.

III.3 Beyond the Lab

Next, a brave beacon was selected to perform the following series of experiments. Zeusling was to be connected with four solar cells in parallel (at the moment, the order for 10 more cells had not yet been placed). The explorations were conducted outside the lab in the hallways, which had lighting much more representative of those commonly found in office buildings. The four-cell structure was placed inside the light fixture,

directly under a florescent light bulb. Some simple wires allowed the current to flow to the beacon Velcro-ed to the ceiling close to the fixture.

III.3.1 Tidal Waves to Calm Shores

As many irregularities were observed in the voltage and current outputs of the solar cells, it was believed that a voltage regulator would be beneficial to the system. Though the voltage did not fluctuate much, it did fluctuate enough to cause problems. Without the regulator, the voltage across the panel was about 2.5 volts, and fluctuates between 2.4 to 2.7V. This is dangerously close to the 2.4V margin where the beacons will stop operating. Hence, a voltage regulator was added to the combination. The regulator used was the TPS60213, regulated 3.3-V 50-mA low-ripple charge pump. Capacitor values chosen were 0.47uF for the flying capacitors C1 and C2. And the input and output capacitors C3 and C4 were 2.2uF (see data sheets for more info).

Curiously enough, the voltage regulator did not work, and the beacon could not operate. Without the beacon load attached, the input voltage was successfully converted to the stable 3.3V output voltage. However, with the beacon attached, the solar cells no longer output a voltage in the valid input range of 1.8-3.6V for the voltage regulator. It appears that the voltage regulator itself requires a significant amount of current to operate. Another voltage regulator was used as well to see if performance improves – the MAX679 3.3V capacitor charge pump. But it too failed for the same reason the previous did not succeed. A performance test was conducted to test the battery lifetime of a voltage-regulated system connected to a beacon. Without the regulator, the beacons would operate for 2 weeks before the batteries run dry. With the regulators, it was expected that the beacons would operate longer, as the regulators will pull up the lower battery voltage to 3.3V when it drops to 2.4V. However, this was not the case. The system only ran for 7 days. This, and the fact that twice as much current (10mA) was being drawn from the batteries with the regulator connected, suggests that the regulators themselves dissipate much current.

There are many more types of voltage regulators that have yet to be tested. Here, only two capacitor charge pumps were used. Step-down, inductor based, and many other types should have a shot at this beacon setup before they are disregarded. Senior Research Scientist Thomas Knight had suggested that Step-down, inductor based voltage regulators might help the situation. Instead of connecting all the cells in parallel, connect them in series to boost the voltage. Then pass them through a step-down voltage regulator to increase current. However, preliminary tests seemed to show that these regulators, too, consume much of the valuable current the cells produce. There shall be further investigation into this matter of regulators.

Luckily, a simple solution that has managed to evade me finally presented itself. Removing the voltage regulator and connecting the beacon directly to the four solar cells would avoid the problem of the voltage regulators dissipating all the current the beacon needs. The beacon works perfectly fine and broadcasts a healthy signal now that the regulator has been bypassed. A listener was setup and the performance was monitored for a few days. And although the voltage fluctuated near that very fine 2.4V line, the beacon never seemed to fail. All seemed well.

III.3.2 Need a Hand?

Four of these 60mm square cells side-by-side amounts to quite a large panel, two to three times the area of a beacon. The solar cells also costs \$3.00~3.50 a cell. If a thousand of these were to be deployed throughout an entire office building, it would be ideal if as few cells were used per beacon, preferably if only one cell was used per beacon. So begins the quest of cutting four cells down to one...

As four panels had been supplying barely 2.5V @ 7mA, it was obvious that 3 panels would not get the beacon going. And not surprisingly, when three panels were connected to the beacon, and placed in the light fixture, the beacon did not operate. Yet, in one of the many trials and attempts to make the beacon work with only three solar panels, a different beacon (not Zeusling) with batteries was used. Zeusling already had its battery pack removed, decreasing its size and weight. This other beacon however, still had its battery pack intact, and had batteries in it. By quite an unexpected coincidence or accident, the battery pack was turned on and the beacon started to broadcast. What was really exciting was that it continued to broadcast after the power switch had been turned off.

Now I must explain a bit about the setup of the beacon's power supply. The solar power panel is connected to the beacon via the programming port. Of the ten pins, pins 1 and 8 are VCC and GROUND respectively. Connecting power through the programming port provided many advantages; mainly that it was easier to plug in². However, in this version of the beacon hardware, the VCC and GROUND in the programming port bypasses the power switch on the beacon. Hence, flipping the switch does absolutely nothing.

In the light of the knowledge above, the accidental discovery becomes more understandable. Above, where both battery and solar power was used, the batteries were connected to the beacon using the battery case and batter power input, which did not bypass the switch. The solar panel was connected to the beacon using the programming port, which did bypass the switch. Hence, when the switch was on, the battery and solar panel was powering the beacon. But when the switch was turned off, the battery power was turned off and the beacon continued to send its signal using solar energy. So, the beacon does work with only three solar cells!

It is here that the "Energy of Activation" of the beacon was discovered; it made perfect logical sense as well. Reflecting back upon the First Attempt and on various other tests and experiments, the behavior of the beacon became more and more understandable. A theory was forming and was soon to take shape. The beacon has an "Energy of Activation"; it needs a slight push on power-up to get it going, and then it'll run fine on its own. It's very much like a car engine, which requires a battery to start up the engine, but afterwards, it runs off gasoline.

² The programming port is already a power port; another power connector is not necessary at all. In another project to power beacons using AC power, the AC adapter was connected to the beacon using the programming port as well. It seems to be more convenient to have a universal power port in which various power alternatives can plug in to. Regardless of whether it is solar power, AC power, or DC power, they should all have the same plug, which plugs into a power socket on the beacon, rather than have each power alternative have its own plug. The programming port was chosen as the universal power port, and all my designs for power alternatives plug into the programming port.

Subsequently, a few more follow-up tests were performed to verify the theory – that there was indeed this Energy of Activation for the beacon. It turns out that the beacon requires about 3 times as much current on startup as in normal operation. During normal operation, the beacon draws about 6mA (during non-transmissions) to 10mA (during transmissions) of current. But on startup, it'll draw about 20mA of current for a fraction of a second, before the current settles back down.

The solution was quite easy. The problem parallels that of a car engine; well, so does the solution. The car engine uses a huge battery; we'll use a huge capacitor. Hence, the Car-Engine solution to the problem was formed – get a huge capacitor to give it that extra juice on startup. But the capacitor must have a high enough capacitance so that its charging time is practical. The particular capacitor in use right now is a 4700uF electrolytic capacitor rated at 16V. This choice of capacitor was of no particular reason; it was simply the best one here, among 5 others. A few test runs with different capacitors suggested that all that was required was a 2200uF capacitor at 4V. In less than a second, such as capacitor could charge up enough for the beacon to start. However, due to the very limited selection of capacitors in the lab, the capacitor meeting such requirements with the smallest volume was chosen, and that was this 4700uF 16V capacitor. Below is a schematic of the solar panel-capacitor setup.

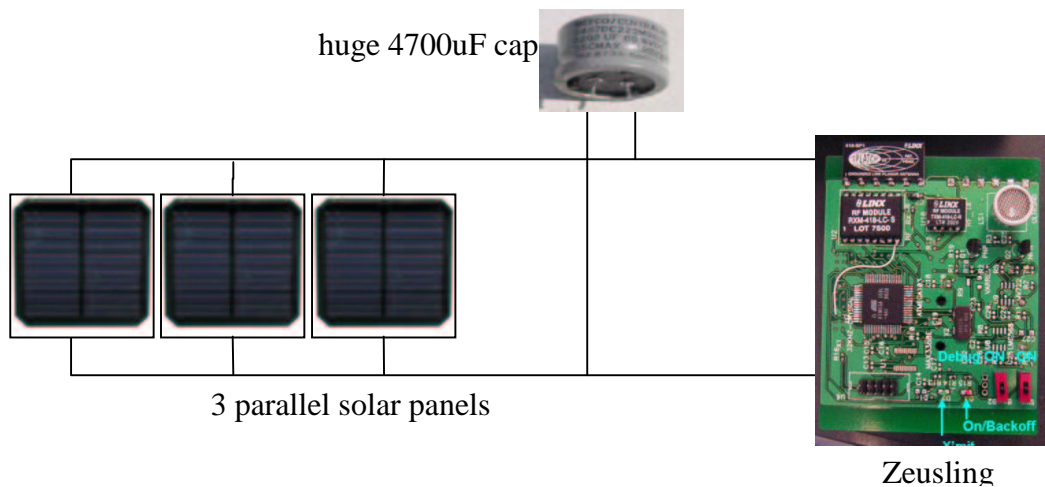


Diagram 1. Setup of the Solar Powered System

Another problem I have observed is that the beacon does not restart if the office lights are turned off and on again. The beacon would be broadcasting perfectly; and if the lights were turned off, the beacon goes off. If the lights were turned back on, one would expect the beacon to continue to broadcast, as turning the lights off and on resembles disconnecting the power and plugging it back in. However, the beacon does not continue to function. Both LEDs turn on and stay on. The only way to reset the beacon is to restart it by disconnecting the power and plugging it back in (as the “On” switch does not work

for the programming port³). This problem is probably correlated to the problem before, where if the solar panel was raised from tabletop to the 1M-point too fast, both lights come on and would not go off until power was disconnected. The logical explanation to this is that the beacon enters some error state when the voltage behaves “funny,” and only resets itself when all power is disconnected. What is exactly meant by “funny” remains to be determined.

Concurrently, another beacon setup is being developed alongside the 3-cell setup for placement within light fixtures. The Uni-cell Beacon has only one solar cell attached to it, mounted in a very compact fashion. The idea is that beacons can also be placed on windows, with the solar cell facing outwards to receive incoming sunlight. As sunlight is much more “powerful” than office light, perhaps these beacons can run on only 1 cell. Actual experiments have not yet begun, but will take place soon. Currently, the setup only has a solar cell attached to the beacon. There is not capacitor or voltage regulator connected to it. Whether these two sub-systems will be necessary or beneficial will be determined after a series of tests, and a final design will be proposed.

IV. Conclusion- The Next Step

Much has been accomplished regarding beacon solar power, but even more remains to be done and needs to be investigated. Below is a short list of some of the things that need to be done (or is currently underway):

- solar experimentation
 - experiment with different solar cells
 - test the Uni-cell configuration
- power management
 - redesign the Cricket PCB to have all power inputs pass through the power switch
 - reduce power consumption of beacons (see Appendix D)
 - search and test for better regulators (compare step-down vs. step-up)
 - purchase more appropriate capacitors
 - research cost/benefit analysis of integrating capacitor and regulator onto the PCB

These are perhaps the most immediate action items that need to be done. There are still many other items and several are intertwined with other branches of the beacon development. For example, in order to mount beacons on windows (instead of ceilings), the “Z does not have to be 0” adjustment must be made to the algorithms. This adjustment, as I understand it, is already being done for another Cricket beacon project. But soon, no doubt, solar powered Cricket beacons will take flight.

³ I strongly recommend that the power inputs for the Beacon should be redesigned. Not only should all power inputs be consolidated to a “universal” input port/plug, but the On/Off switch should also be moved so that no power inputs can bypass the switch.

Appendix A-How Solar Cells Work

Solar cells are composed of a poly-crystalline material that absorbs sunlight. Once sunlight hits the atoms that form the crystal, the electrons are excited and jump up to a higher energy state. If a photon of light carries enough energy, it can eject the electron from the atom completely, ionizing the atom. The atom then loses control of that electron and becomes positively charged. A thin silicon semi-conductive layer is applied over the crystal, which forces the electrons to move towards one side of the cell once they are freed from the atom. Electron-absent “holes” act as positive carriers and are pushed towards the opposite side. So now, a charge separation builds up to form a voltage difference. If a piece of wire is connected across the top and bottom of the cell (its two terminals) then current will flow.

Several problems also inhibit the electrical process. Once an electron is ionized, it may not have gone far from its owner. It is possible that it will fall back and collide with the atom that just lost this electron. When this happens, the electron is then captured by the atom, and it releases a photon of light as it falls back to its natural energy level. In this case, no current or voltage is generated, as the electron does not move towards the terminal. Light with shorter wavelength (or higher frequency) carries more energy. Hence, a photon from a high-energy beam will have a greater chance of successfully ionizing the atom and sending the electron flying off with greater kinetic energy, reducing the chance that the electron falls back to the atom. This explains why higher frequency light shone on the cell will produce more current.

Currently, solar cells operate at 15% efficiency and do not perform well under visible light. Solar light contains a wider spectrum which helps pump out more current. However, researchers at Siemens seem to have found some way of using thin film copper with silicon to create a better photovoltaic effect. They claim that this new technology can produce more current with less area, has a great potential to surpass the efficiency of traditional poly-crystalline cells, and will be more cost-efficient. Currently, they are testing these cells in Arizona, and have already fabricated new cells that can achieve the 15% efficiency mark – no worse than regular cells. Though these cells may not be commercially available soon, or an economical solution for the Cricket beacons, it is something to keep in mind for the future.

Appendix B-Raw Solar Cells

The SiliconSolar solar cells were purchased before the 10 OK-60 cells were purchased. The benefit of purchasing individual, smaller cells is that one can solder together how many they want, in series or parallel, to produce a precise amount of voltage or current. However, the price for such flexibility is not at all small. First, all individual cells must be checked for defects. This is done by measuring the OC voltage and SC current of all cells under the same environment. Any cells that seem to produce too low a voltage or too low a current must have defects within them. To isolate these defects within the cell, one could chip the cell in half. Only half of the cell would contain the precise defect, the other half would be perfectly fine. Hence, the fine half could still be used. Afterwards, the cells must be arranged into an array. Only cells that produce the same current can be put in series, and only cells that produce the same voltage can be put in parallel. By chipping away the edges of each cell, one could adjust the current produced by the cell. Finally, the array must be mounted on a panel, and some form of

protective cover must be placed over the panel, thus forming the solar panel. After ordering a small package of the SS-SC-250T rated 250mA @ .58V by SiliconSolar, I attempted to create such a panel that would produce 3V 7mA under office light. However, the soldering and arranging of the array was too hard to complete without breaking many of the cells, and the process was deemed inefficient for experimentation. Therefore, pre-made, sturdy, unbreakable cells (the OK-60) were purchased for the experiments.

Appendix C-Voltage Regulators

Through the exploration of solar cell application to Cricket beacons, three different voltage regulators were used and tested. Two have been mentioned above, the TPS60213 and the MAX679. These are both step-up, capacitor charge pumps. Solar cells were connected in parallel to boost the current, and passed through one of these regulators. These regulators can convert an input voltage of 1.8 to 3.6V to a steady output of 3.3V, at the sacrifice of current. However, these regulators proved to be too “current-expensive” and were abandoned.

Another regulator was also used. It is a step-up voltage regulator that hacks away at the voltage to raise the current. The model is 2931 M-5.0 by National. This part was found among a pile of other components and was not purchased for the particular use with beacons. The regulator can take an input up to 24V and output a steady 5.0V. It's not exactly the 3.3V we hoped it'd be, but for testing purposes, this is sufficient. As described earlier, the results were negative, and this regulator too consumed too much current. Perhaps if it were to bring the voltage down to 3.3V, it could output more current. But it is unlikely that it would output much more current. One of the tests involved connecting 6 solar cells together in series, bringing the voltage up to 18V. Once passed through this regulator, it output 5.0V. However, with the beacon load, it was unable to output much of any current (but!!! If the regulator was removed, only 3 panels were required to operate the beacon). Other series/parallel combinations were tested as well, including all 6 in series, 3 in series parallel with 3 more in series, and 3 pairs of series cells connected in parallel. After giving the beacons that little extra push (see “Need A Hand?”), they still failed to operate. These combinations were also used with the step-up regulators; none succeeded in operating the beacon.

It seems like a good idea to incorporate some form of voltage regulator into the system, as fluctuating voltages may damage the beacon. I even propose to build the regulator subsystem onto the Cricket PCBs so that any power source must go through this regulator first. Since some power alternatives fail with these regulators (such as solar), it is important to find more appropriate regulators, ones with high efficiency. Another solution would be to lower the power consumption of the Cricket beacons (see Appendix D). Both solutions are currently being pursued.

Appendix D-Power Management

In trying to solve the “Car Engine Startup Problem” and the “Insufficient-current-to-power-both-the-regulator-and-the-beacon” problem, I have very briefly engaged myself in looking into the power consumption of the beacons. It was believed that perhaps the two transistors pulling up and pulling down the Ultrasound device was dissipating most of the energy. Also, if the input to the US subsystem was the “Z” state

(which might be possible if the Atmel processor was shutoff), the current could flow directly from VCC to Ground via the two transistors. However, theoretically, that output of the processor should never go Z, even when the beacon is running in power save mode. Hence, a simple test was devised.

With the two transistors, the beacon consumed approximately 3.3-6.5mA during non-transmissions. When the two transistors were removed (and the US hence disabled), the beacon drew about 2.4-4.2mA of current. There was a ~30% decrease in power, but something else is still drawing quite a bit of power (the remaining 2-4mA during non-transmissions). It has not yet been determined which component is using up so much energy. But once this is done and the power consumption of the beacon reduced, not only will the beacons run perfectly fine on solar power, the beacons will also have a longer battery lifetime.