Solar Power for Autonomous Floats

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ABSTRACT

Advances in low-power instrumentation and communications now often make energy storage the limiting factor for long-term autonomous oceanographic measurements. Recent advances in photovoltaic cells, with efficiencies now close to 30%, make solar power potentially viable even for vehicles such as floats that only surface intermittently. A simple application, the development of a solar-powered Argos recovery beacon, is described here to illustrate the technology. The 65-cm^2 solar array, submersible to at least 750 dbar, powers an Argos beacon. Tests indicate that with minor improvements the beacon will run indefinitely at any latitude equatorward of about 50°. Scaling up this design to current operational profiling floats, each profile could easily be powered by a few hours of solar charging, a shorter time than is currently being used for Argos data communications.

1. Introduction

Profiling floats combine a relatively low cost, an ease of use, the ability to operate autonomously for long periods of time anywhere in the world, and the ability to make stable measurements of an increasing number of important parameters. Existing floats are often limited by battery capacity. A high-end float, MLFII (D'Asaro 2003), sampling temperature, salinity, and pressure every 30 s uses about 40 kJ of energy per day. It carries an approximately 8-MJ battery pack (twenty-three 3.5-V cells with 30 A h each) that costs about $1,500 and can sample for about 200 days. These floats are typically in excellent condition when recovered and could operate for much longer times were more power available. Profiling Argos floats (Davis et al. 2001) typically require approximately 18 kJ per profile and can make approximately 200 profiles. The profiles are typically made only every few weeks, thus leading to missions several years in duration. Profiles could be made more frequently, and the float missions extended, were more power available.

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The following idealized calculation provides an estimate of the solar energy available for floats. Maximum shortwave solar radiation at noon on a clear day in the Tropics is approximately 1000 W m^{-2}. The efficiency of the best photovoltaic cells, converting light to electricity, now approaches 30% (McMahon et al. 2003). Thus, an array comparable in size to the diameter of these floats (e.g., 200 cm^2) would generate about 6 W in full sun and thus could, under idealized conditions, gather enough energy to power an Argos float profile (18 kJ) in less than 1 h. Real performance, will, of course, be less than this. The worldwide array of Argos floats transmits data using the Argos satellite system. This system has a very low data rate, requiring the floats to spend nearly a day on the surface in order to transmit data from one profile. The float's battery could be recharged during this time using a photovoltaic array.

Here, this concept is investigated by developing a much simpler system, a solar-powered recovery beacon. An Argos satellite tracking beacon is powered by solar cells thus allowing a float or other floating object to be tracked indefinitely. Although floats are designed to gather data autonomously and are often not recovered, it is often appropriate to recover floats. This is certainly true during development as it greatly aids the diagnosis of problems. Some floats gather more data than can be telemetered. Sometimes, float sensors must be cali-

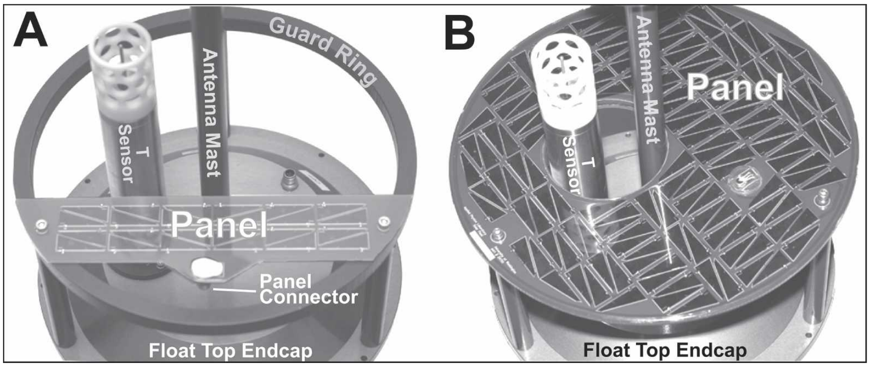

FIG. 1. Two custom-made, submersible photovoltaic panels mounted on the top endcap of an MLFII float. (a) Argos recovery beacon panel consisting of four strings of six cells with a full sun and a no-loss rating of 13 V, 112 mA, and 1.4 W. (b) Panel to power a full float, 29 cm in diameter, with 15 strings of 10 cells and a rating of 21.9 V, 420 mA, and 9.1 W.

brated after the mission. Finally, it is often economical to recover floats despite the high cost of ship time.

Instrument recovery at sea is an uncertain undertaking. The primary requirement for recovery is knowing the location of the instrument. Argos is sufficient for this purpose. However, powering an Argos beacon for many months can consume considerable energy, albeit at a low rate. Unexpected malfunctions can cause an instrument to require recovery much sooner than expected, but inflexible ship schedules do not always allow this to occur. During the last 15 yr of float operations at the Applied Physics Laboratory-University of Washington (APL-UW), we have lost several instruments due to the lack of a simple, long-term method of locating floats drifting on the surface. Many more floats, deployed with no expectation of recovery, could have been eventually recovered if their location had been known.

Photovoltaic power has been commonly used in surface moorings (Chaffey et al. 2004) and has had some application in surface drifters (Smith et al. 1984), autonomous underwater vehicles (Blidberg 1997), and, conceptually, for floats (Potter et al. 1998). The main difference between these previous applications and the one proposed in this note is the use of more efficient modern cells that make solar power for floats considerably more practical.

The remainder of this note describes the basic elements of the solar beacon and its performance and extrapolates these results to the design of larger arrays for powering floats.

2. Design

a. Photovoltaic panels

Compared to many terrestrial applications, oceanographic floats have very limited space and payload and have high value. The use of photovoltaic cells with the highest efficiency, even at higher cost, is therefore appropriate. We use triple-junction cells manufactured by Spectrolab. These are terrestrial versions of cells developed for a spacecraft. By using three p-n junctions of gallium–indium–phosphide, gallium–arsenide, and germanium, respectively, they can use a wide range of incoming light wavelengths and thereby achieve a specified efficiency of 27 ± 3%, roughly double that of typical silicon cells. Individual cells are triangular, so that two cells can be arranged within an approximate rectangular area of 1.55 by 3.18 cm. Such a pair is specified by the manufacturer to generate about 130 mW at about 2.1 V for an incoming solar radiation of 1000 W m^{-2} assuming a standard spectral distribution (AM1.5G) at 25°C. Each pair costs about \$5 in quantities of several hundred.

Submersible panels are made by mounting the cells on custom-built circuit boards. This method gives great flexibility in panel shape and the configuration of the cells. The cells are glued to the boards using conductive epoxy, which makes one of the connections; a small solder joint on the side of the cell makes the second connection. All intercell connections are made on the circuit board. The entire board is potted in transparent epoxy with only a few millimeters of epoxy above the top of the cells. A two-wire underwater connector (Impulse IE55 series) provides an exterior connection. Figure 1 shows two different panels shaped to fit on an MLFII float. The small one, discussed in detail in this note, is designed to power an Argos recovery beacon. The larger one, designed to power an entire float, is shown to illustrate the variety of shapes than can be made. The beacon panel has been pressure tested to 750 dbar. There seems little reason why it should not survive to much greater pressure. Based on our experience with GPS and Iridium antennas potted with simi-

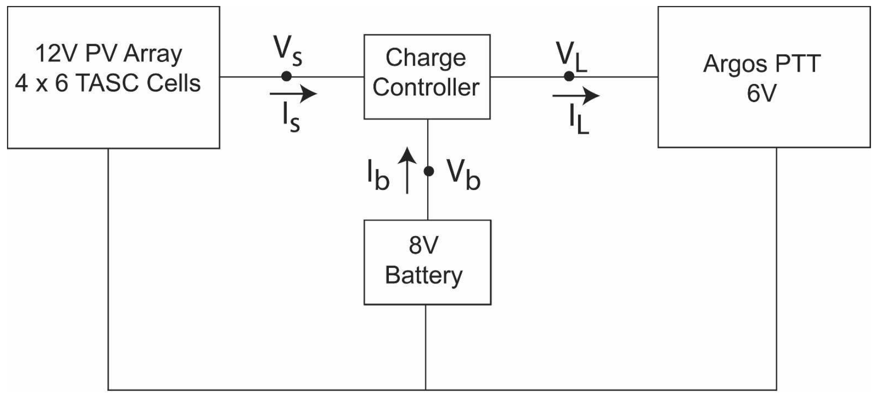

FIG. 2. Functional diagram of solar beacon electronics with voltage and current measurement locations labeled.

lar materials we expect the panels to survive repeated pressure cycling and to survive repeated immersion near the air–sea interface with little degradation. A test panel was operated continuously for about 6 months outside in air with only very minor visual degradation and no measurable decrease in photovoltaic output. This is consistent with other published studies of epoxy-coated cells (Atmaram et al. 1996).

b. Electronics and battery

Figure 2 shows the functional design of the electronics. The Argos beacon Platform Transmitter Terminal (PTT) is powered either by the photovoltaic array or, if this is not supplying sufficient power, the battery. Power from the photovoltaic array is sent to the PTT with any excess going to charge the battery. These functions are handled by a BQ24703 charge controller built by Texas Instruments. This chip, designed for laptop computer battery applications, dynamically adjusts the battery charge current based on the available input current, battery voltage, and battery charge state.

With this system, the output voltage of photovoltaic cells decreases with decreasing illumination. Therefore, if the voltage drops below that needed to charge the battery or power the PTT, the power produced by the cells cannot be used. Accordingly, the solar panel must be designed to generate a much higher voltage at full sun than is needed so that it will still operate at low light levels. The beacon array (Fig. 1a) consists of four parallel strings of six cells in a series with an output of 1.4 W at about 13 V in full sun.

This design does not capture the full power of the photovoltaic panel. The cells operate as a constant current source up to a maximum voltage with the current proportional to the illumination. Maximum power is therefore obtained at a voltage V_{mp} just below the maximum voltage. For this array $V_{mp} = 13.1$ V. The panel was operated with V_s near 10 V, leading to a power output $V_s I_s$ less than the maximum possible, $V_{mp} I_s$.

The battery consists of two lithium-ion cells (each 3.7 V at 1.7 Ah) with a total capacity of about 4.5×10^4 J. The Argos PTT (Seimac "Wildcat") transmits for 1 s every 2 min at a power of 1 W. With a nominal efficiency of 50%, the average power consumption is 17 mW. In reality the efficiency of this PTT varies widely leading to measured average power consumptions from 8 to 26 mW. This can be further reduced by shortening the transmit pulse, at the price of somewhat more difficulty in finding the float using a shipboard radio direction finder. Using 22 mW as the PTT load, the battery could power the PTT for 24 days with no solar power.

The charge controller requires energy to operate and thereby reduces the efficiency of the system. The battery voltage V_b and load voltage V_L are nearly identical, so that when the PTT is drawing energy solely from the battery the power delivered by the battery ($V_b I_b$) is very close to that used by the PTT ($V_L I_L$). However, the battery and load voltages are about $\Delta V = V_s - V_b \approx 2.1$ V less than the output voltage of the photovoltaic panel. During battery charging, therefore, a fraction $\Delta V / V_s \approx 0.21$ of the energy goes to powering the charge controller. Additional inefficiency results from the intermittent loading. The PTT operates only about 1% of the time, but draws about 200 mA from the battery during that time thereby reducing the battery voltage by $I_b R_b$, where $R_b = 2.4\ \Omega$. Other losses, mostly due to resistive losses in the wires, are perhaps 1%.

3. Performance

Figure 3 shows a 2-month test of a beacon system through an exceptionally dark Seattle winter. The panel

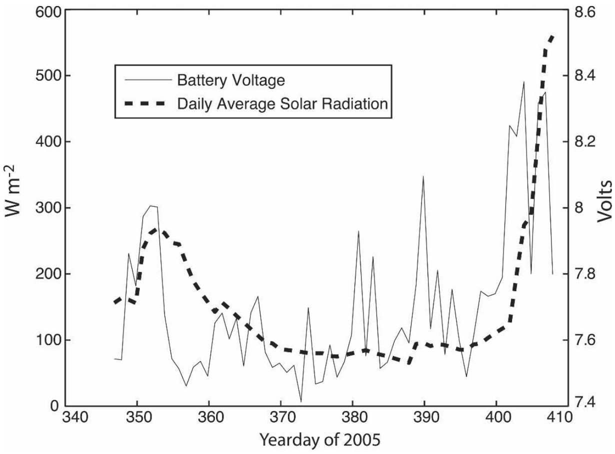

FIG. 3. Daily-averaged solar radiation (solid line) and beacon battery voltage (heavy dashed line) from 12 Dec 2005 to 12 Feb 2006.

was set on the roof of the Applied Physics Laboratory. Battery voltage was measured daily. Solar radiation was measured by an Eppley Precision Spectral Pyranometer (PSP) shortwave radiometer on the roof of the atmospheric sciences building approximately 1 km away. The radiometer, last calibrated in 1999, was found to read approximately 9% lower, compared to the readings on clear days in July and August from 1999 to 2006. Data shown here are corrected by this factor. Daily averaged shortwave radiation (heavy dashed line) decreased through the winter solstice and then increased into the new year. The battery was initially 50% charged with a voltage of 7.7 V. The battery slowly discharged through the darkest days of December and January, but then rapidly charged to full capacity in early February. The test was terminated at this point since it was clear that the increasing solar radiation would keep the battery fully charged for the rest of the year.

Figure 4 shows the performance of this system during a 2-day period with bright sun. Performance at other times is similar, but with a smaller dynamic range. Both the battery voltage V_b and the current out of the battery I_b were measured. The battery charges, on average, with the nighttime discharge compensated by a larger daytime charge (Fig. 4b). The power W (watts) into the battery correlates well with solar radiation I (Fig. 4d) and is accurately predicted by the simple model:

$$W = -L \quad I < I_{\text{thr}}, \tag{1}$$

$$W = -L + b(I - I_{\text{thr}}) \quad I > I_{\text{thr}},$$

where $L = 26$ mW is the PTT load, computed from the nighttime current and voltage. No power is supplied from the cells to the battery for $I < I_{\text{thr}}$ because the panel output voltage drops below the battery voltage. This occurs at a threshold solar radiation level $I_{\text{thr}} = 18$ W m^{-2}. At higher radiation levels the power supplied to the battery increases linearly with radiation with a slope of $b = 9.2 \times 10^{-4}$ m^{-2}. For $I_{\text{thr}} < I < I_{\text{thr}} + L/b = I_0 = 46$ W m^{-2} the power supplied is less than that needed for the PTT, and some power is drawn, on average, from the battery. This situation was common during the darkest days of January. For $I > I_0$ the power supplied exceeds the PTT requirement and the battery charges. The charging can be quite rapid, with a few bright days making up for many dark days.

The above statistical model can be understood from the properties of the circuit as described in section 2b. The efficiency of solar conversion (i.e., the ratio of power generated by the cells to the solar shortwave energy landing on the solar cells) is shown in Fig. 4c from the data (dots) and computed from the properties of the circuit (solid lines). In bright light, it reaches about 20%, well below the maximum cell efficiency of $E_{\text{cell}} = 27 \pm 3\%$. The total efficiency (i.e., the ratio of power supplied to the battery to that landing on the solar cells) is even less, reaching about 16% in bright light. These efficiencies are accurately modeled as $E_{\text{cell}}V_s/V_{\text{mp}}$ and $E_{\text{cell}}V_b/V_{\text{mp}}$.

These data indicate that the power delivered by the cells is likely close to that specified by the manufacturer and the additional losses due to potting and mounting are a few percent at most. A more efficient match of the electrical system to the cell properties could undoubtedly increase the overall efficiency to well above 20%. A more efficient PTT and/or shorter transmit pulse could probably reduce L to 15 mW. Attention to the low-light behavior of the charging circuit could probably reduce I_{thr} to near zero.

The statistical model in (1) combined with the radiation data from Fig. 3 were used to derive a relationship between daily-averaged radiation and daily net power I_{av} into the batteries. For $I_{\text{av0}} > 40$ W m^{-2} there is a net daily power gain. Note that $I_{\text{av0}} < I_0$ because of the nonlinearity of (1) and the large daily variation in radiation. Using $L = 15$ mW, $I_{\text{thr}} = 0$ and 22% net efficiency the value of I_{av0} is reduced to 8 W m^{-2}. With modest improvements in the electronics, $I_{\text{av0}} = 20$ W m^{-2} appears easily achievable.

NASA's Surface Meteorology and Solar Energy project provides global data on solar radiation for energy system sizing (see online at http://eosweb.larc.nasa.gov/sse/). The December and January monthly average shortwave radiation falls below 42 W m^{-2} (1 kW h day^{-1}) at about 50°N in the North Pacific and about 46°N in the North Atlantic. It falls below 20 W m^{-2} at

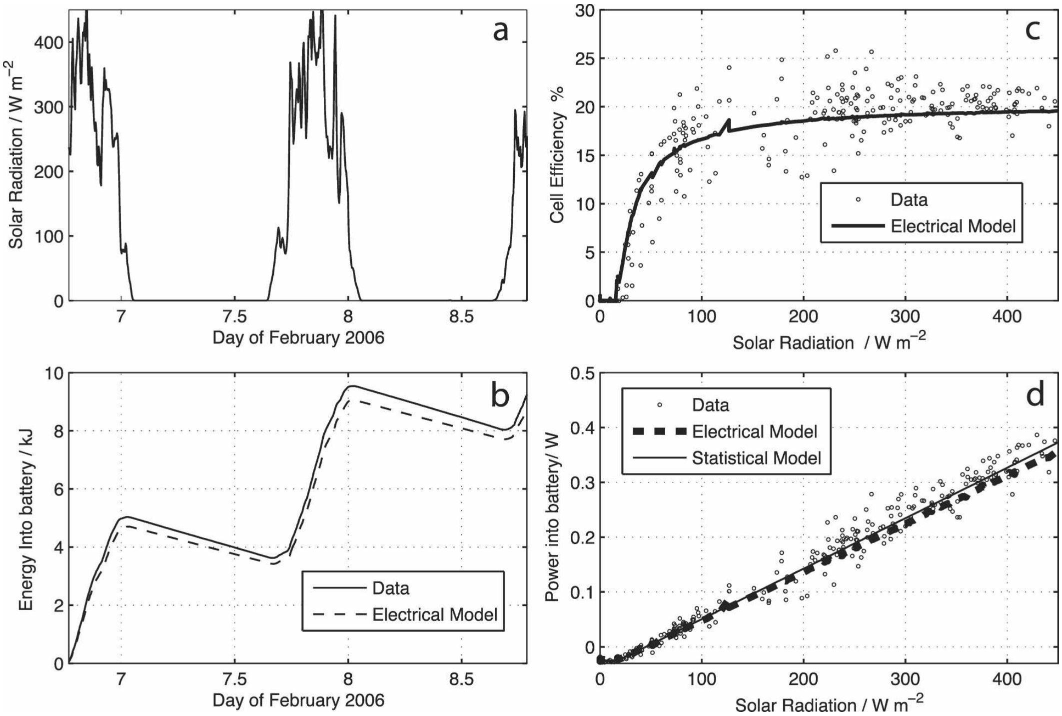

FIG. 4. Performance of beacon array on 6–8 Feb 2006: (a) solar shortwave radiation, (b) cumulative energy supplied to the battery from data (solid line) and electrical model (dashed line), (c) efficiency of solar panels as a function of solar radiation from data (dots) and electrical model (line), and (d) power supplied to the battery as a function of solar radiation from data (dots), the electrical model (dashed line), and the statistical model (solid line).

58° and 55°N, respectively. By February these latitudes have advanced poleward by about 5°–10°. In the Southern Hemisphere, the latitudinal limits are similar. The practical poleward limit for operating the solar beacon continuously in the winter is thus about 50° of latitude depending on the details of the system. Our tests, at 47°N, during which the panels produced slightly less energy than the PTT required during the darkest weeks, confirm this estimate.

These results are now extrapolated to the operation of Argos floats. The radiation data show solar radiation levels exceeding 700 W m^{-2} for a 3-h average around local noon in large areas of the equatorial and subtropical oceans. The 9.1-W panel shown in Fig. 1b operating at 22% net efficiency would generate 56 kJ in 3 h at 700 W m^{-2}, enough for 3.1 Argos float profiles each costing 18 kJ. Solar panels should be able to easily power floats completely in these regions. Assuming that a float is on the surface for a day, the daily average radiation needed to generate 18 kJ with this panel is 28 W m^{-2} assuming $I_{\mathrm{thr}} = 0$. This is only slightly less than the performance of the beacon array, so the practical operating limits of a solar-powered Argos float are therefore similar to those found for the beacon array. The daily-average radiation between 50°N and 50°S is about 200 W m^{-2}. The array can generate enough energy for about seven profiles per day at this light level. The excess energy, six profiles per day on the surface, could completely replenish the energy in the current Argos float batteries, 4 MJ, in 36 days.

Future profiling floats are likely to use faster and more energy-efficient communications systems, such as Iridium or Orbcomm. Since communications is the largest user of energy in current Argos floats, floats using the new communications technology will use significantly less energy, thereby reducing the array size and/or surface time needed for solar power. Such floats will also be required to spend far less time on the surface for communications. However, operators may still choose to have floats spend extra time on the surface for solar charging. The two-way communications capability of the newer systems may also allow solar charging to be scheduled on days expected to have maximal solar radiation.

4. Conclusions

New high-efficiency photovoltaic cells, integrated charge controllers, and high-density rechargable batteries make the use of solar power a potentially attractive option for powering autonomous floats or, as in this study, backup components for such floats. The prototype systems that we have built reveal no serious problems in submersible array design, power control, or energy storage. An overall efficiency exceeding 20% of the available solar radiation appears easily achievable.

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