Some Design Considerations for a Solar Powered AUV; Energy Management and its Impact on Operational Characteristics

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Abstract

The Autonomous Undersea Systems Institute (AUSI) is currently working on the development of a solar powered Autonomous Underwater Vehicle (AUV) in cooperation with the Institute of Marine Technology Problems of the Russian Academy of Sciences. This technology development program is investigating those technologies that will enable the use of solar energy to power autonomous vehicles. This paper will discuss some of the technologies under investigation. This will include discussion of solar module performance, energy transfer issues to include charge control device technology, and energy monitoring devices such as fuel gauges. It will also consider energy management strategies being developed.

A Sampling System For The 21st Century

Ocean environmental monitoring has gained increased importance as the effect of mankind's activities on the world's oceans becomes apparent. There is world-wide concern by research organizations over the inability to collect sufficient data with which to better understand the dynamics of chemical, biological and physical characteristics and processes within the earth's lakes, seas and oceans. Issues such as physical and biological coupling, biogeochemical processes and cycles both natural and human induced, fisheries, and ecosystem modeling must be better understood. The concerns vary from the enormous size of the data and sampling requirements, to the reliability and affordability of the systems presently used to collect data. Spatial and temporal undersampling in the oceans is generally recognized as one of the more important problems associated with current sampling systems. Although more detailed monitoring of the ocean is necessary, current instrumentation does not provide sufficient capability to collect the required data from the ocean on a continuous basis.

This paper considers some of the issues associated with the development and utilization of a solar powered autonomous sampling system. The work described in this paper focuses on some the energy management strategies associated with a solar powered AUV system to address the needs of ocean sampling in the 21st century. The results reported here are preliminary, but they help define the unique constraints to be considered in the design of a solar powered AUV. The results of this and other investigations [Jal,1997] over the past few months have allowed the establishment of a technology database focused on the technologies and components important to the future utilization of solar energy as an energy source for autonomous sampling platforms. Work is currently underway to simulate, fabricate and evaluate a solar powered AUV testbed prototype detailed in figure 2. In water testing and evaluation experiments are scheduled to begin at the end of 1997.

Solar Energy: an Available Energy Source

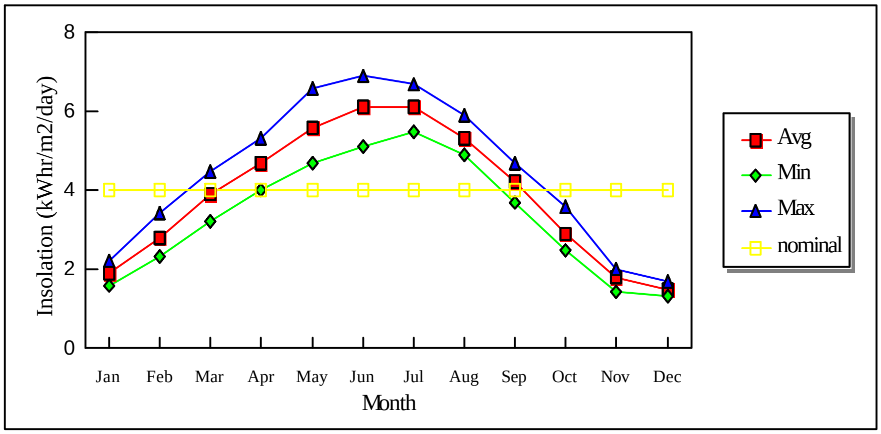
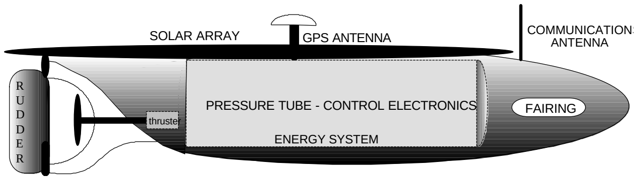


Figure 1 Solar Radiation; Concord NH (Source NREL database)

The amount of solar energy available on the ocean surface varies significantly with latitude, seasons, and weather. The annual mean daily total horizontal solar radiation varies from less than 1 to about 12 kWhr/m^2/day (Bahm, 1994). Conversion efficiencies for commercially available Photovoltaic (PV) arrays are conservatively in the 10% range. Therefore we can expect energy amounts in the range of 100 to about 1200 Whr/m^2/day. This variation in available energy will have obvious impact on possible tasks that a solar AUV might perform. If we look at the latitudes roughly comprising the US, and look at "worst case" numbers which typically are in December, we see an average insolation varying from 1 kWhr/m^2/day (near the Canadian border) to about 4.0 kWhr/m2/day (in the southern US) (Reineke, 1993). We have considered three cases in our design analysis. A nominal case (1) that considers average data close to the New Hampshire coast (Figure 1.); 4 kWhr/m^2/day, (2) data representing a high level of solar energy off the Hawaiian Islands in June; 6 kWhr/m^2/day, and (3) data representing a low level of solar energy available near Vladivostok and Boston, MA in December; 1.5 kWhr/m^2/day .



SOLAR POWERED AUV

Characteristic	Solar AUV (Version A)	Solar AUV (Version B)
Depth	1000 m	1000 m
Daily transit	30-50 km	30-50 km
Length	1.7 m	2.7 m
Width	.7 m	1.3 m
Pressure Case	.24 m (diam)	.4 m (diam)
Array Size	.5 m^2	1.8 m^2
Weight	90 kg	200 kg

Figure 2 Solar Powered AUV Testbeds

If we first consider the two limiting cases, i.e. a small solar powered AUV operating in a low insolation area and a high insolation area, we can develop the following information. With a PV array of .5 M^2 (Figure 2, Solar AUV version A) and a 10% conversion efficiency (PV module), in a low insolation region of 1.5 kWhr/m^2/day, this results in a PV array output of about 75 whrs/day.

If we consider the same vehicle in the high insolation area (6.0 kWhr/m^2/day), we would obtain 300 whrs/day. This would result in the capabilities summarized in Table 1 below when the vehicle was tasked to transit for 12 hours and charge for 12 hours (AUSI, 1996). NOTE: The 10% efficiency for the solar arrays is an appropriate value for today's technology and has been validated by experimenting using a Solarex MSX-30 Solar Module. More importantly, data from an NREL report (NREL, 1995) suggests that the efficiency of PV modules will increase to a level of 15 - 25% by the year 2010.

The above analysis does not consider the energy demands of the hotel functions in a vehicle nor the inefficiencies of converting acquired solar energy into a form suitable for utilization by the vehicle subsystems. Let us now consider the larger vehicle design in a nominal insolation area while accounting for all energy usage. If we assume a PV array of 1.8 M^2 (Figure. 2 version B) with a 10% conversion efficiency, in a region with a nominal insolation of 4 $kWhr/m^2/day$ (represented by the “nominal” plot, fig 1), this results in a PV array output of about 720 whrs/day (March through September). When we include the system inefficiencies (About 15% of the electricity generated by PV modules is lost during conversion and transmission through energy system components; charge controllers, batteries, control systems, wiring, power-conditioning hardware, etc.), we would have about 610 Whrs of available energy on a daily basis. Subtracting the hotel power requirements [AUSI, 1996] leaves approximately 520 Whrs of energy available for a 12 hour transit. This amount of energy allows the vehicle to complete a **42 km transit at a velocity of 3.5 km/hr**.

(1) Hawaii in June (2) Vladivostok, Boston in December

Insolation (Wh/m2)	Energy collected (Wh)	Velocity (km/h)	Range (km)
6000(1)	**300**	**4.15**	**49.7**
1500(2)	**75**	**2.60**	**31.3**

Table 1 Estimated Daily Range Solar Powered AUV (A)

Variability of Solar Energy

The intensity of solar radiation near the sea surface experiences large seasonal and daily fluctuations. Some of these can be estimated beforehand. Other meteorological conditions result in unpredictable changes in available energy both on an hour by hour and day to day basis. To compensate for these unpredictable variations it is important that strategies be developed that effectively utilize acquired energy as well as optimize methods by which the onboard batteries are discharged and recharged.

Seasonal and daily fluctuations of the light radiation without reference to scattering can be determined according to known astronomic formulae. Scattering and absorption of light by the atmosphere vary greatly and an assessment of those variations is best made acquiring local data over long periods of time. To address this issue, measurements of energy generated daily were acquired by monitoring horizontally arranged solar cells at IMTP for a period of one year. Figure 3. shows records of diurnal power in Wh/m^2 produced by a horizontally placed PV panel with the efficiency = 10% in Vladivostok. Records are grouped into seasons of 100 days. The seasons have a small amount of overlap. Figure 4. shows the solar energy collected on different successive days merely to indicate variability.

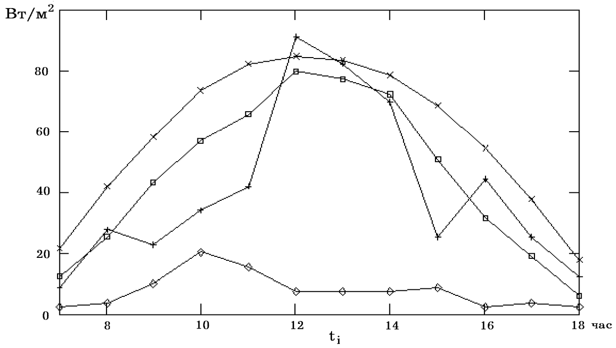


Figure 4. Variability of Daily Solar Energy

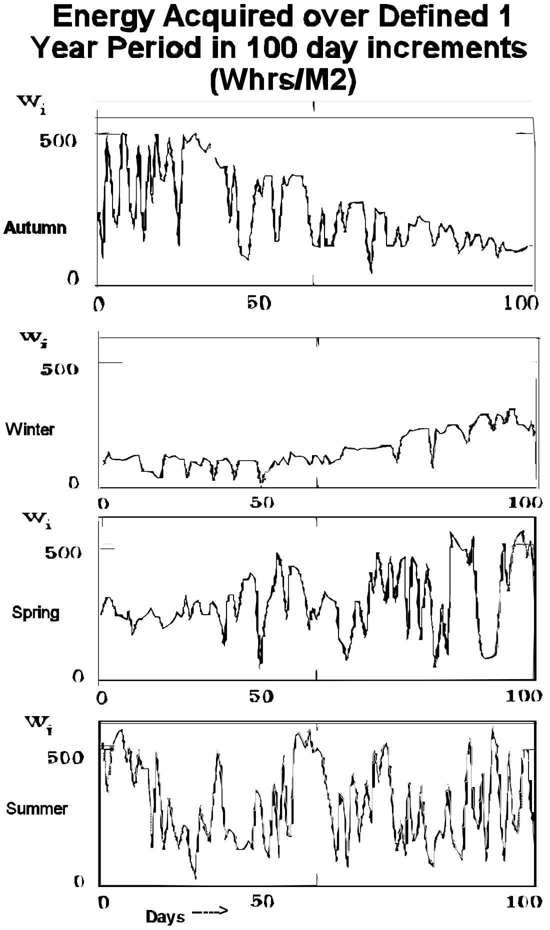


Figure 3 Energy acquired from a horizontally placed solar array in Wh/m2; N=10%, Vladivostok July 1995 - July 1996

The data obtained over the period of July 1995-July 1996 represents a specific example of the variability of solar energy. This cannot be considered to be representative of all locations around the globe, however, it does provide insight into the variability of solar energy. It also helps to verify two aspects of available solar energy. First, data of the average value of irradiation at different regions of the oceans are readily available. Second, based on available and the locally acquired data sets, the patterns of probability distribution are uniformly spread from zero up to maximum and, apparently, in stable, sunny weather - stay within a very narrow spread which can be represented, for simplicity, as a sharp uniform distribution around average values. This preliminary data formed the basis for a number of investigations into strategies for defining and controlling the onboard solar energy system for the AUVs described in Figure 2.

The paragraphs below summarize a few of those investigations. The emphasis was to better understand the alternatives that might exist for managing energy usage based on the variability of real data. The objectives of the energy management task can be defined mainly as follows: to utilize all available energy stored in the onboard energy system; to maximize the cruising range of the vehicle; and to provide an energy reserve in the case of incessantly cloudy weather.

There are a number of ways to implement power/energy management schemes in instrument platforms. We have chosen to categorize them as Active Power Management, Passive Power Management, and Operational Power Management. Active power management is being considered by a number of industries and is concerned with the actual shutting down of individual ICs or components when not in use. Passive power management considers the shutting down of subsystems not required. (An AUSI investigation is looking at this technique currently). Operational power management considers schemes to adjust the operational scenarios required to accomplish defined tasks. This paper focuses on this last alternative

Energy Management Schemes

The power consumed for vehicle motion with velocity $\boldsymbol{v}$ is proportional to $\boldsymbol{v^3}$ or $\mathbf{P = a}\, \boldsymbol{v^3}$. It can be shown that a submersible will obtain maximum range if the hotel power is twice that of the power consumed for motion. However, in the case of the solar AUV we assume that most of the energy will be used for motion. We can then develop a relationship for the total distance traveled **D** [Ageev, 1996].

$$(8) \qquad D = \frac{1}{\sqrt[3]{a}} * \sqrt[3]{t^2} * \sqrt[3]{e}$$

Where **a** is a constant determined by the shape of the vehicle and the properties of the propulsor, $\boldsymbol{t}$ is the time of transit and $\boldsymbol{e}$ is the energy used.

Due to the variability of solar energy, the energy available to the solar AUV each day will vary greatly. If the capacity of the onboard battery is large enough to account for those variations, it is possible to define some average value that can be available each day for transit. Battery size, however, significantly effects the size of the vehicle. If the battery is sized smaller an alternative control strategy can be considered whereby the energy used during the night is equal to the energy acquired during the previous day. The question to be answered is what minimum size battery will account for variations in solar energy such that there is enough reserve energy to account for those times when solar energy is not available. To understand the impacts associated with these two design strategies, it is possible to consider to what extent the total transit distance for **n** days would be reduced if $\mathbf{e_i}$ (daily energy) varies. The worst case arises when the variations of the energy consumed, $\mathbf{e_i}$, over a period of time, are defined by a uniform distribution of **e** from zero to $\mathbf{e_{max} = W_{max}}$ (where $\mathbf{W_{max}}$ is the value of the largest amount of energy acquired in one day during the defined period of time).

If the battery capacity is large, the daily energy consumption $\mathbf{e_i}$ may be constant and equal to an average value of $\overline{W}$ for the defined period. Since the power consumed for vehicle motion is proportional to the third power of velocity, the optimal movement strategy is to move with constant velocity.

In fact, for a given **T** (time available for transit in a day), and $b = \sqrt[3]{a} * \sqrt[3]{T^2}$ then the distance traveled for the ***i***th day, D_i, can be determined by:

$$D_i = be_i^{\frac{1}{3}}, \quad \frac{d}{de}(D_i) = \frac{1}{3}be_i^{-\frac{2}{3}} \tag{1}$$

where: e_i = energy used on a given day; D_i = distance traveled on a given day

The derivative of D_i proves to be a diminishing function since, with equal deviations of e_i, the increase in the cruising range **D** when $e_i > \overline{W}$ will not entirely compensate for the loss of cruising range when $e_i < \overline{W}$. Consequently, the longest cruising range is obtained when $e_i = \overline{W}$ and can be treated as maximally achievable and used as the reference value in considering the other power management strategies. Since the influence of variations in available energy on the cruising range is to the 1/3 power the effect on the total distance covered over many days turns out to be quite small.

To consider this in more detail, three cases can be considered where the variability of the energy acquired over a defined period of time has different characteristics. To evaluate these cases, an efficiency of movement is defined as $\eta_d = \overline{D}/D_0$; the distance obtained in each case relative to the distance that would be obtained if the vehicle moved at a constant velocity each day. The first case{**scheme 1**} is a limiting case and occurs when, for a defined period of time, the available energy is constant i.e. $W_i = \overline{W}$. In this case, the energy available is constant and $e_i = \overline{e} = e_{\max}$ and $\eta_d = 1$. In the second case, {**scheme 2**} the acquired energy **W** has a distribution of uniform density from 0 W $W_{\max}$. The energy used for movement can be defined as:

$$e = W, \quad f(e) = \frac{1}{e_{\max}}, \; 0 \le e \le e_{\max}, \; \overline{e} = \frac{e_{\max}}{2} \tag{2}$$

From formula (1) the maximum cruising range can be determined as: $D_0 = b * \sqrt[3]{\overline{e}}$. With e, distributed according to (2), an average cruising $\overline{D}$ can be determined by formulae

$$D(e) = be^{1/3}, \; \overline{D} = \int_0^{e_{\max}} f(e) * D(e)de = b\frac{1}{e_{\max}}\frac{3}{4}e_{\max}^{4/3} = \frac{3}{4}be_{\max} \tag{3}$$

Based on (2-3) we can determine the efficiency of movement as:

$$\eta_D = \frac{\overline{D}}{D0} = \frac{\overline{D}(e)}{D(\overline{e})} = \frac{\frac{3}{4}be^{1/3_{\max}}}{b(\frac{1}{2}e_{\max})^{1/3}} = 0.945 \tag{4}$$

The general formula in (3) can be used with any law of distribution f (e). In particular a uniform distribution from e_1 to e_2

$$\eta_D = \frac{3}{4} \cdot 2^{1/3} \frac{e_2^{4/3} - e_1^{4/3}}{(e_2 - e_1)\,(e_2 + e_1)^{1/3}} \,,\quad \eta_d \quad 1 \quad \mathit{if} \quad e_1 \quad e_2 \tag{5}$$

Note: In this case if e_1 approaches e_2 we approach an efficiency of 1 as described for the first case above

Finally, the last case {**scheme 0**} is considered to be the worst case where the acquired energy is either 0 or Wmax and there are an equal number of days when no energy is acquired as when the maximum energy is acquired. Using 5 the efficiency of movement can be calculated as:

$$\eta_D = \frac{D(e_{\max}) + 0}{2} = 0.63 \tag{6}$$

More simply stated, the vehicle can move at a constant velocity on the days maximum energy is acquired but does not move at all when no energy is received. Although it can go faster on the days when the maximum energy is acquired, it will not be able to cover as much overall distance during the period as a vehicle that maintains a slower velocity but is able to move at that velocity every day. Although the energy acquired over the total period is the same for each case. The higher speed causes a power penalty hence the efficiency in this situation is only 63%. From this analysis it is seen that losses in the total cruising range compared to the best case $e_i = \overline{W}$ are relatively small (a few percent) even with large variations in the energy acquired each day.

These three cases assume that a sampling strategy has been defined that allows for the possibility of days when no sampling can be accomplished. If, however, the sampling strategy demands that samples be taken each and every day then a different set of factors must be considered. In this case the length of transit is not as important as a guarantee of some ability to sample. The amount of distance traveled is not of primary importance. To account for this another energy management strategy must be considered.

This energy management strategy {**scheme 3**} must consider the need to have a fixed amount of energy available each day. This insures that sampling can take place on a regular basis. The impact is that the amount of energy available for movement is smaller than that available utilizing other power management strategies. Consider the graph in figure 5. An arbitrary energy value is defined since the specific amount of energy will be determined by the task constraints associated a given mission. What is considered is the impact on the energy system and the efficiency of energy use.

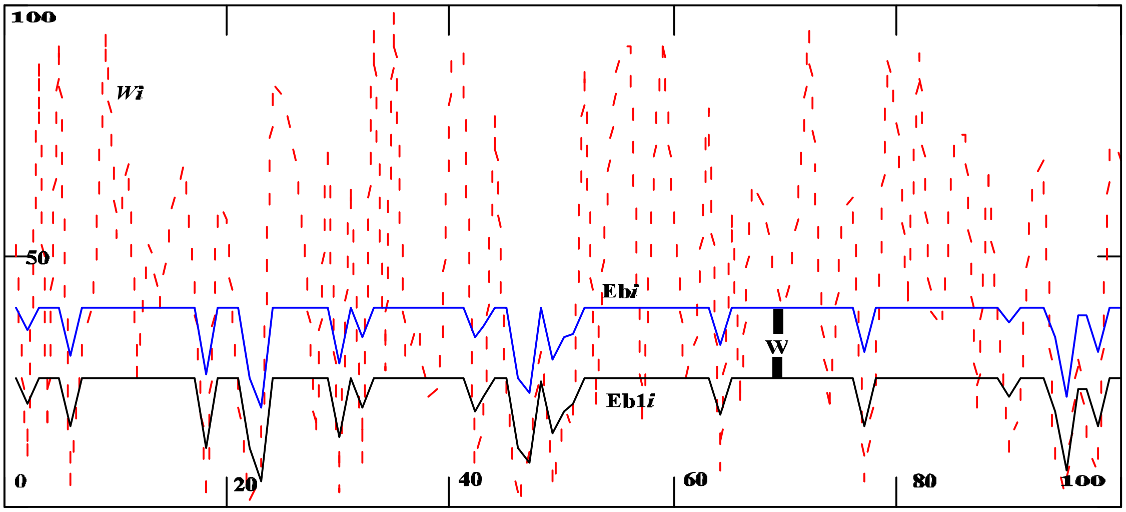


Figure 5 Effect on energy available if a guaranteed level is available each day
Wr = 100 whrs; Ebmax = 40 (storage battery capacity); W = 14.4; Ebmin = 5.5

We will choose a battery size **Ebmax** that is some percentage of the maximum energy available on any day during the operational period. If we consider the maximum energy available at the solar array is $\mathbf{W_r}$ and we again consider a uniform distribution of energy over the operational period the average value of energy at the solar array **Ei** equals ½ $\mathbf{W_r}$. Range is proportional to $(\text{power})^{1/3}$ hence efficiency can be defined as

$$\eta = W^{\frac{1}{3}} / (E_i)^{\frac{1}{3}}$$

In other words, if we use available data from existing solar energy databases, we can obtain an average solar energy available for a period of time at a given location. If we then assume that the solar energy conforms to a uniform distribution, we can determine a maximum available solar energy value. If we size the onboard battery such that it matches that value, then it is possible to estimate the range that the solar powered AUV can transit every day. Table 2 summarizes the results of this analysis.

Battery Capacity as a (%) of total solar energy (Ebmax/Wr)	**100**	**90**	**80**	**70**	**40**
Energy available each day (Watt hrs) (W)	**33**	**30**	**27**	**24**	**14.4**
Efficiency of transit relative to optimum case (%) (η)	**87**	**84**	**81**	**78**	**66**
percentage of available solar energy utilized (%) (W/Ei)	**66**	**60**	**54**	**48**	**29**

Table 2 Impact of total energy available as battery size is decreased

Effect of Different Power Management Schemes on Total Distance Traveled

The goal of this analysis is to understand the effective range of a solar AUV. To determine this range, a number of factors must be considered. First and foremost is to understand the amount of solar energy available at a given location during the operational period. Although having an accurate number is like predicting the weather, it is possible to acquire, from exiting solar insolation databases, an average value for a region close to the region of interest. If we then assume that the variability of this energy conforms to a uniform distribution, we can assume that the maximum value will be twice the average value. This then allows us to determine a battery size for the solar AUV (assuming that the size is such that it will fit within the size of the AUV platform). Once the battery capacity is determined, it is possible to make a number of assumptions as to the range of the solar powered AUV.

One of the objectives of the ongoing program is to determine the range of the solar AUV testbed per unit of energy. Once determined, it will be possible to establish operational constraints and capabilities for a given platform and given task. e.g. The solar AUV prototype vehicle the battery capacity is 420 Whrs. Since the charging efficiency of the batteries (Eout/Ein) is approximately 80% then the available energy is approximately 330 whrs. If we now consider the analysis of the energy requirements of the prototype, we can determine that the propulsion system at 5 watts for 12 hrs will consume 60Whrs (vehcile will have a velocity of 2 km/hr) and assume the hotel load will be approximately 2 W for 24 hours or 48 Whrs. The total energy consumed will be 108 Whrs. This suggests that the **optimum** range of the solar AUV in a location where the solar insolation level is approximately 2000 Whr/m^2/day (which is less than the available solar insolation in Boston from Feb. through Nov.) is approximately 24 km/day. Table 3 summarizes this information for the three power management schemes discussed.

Total endurance 2km/hr (12 hrs/ day)	**Energy management scheme effect on total range (scheme 3 guarantees 20km/day)**			
	Scheme 1 (100%)	**Scheme 2 (95%)**	**Scheme 3 (87%)**	**Scheme 0 (63%)**
30 days	**720 km**	**680 km**	**626 km**	**450 km**
60 days	**1440 km**	**1360 km**	**1252 km**	**910 km**
360 days	**8640 km**	**8110 km**	**7516 km**	**5440 km**

Table 3 Effect of Different Power Management Schemes on Total Distance Traveled

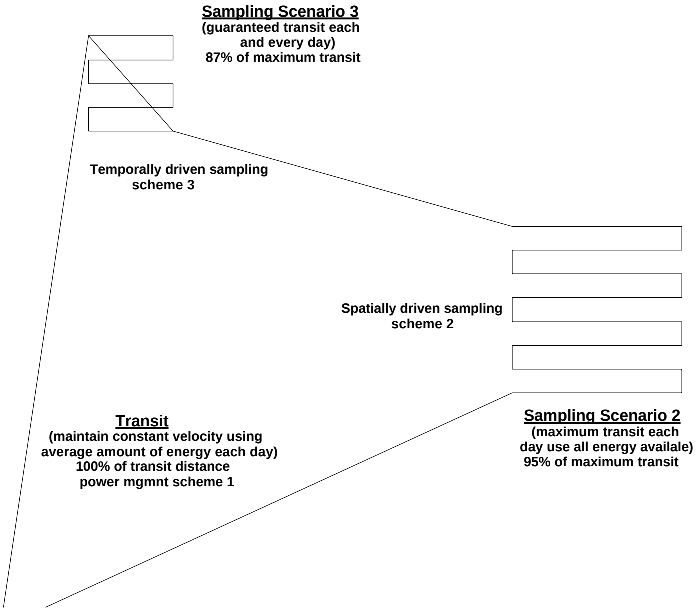


Figure 6 An Example Sampling Scenario

Table 3 summarizes the variations in total distance traveled as a result of using different management schemes. It also suggests that different energy management schemes are more appropriate for different operational tasks.

Consider the figure 6; this represents an operational mission consisting of a number of different types of sampling tasks. When the vehicle begins its operation, its concern is to get from the beginning location to an area where it is tasked to perform a sampling task. It chooses to use energy management scheme 2. Using this scheme, it will travel the largest distance for a given amount of energy. If it must stop due to poor weather, the effect on its operations is minimal.

Once it reaches its first sampling area, it is responsible for sampling over a given distance each and every day. To insure it is able to meet this objective, it chooses scheme 2 since this energy management scheme will guarantee that it will be able to sample each day. When moving from area 1 to area 2, scheme 2 is again chosen. Upon arriving at area 2, it may or may not choose to modify its energy management scheme since the demands of its task at that area do not require it to sample each and every day. It may well be, however, that since it is remaining in a relatively small area, it will be able to understand the variability of the solar energy such that it can determine an average value of energy it receives each day. If so it may well determine that it can use scheme 1 and extend the transits it is able to undertake each day.

In the final analysis, it is clear that the energy control system for a solar powered AUV must have the flexibility to be configured for very different conditions. Final design details must be uniquely determined for a specific region. More work will be accomplished to better understand the variability of solar energy and its impact on the management of onboard energy in a solar powered AUV.

Limitations and Benefits of Solar Powered Auvs

Solar energy systems allow the endurance of AUVs to be increased dramatically thereby allowing sampling systems to acquire needed scientific data over large volumes of ocean and across long time scales and to overcome the burden of recovering and recharging vehicles on a daily basis. While these solar powered AUVs have the potential to achieve these goals they, like most systems, have limitations that must be understood. These systems can store only a limited amount of energy therefore they must be efficient in terms of energy utilization.

In general, a solar powered AUV must surface on a daily basis for recharging. In some missions such as shallow depth missions or those which require variable depth trajectories, this is not a problem. For missions requiring the acquisition of data from great depths the energy to ascend and descend must be part of the overall energy budget. There will also be times, depending on weather conditions, when a solar powered AUV may not have sufficient energy to operate according to a pre-defined schedule. It may miss a day or two. If data acquisition needs to be completed during daylight hours, the system would have to operate on a 48 hour cycle rather than a 24 hour cycle (i.e charge/discharge cycle period).

Certainly there are other limitations that must be considered. The ability to undertake long endurance remote operations without the need for support ships and platforms and the reduced costs of acquiring that data make the development on Solar powered AUVs an important goal for today’s ocean community. Inherent communication capability resulting from the need to surface on a regular basis provides the user/scientist with daily updates of data via satellite telemetry and an opportunity to change the mission based on results while the sampling system is at sea. One can envision a scientist sitting at his/her desk studying newly acquired data, and, based on the results of that analysis, modifying parameters of the data acquisition task, and within minutes issuing a new command to the remote system while it recharges its energy system and updates its navigation system via GPS.

Solar powered AUVs offer the potential of acquiring continuous information for periods of time measured in terms of weeks to months to years. These sampling systems allow for the acquisition of data across long time scales and large ocean volumes which heretofore have proved very costly and in some cases impossible to obtain.

Acknowledgments:

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