Solar Powered Autonomous Undersea Vehicles

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If we are to understand the impact of the world's oceans on our environment, we must gather data with which to understand that impact. Low cost, unmanned, long endurance mobile sampling systems are, in many cases, a desirable alternative to the currently used, oceanographic research vessels requiring large investments in manpower and equipment, or by buoyed instrument strings constrained to a fixed position. AUV technology has evolved over many years. Many of the technological roadblocks preventing routine operational use of these systems have been overcome. Three issues remain as primary limitations; energy, navigation over extended times and distances, and communication of a user with the remote platform on a relatively real-time basis. Solar powered AUVs begin to overcome all three of these limitations. They must surface to recharge the onboard energy system but the available energy is limitless. When surfacing to recharge, they are able to take advantage of GPS navigation to update position **[GPS]**. They are also able to take advantage of the evolving communication infrastructure **[SatComs]** such as existing satellite based communications and the soon to be in place Low Earth Orbiting Satellite (LEOS) communication system. When sampling areas are located near land, it is possible to take advantage of RF telemetry and communicate directly with a user. With continually easier access to the Internet, onshore receivers place data retrieval and mission control within easy reach of geographically dispersed users.

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 1 Solar Powered AUV Testbeds

The Development of a Solar Powered AUV

The Autonomous Undersea Systems Institute (AUSI) along with the Institute for Marine Technology Problems (IMTP) in Vladivostok is investigating the characteristics and limitations of a solar energy system as an energy source for a long endurance AUV. It seeks to understand the impact of the unique system components (specifically the photovoltaic array, the charging system, the energy storage system, and the power management system) on the design of an AUV. It also seeks to identify constraints that an AUV system places on the solar energy system components. In parallel with these activities and experiments, a small prototype, solar powered AUV testbed has been developed. This prototype vehicle is being used to evaluate the results of a number of analyzes related to the use of solar energy to power a long endurance data acquisition systems. The ultimate AUSI program objective is to develop a solar powered AUV system for the marine community with an endurance in excess of one year.

Solar energy systems allow the endurance of AUVs to be increased dramatically thereby providing 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. 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 of 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.

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 and must be efficient in terms of energy utilization. This limits the type of mission sensors carried onboard to relatively low power devices. While developers of scientific sensors are constantly reducing power requirements, many sensors require too much power for application on a solar powered AUV. Most importantly the long endurance sensors must maintain calibration for extended periods of time or be capable of being remotely calibrated while at sea. Biofouling of both the scientific sensors and solar panels used to collect energy is a problem. This is particularly true when operating in the photic zone. At deeper operational depths, the problem is not as severe.

The Technology Evaluation and Development Project at AUSI

A solar energy system testbed is being fabricated to evaluate hardware and software concepts, as well as for investigations into the implementation of energy collection and utilization strategies. Sea wave and sea water interaction experiments as well as bio-fouling experiments are currently underway. Investigations into various energy management strategies, essential to the success of integrating solar energy technology with an AUV are underway. These will be evaluated on the energy system testbed. Empirical data on solar energy collection systems is being compiled and the effects of the ocean environment on the system is being investigated.

Models of the basic components of the solar energy system and analysis tools for assisting the design of solar AUV systems are being developed. The knowledge, concepts, and models developed during this program are being integrated into a "solar AUV design tool-kit". The models and tools will then be used to assess the various power management strategies developed under this program and ultimately assist in the design of future solar AUV systems.

A small solar AUV prototype is being designed and fabricated during the first year of this program. Some basic engineering tests of the Solar AUV prototype will begin in the latter part of 1997 (at Vladivostok) and into the spring of 1998. During the Summer and Fall of 1998, in-water tests of the prototype will be conducted in New Hampshire. Much of the at-sea tests to be conducted at that time will serve to assess and verify the subsystem concepts, power management strategies and overall energy performance of this prototype solar AUV system. One of the important sets of experiments will be designed to measure solar AUV range for different types of energy management strategies as related to various mission scenarios.

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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 these limitations that must be considered. Solar powered AUVs, however, 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.

A Need for Long Endurance Autonomous Sampling Systems

Changes to the global environment brought about by both natural forces and man's activity are a subject of concern to much of the world's population. A number of international research programs are focused on developing a better understanding of ocean processes that impact our environment. A common thread, seen in all of these efforts, is the need to obtain a significant increase in our ability to acquire data from the ocean. Some estimates suggest that we must increase our data gathering capability by two to three or more orders of magnitude in order to meet current needs. This limitation is reflected in the world-wide concern by research organizations over the lack of sufficient data with which to 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. 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 problem of under-sampling of the ocean is a roadblock to many investigations. Few sensors exist that allow us to remotely sample large volumes of the ocean reliability. We are forced to use sampling techniques that have remained relatively the same for over a hundred years. We infer detailed processes by considering sparse data sets. If we are to meet this goal of significantly increasing our ability to acquire data and information, we must consider new technology.

AUVs have a unique capability in that they are able to transit the ocean in three dimensions following a pre-defined path. If their endurance is increased to a year or more, they will allow the data gathering required to better understand global ocean processes. These autonomous sampling platforms offer the potential to acquire measurements at any point in the ocean. Current computer technology and satellite-based navigation and communications provide an opportunity to create systems that can work autonomously for long periods of time. To obtain the required endurance (range and duration), an inexpensive energy source is needed. The only practical method is to extract energy from the environment, and the most obvious type of environmental energy is solar energy.

Solar Powered AUVs Require Answers to Some New Design Questions

When considering the development of a solar powered autonomous platform with an endurance of one year a number of questions must be considered. Most important are those that are unique to the solar powered aspects of the vehicle system. Is there enough solar energy to accomplish important tasks? Can we acquire and utilize that energy to power an autonomous sampling system? What is the impact of the solar array on the design of the vehicle platform and its performance...what are the unique characteristics of this vehicle? What are other problems that must be overcome..... impact of the ocean environment? The ongoing program is attempting to answer these questions. The following paragraphs summarize some of the activities of that program.

Is There Enough Solar Energy to Power an Autonomous Vehicle?

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 $kWhr/m^2/day$ [Bahm94]. 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) **[Rein 93]**. In order to establish some boundaries as to the range that can be expected from a solar powered AUV, we consider two levels of solar insolation; (1) data representing a high level of solar energy off the Hawaiian Islands in June; 6 $kWhr/m^2/day$, and (2) data representing a low level of solar energy available near Vladivostok and Boston, MA in December; 1.5 $kWhr/m^2/day$.

It is possible to calculate the range of a small, solar powered AUV operating in a low insolation area and a high insolation area. With a PV array of .5 M^2 (Figure 1, 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 96]**. 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.

Insolation (Wh/m2)	Energy collected (Wh)	Velocity (km/h)	Range (km)
6000 (Hawaii)	300	4.15	49.7
	75	2.60	31.3

Table 1 Estimated Daily Range Solar Powered AUV

The intensity of solar radiation near the sea surface, however, 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 strategies must 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 2. 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.

From this data it is readily observed that the solar energy system for an autonomous sampling platform must account for the variability of available solar energy. A power management strategy must effectively use onboard energy as well as adjust utilization of that energy to account for the high variability to be expected.

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

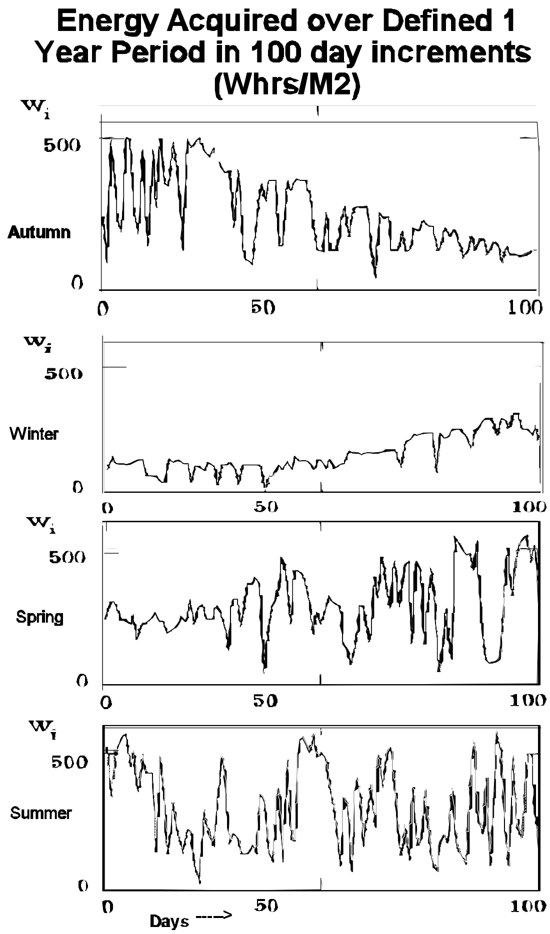

Figure 2 Energy acquired from a horizontally placed solar array in Wh/m2; N=10%, Vladivostok July 1995 - July 1996

to define some average value that can be available each day for transit. 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. By moving at a constant velocity at all times except when the vehicle is recharging on the surface (power management scheme 1), the maximum distance can be covered. The battery must be large enough to store extra energy that it can make available to the vehicle when there is little or no solar energy. 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. This allows a the total transit to be maximized each day (power management scheme 2). If however, there is no available energy on a given day, the vehicle will not have enough reserve energy to continue and must wait for another day to recharge its batteries. For some sampling tasks this is not critical but others demand that the vehicle move a defined distance each day. This forces us to consider an energy management scheme whereby the vehicle can move a defined distance each day (power management scheme 3). The efficiencies of energy utilization are different for each of these power management schemes, however, by using such schemes it is possible to tailor vehicle performance to meet the needs of different sampling tasks.

What Are the Unique Characteristics of this Vehicle

Two versions of the solar powered AUV prototype are being considered during the design process (figure 1). One platform (version A) is being tested off the New Hampshire Coast to understand the effects of surface motion on the efficiency of the array in acquiring solar energy. Preliminary analysis suggest that the effects of wave motion may be quite minimal as the arrays are relatively insensitive to angular orientation within +/- 25 degrees from the direction of the sun. Also that the effect of water washing over the array is minimal if the array is less than 20 to 30 cms below the surface **[Jal 97]**. A second platform (version A), being completed in Vladivostok will contain the electronics required for initial in water evaluation tests of vehicle performance to be undertaken during the latter part of 1997 and spring of 1998. These tests will be conducted to initially evaluate vehicle flight and control characteristics, but more importantly to evaluate and experiment with the solar energy system, the intelligent control of that system, and the various strategies for energy management developed in this project. A primary objective of these tests is to determine the range of the vehicle per unit of energy. Once determined, it will be possible to establish operational constraints and capabilities for a given platform and given task.

A solar powered AUV is unique in that it must include a solar array large enough to collect sufficient solar energy to accomplish a usable sampling mission. An interesting analysis of the design factors associated with a solar AUV can be seen in **[Ageev 95].** In this analysis, a conclusion is reached that the effective range of a solar powered AUV is determined only by the efficiency of the array used to collect solar energy and not by the size of the array. Intuitively one would think that the larger the array on a solar powered AUV, the more energy that can be acquired, hence the longer the distance that can be traveled. The problem is that as the array is increased, so is the drag on the vehicle system hence the larger the amount of energy necessary to push the vehicle through the water. This hypothesis, as yet unproven, suggests that the size of a solar powered AUV can be adjusted to meet the demands of the payload (sensor size, battery size, etc.). The range, however, will not be significantly effected. If, on the other hand, the efficiency of the solar array is increased, the range of the vehicle will be increased in a similar manner. This unique characteristic emphasizes the need to clearly understand those factors that impact the range of the solar AUV.

The analysis to determine the effective range presented above assumed that all of the available energy was used for propulsion. The goal of this analysis was to understand the limits associated with the effective range of a solar AUV. To accurately determine this range, a number of other factors must be considered. First and foremost is to understand the amount of solar energy available at a given location and its variability during the operational period. Although having an accurate number is like predicting the weather, it is possible to acquire, from existing 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 **[UUST 97]**, 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. By considering different power management schemes it is possible to obtain more realistic endurance numbers for a solar powered AUV.

For example the solar AUV prototype (figure 1.) vehicle 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 (at 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

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%)**
30 days	**720 km**	**680 km**	**626 km**
60 days	**1440 km**	**1360 km**	**1252 km**
360 days	**8640 km**	**8110 km**	**7516 km**

Table 2 Effect of Different Power Management Schemes on Total Distance Traveled

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 2 summarizes the total endurance of the solar powered AUV prototype for the three power management schemes discussed above.

Impact of the Ocean Environment

The analyzes performed to date emphasize the potential of a solar power AUV as being an ideal sensing platform. There are, however, some questions that remain unanswered and must be resolved. AUVs have been used in the ocean for a couple of decades and their designs are well suited to the ocean environment. The addition of solar panels prompts a consideration of the interactions of the ocean environment and this technology. There are four potential hazards which impact the design of a solar powered AUV: corrosion, bio-fouling, collision with boats while recharging, and the mechanical effects of wave action on the system. Of primary interest are corrosion and biofouling. Most serious of these is biofouling.

Surface fouling of PV-collection surfaces by biological organisms is a serious concern for shallow-water solar-powered AUVs. There is no simple anti-fouling technique proven to be 100% effective against all organisms. In order to minimize the impact of marine fouling on solar cell surfaces, a two-pronged approach is being investigated. First, any protective coating or laminate must provide "easy-release" surface characteristics. Secondly, some mechanical method of "wiping" the array during operations must be implemented.

Easy-release surfaces exhibit a low surface tension to water, a quality which also significantly lowers the potential for permanent attachment by living organisms. Some commercially-available solar panels--such as the Solarex MSX-Lite series--are coated with transparent EVA (Ethyl Vinyl Acetate), a polyethylene laminate known to provide superior release characteristics to glass. The survivability and anti-fouling quality of one such panel was recently demonstrated after a one-year immersion at approximately 1000 feet in the gulf of Maine.

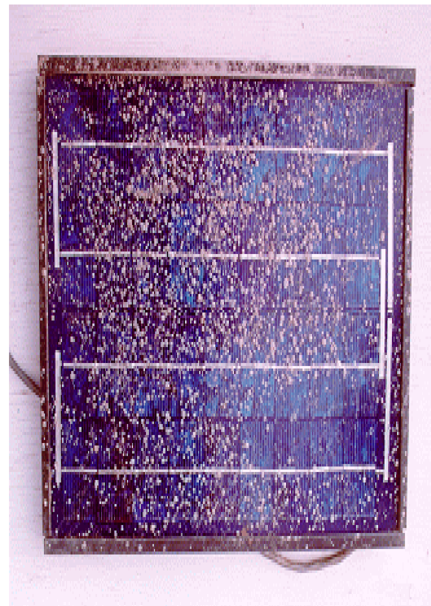

Figure 3 MSX 10 Solar Module

We were able to obtain a solar array that was part of instrumentation buoy being used by the Ocean Processes Analysis Laboratory at the University of New Hampshire. This particular array (see attached figure) had been on a buoy that sunk in 275m of water in the Gulf of Maine. The Solarex MSX 10 array had been on the bottom for approximately one year. The array had not been cleaned when we acquired it for test purposes. We were able to make performance measurements prior to cleaning and immediately after it was retrieved by a fishing trawler. There was a degree of biofouling and some mechanical faults. As can be seen from the figure 3., the array was covered with barnacles but beyond this seemed unaffected with the exception that a junction box on the back of the array had imploded due to pressure. The hard anodizing has been scraped from the upper aluminum frame piece.

Measurements prior to cleaning of the array determined that, when placed in the sun it functioned as if there had been no electrical damage whatsoever. The array was then sent to the manufacturer for a complete test and the results verified that indeed there had been little effect from being submerged. The array functioned within the original specification of 10 watts +/- 10% and an efficiency of 11.5%. This experience provides some level of confidence as to the durability of current PV arrays in the ocean environment. Although not conclusive, it does provide a significant data point.

An important consideration is the overall system reliability. The reliability of sensors over extended periods of time is an unanswered question especially when considering months to a year of unattended operation. Along similar lines is the question of overall platform and subsystem reliability for periods of months to years. Certainly there are examples of systems with this reliability but few have been demonstrated in the ocean environment especially when one half of there operational time is spent at the surface. The design of solar powered AUV systems with extended endurance will be an evolutionary process. The potential of these systems, however, suggests that the process be endured.

Acknowledgments:

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