A Cross-Platform Microstructure Turbulence Measurement Package

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Abstract

Ambient turbulence in the ocean is responsible for dissipating the kinetic energy in the ocean at very small scales. Small autonomous underwater vehicles (AUVs) provide versatile mobile platforms for surveying a shallow water coastal environment at low operational costs. The platforms are uncoupled from the low frequency vibrations associated with platforms towed from surface ships. Measurement of turbulent microstructure and the associated dissipation rate using an AUV requires accommodation of the inherent vibration characteristics of a self-propelled platform [1],[2]. Often such vibrations are in the range of flow measurements of interest and may corrupt the data. At Florida Atlantic University, a turbulence measurement package has been developed which implements vibration isolation from the AUV platform. The sensors in the package include two shear probes, a fast response temperature probe, a fast response conductivity probe and accelerometers for monitoring vibrations. In addition, the turbulence package developed is modular and interoperable in the sense that it may be mounted on a variety of platforms in a simple robust fashion without changes to the platform. The AUV platforms used thus far include the Ocean Explorer vehicle at Florida Atlantic University [3] and the Autosub [4] at the Southampton Oceanography Center. These vehicles vary in size from 2 meters long and under 200kg for the OEX to over 7 meters long and over 1500kg for the Autosub. The design of the turbulence package and results from implementation aboard these very different autonomous underwater vehicles will be described.

I. INTRODUCTION

Turbulent mixing and consequent dissipation of energy plays an important role in the spread of contaminants, on sedimentation processes and on nutrient levels throughout all of the ocean zones. An understanding of the distribution of turbulent energy under various background conditions is therefore essential. Oceanic turbulence is created through a variety of mechanisms. In the upper layer, wave breaking, wind shear and currents contribute to turbulence. In the bulk of the ocean, internal breaking waves, convective flows, interfacial shear and, again, currents contribute to turbulence. Near the bottom, the turbulence is generated primarily through shear in the benthic boundary layer or plumes from a bottom source. It is believed that the largest eddies contain the bulk of the ocean's kinetic energy. The energy is transferred to smaller eddies through instability and break-up of the larger eddies. The smaller eddies, in turn, similarly transfer energy to even smaller eddies and so on to the smallest eddies which then dissipate energy by viscous diffusion. According to Kolmogorov [5] if the dissipation rates of the micro-scale eddies can be measured, then, under certain circumstances, the rate of energy production can be estimated. The focus here shall be on the measurement of fine and micro structure which lies in the so-called inertial subrange and dissipation range of the spectrum of turbulence. This range is important in the cascading of energy from the inertial range down to where the dissipative effects of viscosity transfer inertial energy to thermal energy.

II. MEASUREMENT PLATFORMS

The development of vertical profilers and towed arrays along with more sophisticated probes in the seventies allowed for the resolution of increasingly more detailed mapping of the physical scalar and vector fields. An early vertical profiler specifically for microstructure measurement was used to collect data in Howe Sound [6]. A contemporary vertical profiler typical of the type is TOPS shown in Fig. 1.

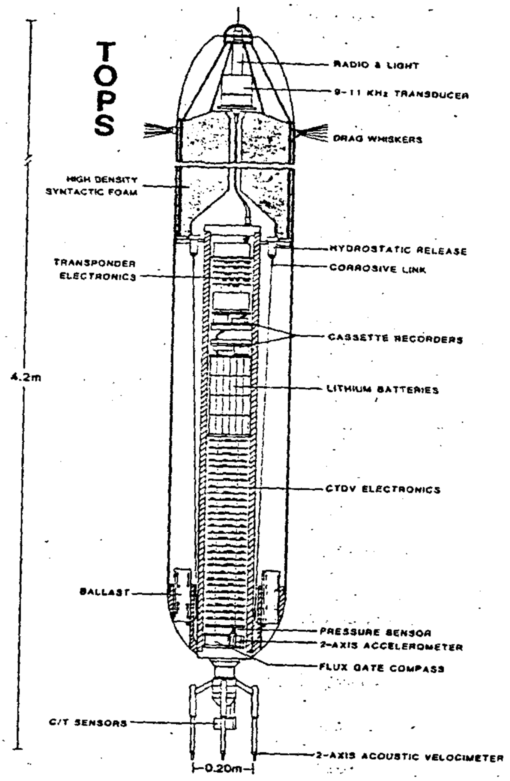

Fig. 1. TOPS vertical profiler [7].

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A multiscale profiler was used by Gregg [8] in the Patches Experiment in the eastern North Pacific. From vertical profile data, epsilon and shear are compared to a model by Barrett and Munk. A vertical profiler may also be freely rising rather than free falling. A. Anis and J. N. Moum [9] used a freely rising vertical profiler to measure vertical profiles of the microstructure in the upper oceanic boundary layer. The manned submersible Pisces IV (figure 3.2-1) was used to collect turbulence data [10]. A submersible promises lower vibration contamination at slower speeds and flexibility of operation. Modifications made to the Pisces IV to accommodate turbulence measurement include stabilization fins and a cantilevered strut for mounting the probes. Towed horizontal profilers have also successfully measured turbulent microstructure. One of the very earliest studies of dissipation range turbulence used a towed vehicle with hot film sensors [11] (Fig. 3.). Low frequency measurements were contaminated (below 1 cps) but the dissipation range was well documented. Towing systems have more recently been developed which decouple the motion of the measurement platform from the surface vessel to a great extent [13]. Gliders represent a class of vehicles that promise more complex mission profiles than the simple vertical profilers but without the mechanical complexity and noise of a motorized vehicle. The EPSONDE is a tethered glider designed specifically for turbulence measurement [12]. It collects data on the decent while traveling with a maximum velocity of 0.6 m/s.

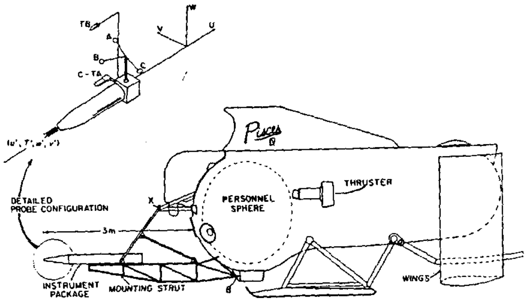

Fig. 2. Pisces IV submersible with microstructure sensor [10].

The use of an autonomous underwater vehicle (AUV) as a platform for turbulence measurement clearly has many advantages [1], [2]. It allows the possibility of making turbulent microstructure and possibly meso structure measurements not previously possible due to time, money or platform constraints. Multiple path missions at widely varying depths in deep or shallow water will allow measurements to be made in a variety of conditions within a meter of the bottom or sea surface. Profiles may be made in any pattern desired from horizontal to nearly vertical and from straight lines to corkscrew patterns. With its flexibility in mission types, the AUV overcomes the inherent problems of lack of control to perform these maneuvers. Maneuvering does however introduce errors in the turbulence measurements from the vehicle self motion and vehicle structural vibrations requiring special measures to minimize contamination of measurements.

Fig. 3. Towed profiler [11].

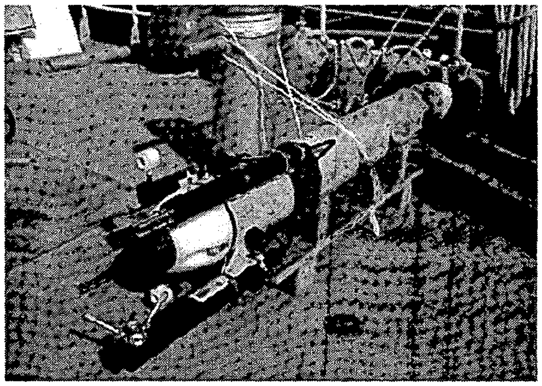

Fig. 4. Remus vehicle with the turbulence measurement package [14].

Early measurements of turbulent microstructure using an AUV include [1] at Florida Atlantic University (FAU) and [2] at the Navel Undersea Warfare Center (NUWC). The group at FAU implemented Two shear probes, a fast response thermister and an electromagnetic current meter as sensors on the Ocean Explorer series of AUV's. Additionally, accelerometers were mounted inside the package to measure the vibration. This information may then be used to post process the data and substantially remove vibration contamination from the shear probe signals. The group at NUWC used the Large Diameter Unmanned Underwater Vehicle (LDUUV) owned by the U. S. Navy and is about 21 feet long with a maximum diameter of about 2.5 feet. This size most likely puts any contamination due to vehicle motion below the frequency range of interest for microstructure measurement. Mechanical noise from the thruster and actuators influence the turbulence measurements and the turbulence signals are post-processed to reduce the error. This same group has recently integrated a turbulence sensor package into the REMUS AUV [14] Sensors include two shear probes, an ultra-fast thermistor, an upward and downward looking ADCP, two vertically separated CTDs, and an ADV-O.

III. INTEROPERABILITY

In all of the measurement platforms previously discussed, the instrumentation package was custom built though all of them have very similar functions and hardware. Sensors, usually shear probes and thermisters, analog signal conditioning and data acquisition systems are used to capture the turbulent microstructure information. In contrast, the package described here is designed not for a specific platform but as an interoperable scientific package available for a platform of opportunity.

The basic design philosophy for the Interoperable Turbulence Package (ITP) encumbers the following features. First it has to be modular in the sense that as a unit it can be implemented either stand alone or with modular enhancements. This facilitates implementation on a wide variety of platforms including towed systems, buoyancy driven vehicles and AUVs with minimal reconfiguration of either the platform or the turbulence package itself. Secondly, as much of the turbulence package as possible should be assembled from COTS hardware and software in order to speed up delivery time and allow simplified reproduction and minimize costs. Additionally the package needs to be small so as to allow implementation on small platforms and also ease in transportation to often distant and remote locations, indeed it is small enough to fit in a suitcase. Also it must implement existing sensor technology accepted in the physical oceanographic community. Finally, the user interface should be familiar to most engineers/scientists.

The technical system requirements for a cross-platform turbulence measurement package include a sampling rate of at least 300Hz in order to resolve the viscous roll off in the dissipation spectrum. Additionally the system should be able to resolve dissipation rates down to 10e-9 or better. Given that the system will be mounted on a variety of platforms it is desirable to be self-powered or host-powered. The large amount of data must be stored in a secure fashion so as to be recoverable even after catastrophic failure of other systems such as power or even the pressure vessel itself.

In selecting the sensor systems it is assumed that the host platform measures CTD as well as the mean velocity and altitude. This assumption is usually correct in the case of AUV platforms but may be presumptuous for some towed or vertical profilers. The sensors included in the ITP include two shear probes (made at FAU), a fast response thermister (*Thermometrics FP07*), a fast response conductivity probe [15] and a three-axis accelerometer (IC Sensors 3140). This basic sensor array will give the velocity, temperature and conductivity microstructure and allow the calculation of the density microstructure. The electronics include a custom analog interface board with amplifiers and anti-aliasing filters. The data acquisition is accomplished with a PC 104 stack including a 16bit A/D board, a 386 CPU board 1.5G flash drive and a custom power supply board. The 386 board includes a VGA adapter, keyboard, IDE and Ethernet port. QNX is the operating system with the software written in C. The Ethernet port is used to communicate to the package externally. The flash drive is extremely rugged and preserves the data even if completely flooded with salt water. The system may be self powered with 20 AA alkaline batteries for up to 6 hours of operations or the system may be optionally powered from the host platform with a single underwater cable. This cable carries the supply voltage of 12 to 72 volts, a serial CTS line used to trigger data collection and RS 232 communications. The physical attachment to the host is through a 6inch diameter ring screwed or bolted to the nose of the host. The package may be quickly connect/disconnected from the ring; even by a diver if necessary. For deployment aboard any platform, only two custom pieces are required: the mounting ring and the adapter cable. The pressure housing is made of aluminum pipe and is rated to 300 meters.

The most important consideration for turbulence measurement using shear probes, are vehicle induced vibrations; both at the high frequencies associated with the moving machinery and at the low frequencies associated with the rigid body motions of the entire vehicle. Non-motorized platforms have an advantage with no moving parts but careful vibration isolation reduces the machinery noise to acceptable levels. The narrow banded vibrations, which are of the same order in magnitude as the measurement, can be removed through the use of signal processing techniques. Even though it is best from an engineering standpoint to reduce vibrations at the source, this is not always possible since the package is dependant on a host of opportunity and vibration reduction at the ITP became paramount. This was implemented with a second flooded housing over the pressure vessel with isolation mounting between them. The second flooded housing is then mounted to the vehicle resulting in vibration isolation between the package and the host. The resulting system transfer function was measured to have a damping coefficient of 0.3 with a resonance at about 8Hz and an approximately 2nd order roll off above this.

A second influence of the platform is that the body will cause the fluid velocities to change and result in a distortion of the flow measured by the turbulence measurement system. A potential flow analysis of the flow distortion estimates the change in the mean velocity of the flow that may then be used to correct the measurements. The turbulence itself is distorted but the frequencies of the measured spectrum remain the same. The potential flow is created by a simple distribution of sources and sinks Since the analysis is done is for the flow over the leading edge of the body, boundary layer effects need not be considered. Once the flow is modeled it is a simple calculation to find the fluid velocity vector at any point in the fluid. The velocity vector may then be used to correct any calculations. A potential flow analysis of the turbulence package results in a reduction of the mean velocity at the probes to 94% of the free stream [1].

IV. IMPLEMETATION ON THE OEX

An *OEX* series AUV, designed and built at Florida Atlantic University [3] is typically 2.4m long (Fig. 5.) with a modified Gertler's Series 58 Model 4154 fiber-glass hull of 0.53m maximum diameter. The *OEX* is designed to support multiple *in situ* sensor payloads for performing search and mapping operations in coastal shallow-water environments. Its unique feature is a modular bayonet-mount interface between its payload and tail-section, allowing easy switching between payloads. The 1.2m tail-section houses navigation, control and propulsion components, including a 1200kHz ADCP, a CTD, a GPS receiver unit, a Watson-Block self-motion sensor, whereas a nominal 1.2m payload section, which may be extended to 2.4m, is dedicated to housing mission-specific instruments. In air, the *OEX* weighs approximately 181kg, and is designed to be neutrally buoyant. Its maximum depth rating is 300m. Using its onboard rechargeable NiCad batteries, which can provide approximately 2kWh total energy, the *OEX* can maintain a cruising speed of 3 knots (a speed range of 2-5 knots) for approximately 8 hours continuously between the recharge cycles. A Motorola 68060 CPU with a VX operating system and 1 Gbyte disk storage capacity allows logging a significant amount of navigation and environmental data. The AUV location is continuously tracked acoustically via an USBL transponder from a research vessel, which is also used to launch and recover the AUV. During the mission, 113 different variables are recorded on the on-board computer, including its depth, velocity through the water, and, where bottom-lock is possible, its ground velocity and altitude, its position in latitude and longitude, and *in situ* conductivity and temperature.

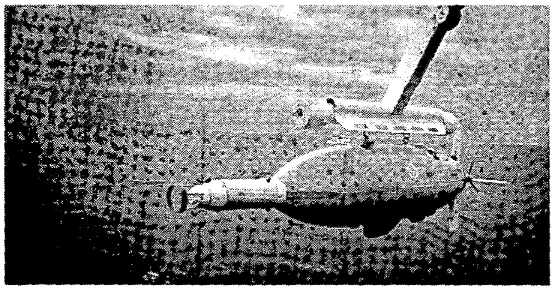

Fig. 5. The Ocean Explorer AUV, shown with the Interoperable Turbulence Package.

A series of experiments were conducted with the ITP mounted on the OEX. The objective of the experiments was to make measurements of small-scale turbulence, kinetic energy and ambient noise as well as of background current, temperature, salinity and sound velocity profiles in the shallow water column during the passage of a cold front over the warm continental self off the East Coast of Florida [16]. The long-term aim is to investigate the impact of such fronts on mixing, air-sea interaction, sediment transport and the noise characteristics in the shallow water column. The technical aims include determining suitability of AUVs as oceanographic measurement platforms and the influence of adverse conditions on acoustic propagation and in turn on navigation, underwater communication and control performance.

The experiment was conducted on the SFTF range, in the vicinity of the location 26 ^{0} 03.7'N and 80 ^{0} 05.56'W, about 2 miles offshore of Ft. Lauderdale, south of Port Everglades. The schematics of the operations are shown in Fig. 6. The tail section carried a Falmouth CTD package, a 1200kHz ADCP and a GPS navigation system.

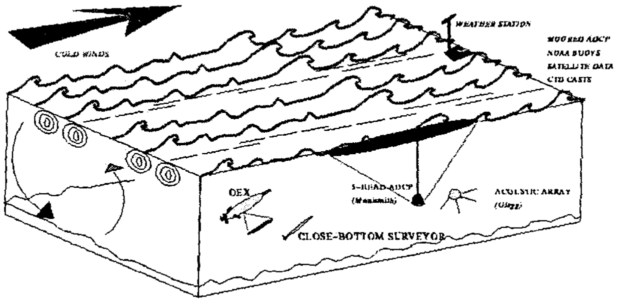

Fig. 6. Schematic of the Adverse Weather Experiment.

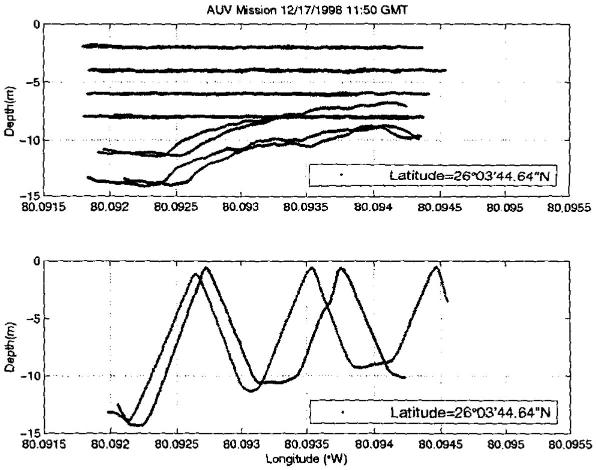

Fig. 7. Mission path for the OEX.

The OEX was launched from the surface vessel and carried out box-pattern surveys over the bottom-mounted, upward-looking 5-head ADCP. The path of the OEX AUV during Dec. 21, 1998 operations is shown in Fig. 7. The turbulence levels and the associated mixing rates were high, with dissipation rates of O (10^{-7} W/kg), throughout the shallow water column in response to the cooling of the surface waters, giving rise to fairly homogenous conditions in the water column. Sample turbulence spectra as measured from the mobile AUV platform is shown in an attached Fig. 8. The dissipation rate as a function of time is being developed and together with the 5-head ADCP will provide useful information about the energy balance in the water column. Simultaneous CTD and ADCP measurements using the AUV, together with measurement from a bottom-mounted 5-head ADCP and CTD casts from the mother ship provided sufficient background information to put the small-scale measurements in proper context and determine implications for mixing rates and rates of energy dissipation. Work is in progress to synthesize the various data for a full analysis of the experiment.

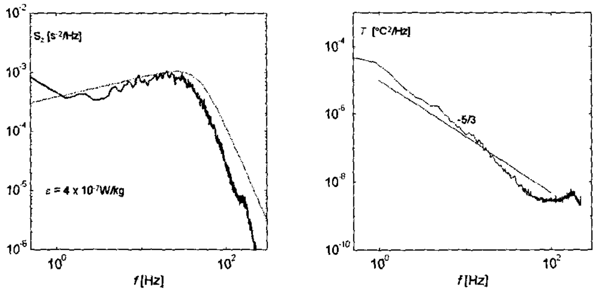

Fig. 8. Sample shear and temperature spectra from 2-minute time segment on December 21, 1998.

V. IMPLEMENTATION ON THE AUTOSUB

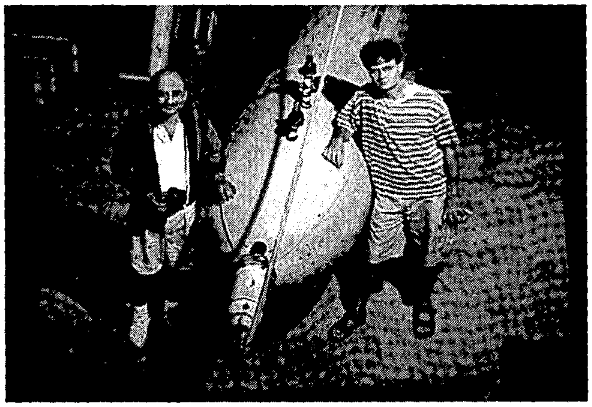

Fig. 9. The Authors standing by Autosub with the ITP.

Small-scale turbulence measurements were taken with the ITP in the Sargasso Sea, south-east of Bermuda, using SOC's Autosub during summer 1998 [4]. Three successful profiling missions, to depths of up to 400m in over 800m deep waters were carried out with the Autosub in an international collaborative project. Two of the mission paths are shown below in Fig. 10. As a result of the measurements, we have obtained high quality two cross-stream shear and microstructure temperature data over a total of six hours (around 210Mbytes). Sample shear and temperature spectra of the turbulence measurements are shown in Fig. 11. Dissipation rates as low as $O(10^{-10}$ W/kg) were measured. The AUV also collected background ADCP and CTD data that put the distribution of the rate of kinetic energy dissipation, inferred from the turbulence measurement sensors, in its proper context. The region near the time-series station Hydrostation S, Bermuda is well studied for its biogenic activities and involves determination of such quantities as sediment flux, fluorescence, dissolved oxygen and carbon dioxide and nitrate levels in the water column, the distribution of all of which is significantly influenced by the level of mixing induced by turbulence. The mixing rates reach their peak during hurricanes. Our profiling was carried out on three consecutive days prior to hurricane Bonnie reaching Bermudan latitudes. We observed increasing winds, from 0 to 15 knots during the three days with swells of up to 6ft and chops of up to 4ft. The following day 10ft swells were present and would have prevented boat activity. The missions were partially funded through NICOP, Office of Naval Research.

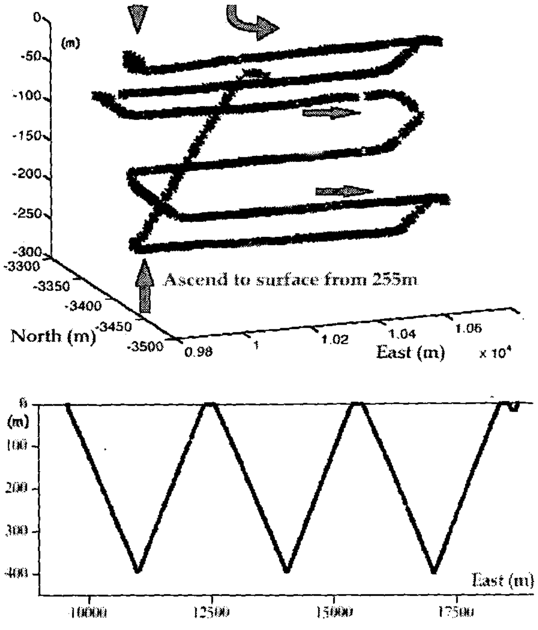

Figure 10. Autosub paths: (a) "Staircase" survey, 8/21/98, (b) "See-saw" path, 8/22/98

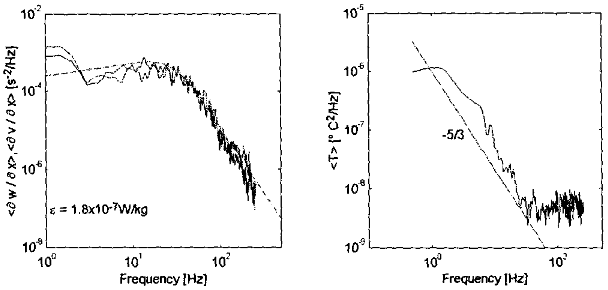

Fig. 11. Sample (i) shear (ii) temperature spectra measured on 8/21/98 near the water surface.

IV. FUTURE WORK

Future platforms include possible collaboration with the ARL lab at Penn State University aboard one of their vehicles. Possible missions may include self-wake measurements and tidal currents in Puget Sound. Another future platform may be the Autonomous Station Keeping Buoy (ASKB). This platform is an autonomous surface vessel for scientific investigation of the air-sea interface. Studies of heat and chemical exchange between the atmosphere and ocean including shear induced turbulence may be included as part of a larger experiment. The Morpheous AUV, currently under development at FAU, may also be used with the ITP. All of these are future examples of how the ITP is easily adapted to fit a wide variety of platforms with little modification and low cost. Future enhancements to the ITP include active vibration control using a small microprocessor and piezo actuators to reduce vibration contamination of the turbulence signal. Numerical simulations of such a system have resulted in an order of magnitude reduction in broad-banded noise.

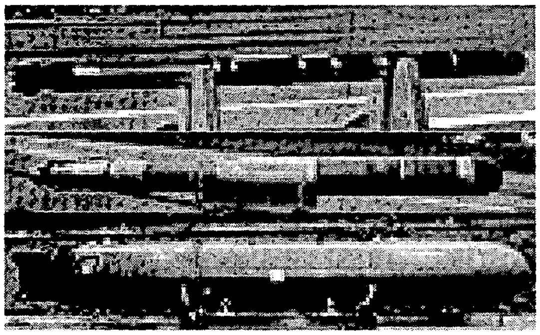

Fig. 12. Vehicles at the ARL

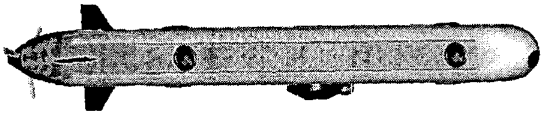

Fig. 13. Morpheous AUV under development at Florida Atlantic University.

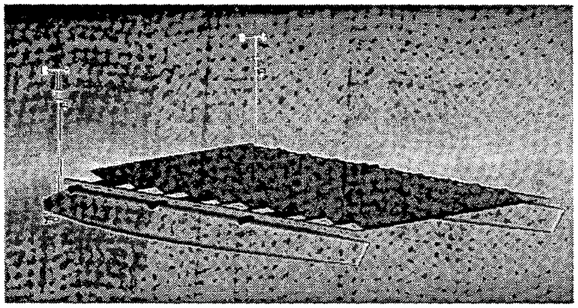

Fig. 14. Autonomous Station Keeping Buoy.

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