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Report on Air Launched
Autonomous Underwater Vehicles

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ABSTRACT

The feasibility of Autonomous Underwater Vehicles (AUVs) being launched from aircraft was funded through the NERC Oceans 2025 programme, investigating a more economical of seeding wide swaths of ocean with sensors carrying out wide scale, synoptic physical oceanographic surveys. Small AUVs would be parachuted down, upon hitting the water, they would begin their AUV missions.

As well as applications for wide spatial surveys, opportunities were seen for supplementing existing surveys such as the Atlantic Meridional Transect (AMT), Porcupine Abyssal Plain (PAP), Meridional Overturning Circulation (MOC). The faster response time of mobilising an aircraft compared with a ship opens possibilities for rapid response surveys, e.g. pollution spills, and algal blooms. A unique application particularly well suited to Air Launched AUVs (ALAUVs) is the survey of polynyas in the Polar Regions which are uncharted and important to setting the conditions for circulation beneath the ice shelves. Beyond environmental research and civil survey work, the concept also has naval applications for sound velocity profiles, bio luminescence, and with the ALAUV being much smaller and semi disposable compared with existing vehicles, covert surveys.

Key to the overall success is creating an economical AUV that could be considered to be semi disposable by means of small overall size, simple design with minimalist the sub systems. With the developments of miniaturisation and lower power requirements of subsystems and to a lesser extent, battery technologies, there exists an opportunity for developing an AUV weighing in the region of 2.5kg but which still has a range of some 350km at $0.5ms^{-1}$. A number of small sensors in the market place used for tagging fish and mammals and the research work at the National Oceanography Centre (NOC) on miniaturised sensors all help support the case for further development.

The conclusion is the ALAUV concept is feasible, opens new applications and new *modus operandi* of working with AUVs.

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Summary

The concept of Autonomous Underwater Vehicles (AUVs) being launched from aircraft was funded as a feasibility study through the Oceans 2025 programme running from 2008 and to March 2011. The original concept was to have a more economical means of seeding wide swaths of ocean with sensors for carrying out wide scale, synoptic physical oceanographic surveys. The means considered for achieving this was to launch multiple AUVs from high altitude and have them glide 100km or more, navigating themselves to specific locations. Upon hitting the water, they would begin their AUV missions.

As well as applications for wide spatial surveys, opportunities were seen for using aircraft of opportunity for supplementing existing surveys such as the Atlantic Meridional Transect (AMT), Porcupine Abyssal Plain (PAP), Meridional Overturning Circulation (MOC). The faster response time of mobilising an aircraft compared with a ship opens possibilities for rapid response surveys, e.g. pollution spills, and algal blooms. A unique application particularly well suited to Air Launched AUVs (ALAUVs) is the survey of polynyas in the Polar Regions which are uncharted and important to setting the conditions for circulation beneath the ice shelves. Beyond environmental research and civil survey work, the concept also has naval applications for sound velocity profiles, bio luminescence, and with the ALAUV being much smaller and semi disposable compared with existing vehicles, covert surveys.

Key to the overall success is creating an economical AUV so they could be considered to be semi disposable; crucial to this is keeping a small overall size to simplify the design, minimise the sub systems and manufacturing costs. With the developments of miniaturisation and lower power requirements of computing systems, Global Positioning System (GPS) receivers and antennae, advancement of satellite communications and, to a lesser extent, battery technologies, there exists an opportunity for developing an AUV very much smaller and cheaper than AUVs to date but which is still have a practical range. A number of small sensors in the market place used for tagging fish and mammals and the research work at the National Oceanography Centre (NOC) on miniaturised sensors all help support the case for further development.

The project has worked through the concept of an Unmanned Air Vehicle (UAV) becoming an AUV; investigating a conventional looking glider and an autonomous parafoil. The key question the original (UAV becomes an AUV) concept needing to be answered is 'why not have the deployment aircraft cover the swath width by returning on a parallel course offset by the desired swath?'; especially since it is likely the aircraft will return from whence it came. This led to the more simple idea of a parachuted vehicle freed from the complexities of needing to survive the transition from a turbulent launch to glide path and associated requirement to control and navigate. The idea was found to have credibility, practicality and present day applications.

Atmospheric measurements are taken from small parachuted dropsondes and the size and launch infrastructure of these devices was taken as a starting point for considering an AUV of a similar size. Utilising the latest technologies for mission management, logging and communication with the emerging technologies of miniaturised sensors an AUV with practical range (>300km at 0.5m/s) and operational depth (500m) could be as small as a drop 'sonde (83mm diameter), weighing approximately 2.5kg. With the limited life and recoverability requirements, the AUV can be stripped of systems like acoustic communications, emergency abort weight, brushless motors, all of which should reduce the build cost.

The conclusion of this study is that the ALAUV concept is feasible, opens new applications, new ways of working, and avenues for funding hardware development within the context of a motivating science mission should be actively explored.

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1.0) Introduction

Funding for the Air Launched Autonomous Underwater Vehicles (ALAUV) project was awarded through the NERC Oceans 2025 programme, running from 2008 to March 2011. The remit was to investigate the feasibility of changing the *modus operandi* of Autonomous Underwater Vehicles (AUVs) working from ships or boats to launching multiple AUVs from aircraft. This would broaden the survey areas, potentially covering entire seas to obtain near synoptic data. The concept described in the Oceans 2025 was to have a vehicle launched from an aircraft and glide autonomously to navigate itself to a target spot on the ocean whereupon it carries out an underwater survey [1] (Fig 1).

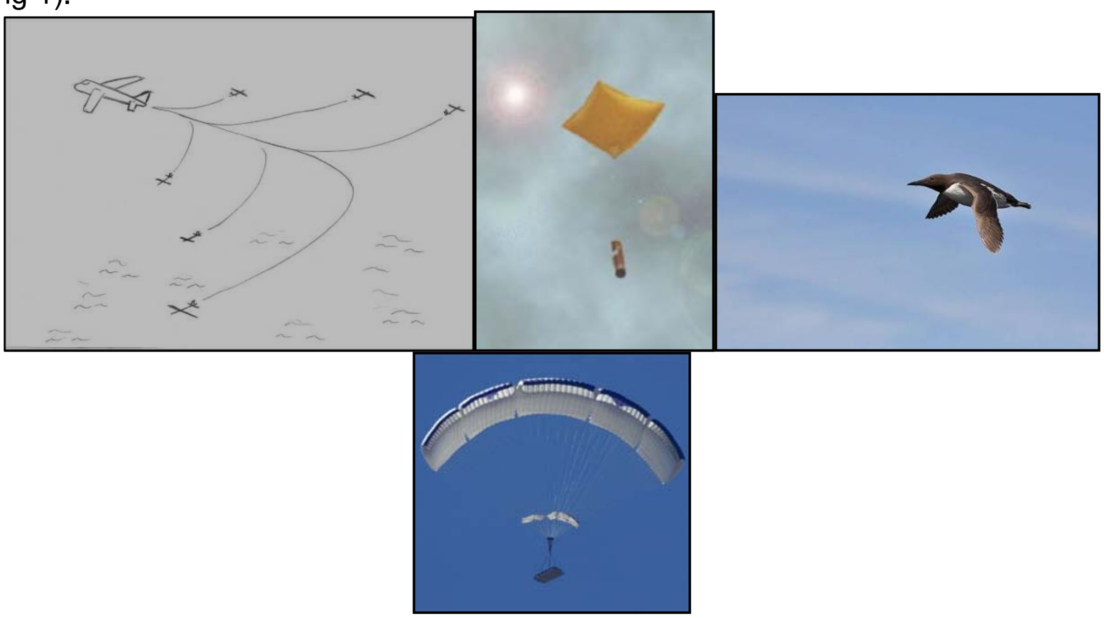

Fig 1. Images to convey concept of Air Launched AUVs, starting top left, working clockwise:-

1) *Autonomous glider launched from an aircraft*
2) *Parachuted instrument*
3) *Mimicking nature, e.g. a guillemot which able to fly through air and water*
4) *Autonomously navigated parafoil air dropping supplies*

The ALAUV concept has been considered as a vehicle operating both as an Unmanned Air Vehicle (UAV) and AUV and as a simplified parachuted version. The latter version has generated considerable interest through a paper given at Bremen [2], talks at the Marine Measurement Forum[1] , NOCs POETS Corner[2] an exhibition stand at OI2010[3] and the NERC 5th Technology Forum[4].

[1] Held at NPL, Teddington, 4th November 2009
[2] Held at the NOC, 12th November 2009
[3] Oceanology International held at ExCel, 9th-11th March 2010
[4] Held at BGS Edinburgh, 17th-19th May 2010

2.0) The case to be made

AUVs and oceanographic instruments to date have been mostly launched from boats or the shore for coastal work and from ships for work further afield. Some exceptions are Air launched Expendable Bathy Thermographs (AXBTs) [3], surveillance sonobouys, APEX profiling floats and the Bluefin AUV launched and recovered using a rotary wing aircraft, although the latter is not routine. Oceanographic cruises take a great deal of planning in:-

- Getting funding established.
- Establishing a scientific party with enough variation of work to ensure the ship is being put to good use twenty hours a day.
- Arranging the logistics of port, crew and scientific party to be away for weeks or months.

The cost for ocean going research ships range typically from £12k/day to £36k/day[5] and the constraints of mobilising large ships make it difficult to react quickly. Furthermore, synoptic surveys over large regions require multiple ships to expedite the science. For example, the physical oceanography World Ocean Circulation Experiment (WOCE), by far the largest oceanographic programme, involved over 30 nations with a field programme spanning 1990-1997 [4]. Quoting Carl Wunsch, '*A challenge to oceanographers and climate scientists working in the post-WOCE period is to find a way top maintain, upgrade, and them sustain the global aspects which WOCE dealt with momentarily*' [5]. With the ever increasing need for environmental data and especially data on rates of change, there needs to be a more economic model for gathering worldwide data sets.

In contrast to ships, aircraft can be mobilised more quickly, cover distance far more quickly and, mile for mile, are cheaper to use (Table 2.1) [6]. The concept of ALAUVs is to capitalise on these advantages and use them for populating and surveying specific areas.

Platform	Approx charter rate	Approx full economic cost
(Old) RRS Discovery ship	£12k/day (£500/hr; £50/nm at 10 knots)	
RRS James Cook ship	£36k/day (£1500/hr; £150/nm)	
BAS Twin Otter aircraft		£1020/hr (c£7.50/nautical mile @ 135 knots)
BAS Dash 7 aircraft		£2770/hr (c£14/nautical mile @ 200 knots)
FAAM BAe 146 aircraft		C£11000/hr (c£28/nautical.mile @ 400 knots)

Table 2.1. Approximate charter rates and costs research ships and aircraft

There are some AUV technologies which are addressing the problem of how to carry out more economic surveys. The on-going ARGO float programme has successfully deployed over three thousand floats worldwide to telemeter CTD data. These floats

[5] Ref conversation with Andy Louch, Sea Systems, NOCs. May 2008

are air or ship deployed (ship deployment being more common) and designed to sink at the end of their life, the data is telemetered via the Argos environmental satellite tracking. Another example in use is the Teledyne Webb Research glider AUVs, propelled by a buoyancy engine carrying out long profiling missions. A more recent innovation is the Wave Glider propelled by wave power with sensors powered by solar cells, these AUVs have travelled some 16,000 kilometres, carrying out surface measurements. These instruments and technologies are compared with the feasibility of the ALAUV concepts in section 11. Clearly, if ALAUVs are to succeed they need to do something different, better or significantly cheaper than existing and emerging technologies.

3.0) Scope of the project

The funding through Oceans2025 is to explore the scientific applications, technical feasibility and start dialogues with scientists and agencies operating aircraft, especially those using aircraft for environmental research. This report answers and addresses some basic parameters such as:-

- Scientific and commercial applications
- Desirable and possible sensor payload (size, energy, mass, special requirements)
- Maximum operating depth
- To be disposable or to be recovered?
- Feasibility of a practical AUV, in terms of performance and economics (endurance, speed, navigation accuracy, production cost).
- If it is to be disposable or semi disposable, what is the environmental impact?
- Data retrieval method
- Aircraft to air and air to sea interface
- Production costs

4.0) Applications

There are many areas of interest where improved quality, breadth and frequency of surveys would assist environmental research and the quest for solutions to environmental problems.

4.1) Augment existing surveys

Long time series measurements play an important part oceanographic research. Often using ships of opportunity on their transect legs, these surveys have been pursued for decades and in the case of the Antarctic circumpolar current, c100 years. The programmes have to evolve with new technologies and funding opportunities, the introduction of ALAUVs provides the potential for greater coverage through introducing a volumetric data set as oppose to the present two dimensional ship track and depth.

Atlantic Meridional Transect (AMT)

The AMT programme received funding through NERC's Oceans 2025 programme as a Sustained Observatory within Theme 10 and is coordinated by Plymouth Marine Laboratory in collaboration with the National Oceanography Centre and has secured the continuation of Atlantic measurements (started in 1995) from 2008 to 2012.

Instruments on research ships of opportunity on the 13,500km Atlantic Ocean transect between the United Kingdom and Falkland Islands are used to measure physical, chemical, biological and optical variables in the upper 200m of the water column in order to characterise the Atlantic Ocean over broad spatial scales. This provides understanding of the role of the world's oceans in carbon cycles and valuable ground truthing for the calibration and validation of satellite remote sensing (i.e. ocean colour and surface temperature) of the oceans [7]. The use of ships during their transect makes good use of ship time and is essential in carrying out the broad scale research. The data define the areas of greatest plankton abundance and productivity, as well as regions of hydrographic contrast. In turn this leads to a more focused and targeted strategy for intensive sampling and analyses.

The sensors, measurements and samples taken vary from cruise to cruise depending sensor development, availability of equipment and the time on station the ship can spare, this can be a mix of lowered CTD and water sampler or towed platform with sensors such as the Moving Vessel Profiler (MVP) [8]. While a small AUV cannot compete with the range of measurements taken, they can give added value in providing a swath of (for example) CTD profiles either side of the ship track which is synoptic with the ship gathered data. The relatively shallow depth requirement of 200m makes for a lighter AUV pressure housing, allowing a greater payload. Such AUVs could be ship deployed or air deployed to provide a wider swath although the latter has logistical issues associated with the range from an air base and operating costs.

Antarctic Circumpolar Current (ACC)

Transport measurements across the Drake Passage between S. America and the Antarctic Peninsula are important in the studies of changing sea levels and climate. Being the narrowest constriction of the Antarctic Circumpolar Current (ACC) in the Southern Ocean, it has implications for global ocean circulation and climate. Long-term sustained monitoring programmes have been conducted at Drake Passage, dating back to the early part of the twentieth century and have lead to numerous breakthroughs in understanding the complex structure and early quantifications of its transport. Monitoring this passage remains a high priority for oceanographic and climate research, but the scientist's view is that strategic improvements could be made concerning how this is conducted, quoting Meredith et al *'…Further, there is a need for better international resource-sharing, and improved spatio-temporal coordination of the measurements. If achieved, the improvements in understanding of important climatic issues deriving from Drake Passage monitoring can be sustained into the future'* [9].

Meridional Overturning Circulation (MOC).

Any changes to the Atlantic thermohaline circulation are important for Northern European climate and there is international interest in researching, monitoring trends and modelling any change [10]. For instance, the NERC RAPID programme is largely dedicated to the development of a system for monitoring the MOC. ALAUVs could, again, augment these areas of work in a similar way to that described for the AMT and ACC.

Porcupine Abyssal Plain (PAP)
Sustained observations of both water column and sea floor processes in the North Atlantic are coordinated by the NOCs through a multidisciplinary observatory. For over 20 years the observatory has provided key time-series datasets for analysing the effect of climate change on the open ocean and deep-sea ecosystems. An AUV that could track mesoscale features in the upper ocean would be a useful addition to existing programmes and methods, ideally recording CTD, oxygen, nutrients and fluorescence [11].

4.2) Rapid response surveys

The option of a more rapid response mode opens possibilities for carrying out smaller scale studies and responding to small scale events. These may be rapid environmental assessments such as oil spills where knowledge of the dynamics of the spill and subsequent effectiveness of the clean up operation would be useful for the present and future environmental management. Present data to support the use of dispersants is largely restricted to tank experiments, greater demonstrability of effective clean up operations encourages governments, oil producers and shipping companies to work more closely with response agencies to carry out appropriate and timely action. The survey data from ALAUVs would assist environmental and insurance communities in agreeing courses of action and serve to improve the overall cost effectiveness.

Other mesoscale features such as algal blooms, which can be harmful to sea life and humans, are another application where the event is seasonal, localised and may be triggered by a pollution event which may be relatively short lived

4.3) Twilight zone (mesopelagic)

Many forms of organic recycling occur in the mesopelagic zone that are important to carbon cycles but absolute measurements have yet to be made in any quantity and what evidence there is shows a great deal of variability. Once some regional baseline has been established, the interest will progress to measuring rates of change, requiring repeated surveys over time. An AUV glider programme would fulfil this requirement but is presently unaffordable. [11].

4.4 Survey of polynas

The use of ALAUVs to survey polynas (regions of open water which are ice bound) presents a particularly neat application since these regions can be inaccessible except by aircraft operating in the Polar regions (e.g. BAS Twin Otter and Dash 7 aircraft).

'The polynya area is also stationary, leading to a concentrated impact on the local oceanographic conditions with high levels of sea-ice production, salt rejection and water densification, with associated vertical overturning. These polynya processes play an important role in the oceanographic regime of the continental shelf. The problem in studying processes in polynyas is that they are largely inaccessible during the winter months when the important processes are often still active.

Instrument moorings can be deployed if the polyna is accessible during the summer (and many are not), but they cannot extend high in the water column for fear of being destroyed by icebergs. There are several coastal polynyas around the continent that *are of great interest. Simple temperature and salinity sections would shed light on the processes.'*[6]

4.5) Naval survey and civil search and applications

Small AUVs offer new opportunities for quickly and covertly deploying many vehicles which would not necessarily have to be recovered for naval surveys and reconnaissance, for example, mapping areas of sound velocity and bioluminescence. Depending how the vehicle payloads were developed, there could be opportunities for carrying out covert surveys where the small-ness and submerged nature of the vehicle would make it very difficult to detect, even if were on the surface for part of the time.

If deep diving ALAUVs were developed to operate acoustic receivers, could they be used in search and rescue operations detecting and locating emergency beacons from sunken aircraft of vessels? In June 2009 the Air France flight 447 from Rio de Janeiro to Paris crashed into the Atlantic. Eleven months later, after a £24 million search operation, the flight recorder 'black box' was located to within a 3 to 5 km^2 area [12]. The search resumed in Nov 2010 (18 months after the accident) and the 'black box' was located by a REMUS AUV and finally recovered nearly two years after the accident.

The scope for naval and civil search applications could be very broad but is largely considered to be outside the remit of this study.

5.0) Key questions and some economic pointers

At the outset, a few blunt questions need to be asked, the answers will hopefully help steer the project and give it some aim, these (in no particular order) typically are:-

- Instead of using aircraft, why not deploy multiple AUVs/sensors from ships of opportunity?
- What are the legal issues with ALAUVs?
- Instead of developing a vehicle that can autonomously glide and navigate through the air, why not get the aircraft to create the breadth of survey and use a more simple parachuted device?
- Could existing air deployed sensors be adapted?
- Can gliders be air launched from an aircraft (problems of turbulence, boundary layer, sophistication of control to gain stable flight from tumbling)?
- What suitable aircraft are available to the research and operational communities?
- What level of funding is required to achieve the required aims?

[6] Extracts from Keith Nicholls (BAS) email 11th Feb 2011

Following this, a skeleton of requirements need to be determined, e.g.

- Endurance, speed and navigation accuracy
- Maximum operating depth
- Essential and possible payload (energy, mass, volume, special requirements)
- Should they be disposable or recoverable?
- Environmental impact of a lost or disposable vehicle
- Energy source
- Data retrieval method
- Production costs

5.1) Economic pointers

Deploying small ALAUVs to execute unattended missions run the risk of them being lost, it is important that if the vehicle becomes lost, the data is not, they need to telemeter data back to a base and then **if they are recovered, it should be because the individual circumstances make it easy to do so and not because of an economic imperative dictating we scarcely afford to lose the vehicle(s) or valuable data.** If a ship or boat has to be sent out to collect them, the advantage of them being air launched is mostly lost. Throughout this report ALAUVs will be considered to be semi disposable. This sets an idealistic base line production cost of the vehicle to be no more than what it would cost to recover at sea, i.e. it is cheaper to replace it than to go looking for it; say 2 hrs ship time if an appropriate ship is in the vicinity (£1000 to £3000?). This sets a very ambitious target against a backdrop of a budget cost of £200k for a 40kg REMUS 100 AUV[7], £75k for a Teledyne glider and £10k for an ARGO float. None the less, an ideal maximum cost can still be useful when considering fresh designs on a clean sheet of paper.

Beyond this, the cost of the ALAUV with sensors needs to be compared with the cost of gathering equivalent data by other means. The cost of chartering the NERC ships helps provide a guideline for assessing these comparisons (see Table 2.1). Alternatively, the data has added value by virtue of the means of collection, e.g. multiple deployment of ALAUVs make for more synoptic data. This latter intrinsic value of the data may not be as easy to cost in monetary terms but sensible judgements ought to be possible, e.g. the Autosub Under ice programme was considered to be worth the risk [13].

[7] Ref Hydroid budget quote 2007 for 'Feasibility of using AUVs to support offshore exploration and production in Arctic seas' report

5.2) Benefits of small vehicles

If the production cost is driven down to the point where the vehicle can be considered to be semi disposable then some subsystems often found on larger AUVs become less important or unnecessary; for example

- Emergency abort systems; fitted to most AUVs, including all present Autosubs (Autosub1, 2, 3, 6000 and Long Range)
- Acoustic telemetry; fitted to Autosub1, 2, 3 and 6000 in varying forms
- Emergency acoustic communications; fitted to Autosub6000 and Long Range for engineering trials.
- Wi Fi communications; fitted to Autosub2, 3, 6000 and Long Range
- Redundant location systems such as strobe lights and Argos beacons; Fitted to Autosub1, 2, 3 and 6000. Autosub Long Range only had single systems.
- Bespoke launch and recovery gantry

These systems are not only expensive but have taken considerable effort to develop and integrate into the present range of Autosubs. From an operational point of view, they add to the

- AUVs' hotel load (the power required to drive everything except the propulsion) and so reduce their endurance.
- Ship mobilisation effort (launch and recovery gantry, installing aerials, mobilising ships' hull mounted acoustic transducer),
- Maintenance and consumable costs (failures at sea, damaged parts, dropped abort weights).

The hotel power for has reduced dramatically over the years, this creates a virtuous design circle where the lower mass and power requirement of the subsystems leads to a smaller vehicle, less drag, less propulsion power etc etc (Fig 5.1).

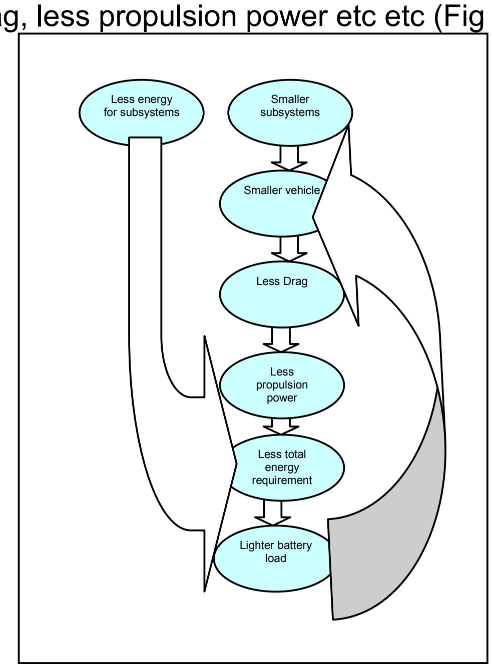

Fig 5.1. Design circle where reductions in the base payloads and energy has a positive effect on the whole design

Smaller AUVs bring about production cost benefits (less mechanical hardware to be cut, processed or in some way manufactured) which in turn requires smaller machine and processing tools and less space (with overheads) to manufacture parts and finally build it. Small, low specification designs can begin to take advantage of mass market model engineer items. These are often highly developed, built to an extremely competitive cost and can dramatically reduce design and development times.

Low mass vehicles reduce the problems of designing for shock loadings (namely, when the vehicle hits the water) and vibration. As a simple example, compare the number of crash landings a toy helicopter survives with the real thing. Because low mass assemblies are better suited to shock environments, the design can be more simple.

Smaller vehicles clearly take less preparation and are easier to use. A SeeByte press release 5th June 2008 describing a '*New World Record Set for Autonomous Pipeline Tracking Using a Two-man-portable AUV*' made a point in bold print that the 'Two-man-portable AUVs can be launched from vessels or the shore by two personnel without the need for specialist cranes or lifting equipment'. One wonders if this is a pointed reference to SubSea7's limited success with Geosub?

There is a danger when designing any new machine with a relatively 'clean sheet of paper' that the size steadily grows before it leaves the drawing board. There are many economic and operational reasons to resist this.[8]

6.0) Range of aircraft available

Numerous aircraft are used around the world for scientific research; a summary of aircraft, operators, payload capacity, range and ceiling height is reproduced from Higgins [3] in Appendix A.

6.1) Aircraft used for research in the US

The largest fleet is operated by the National Oceanic and Atmospheric Administration Aircraft Operations Center (NOAA–AOC), based at the MacDill Airforce Base, Florida, USA [14]

Lockheed WP-3D Orion

Use and instrumentation:-

- Cloud Physics — 1 and 2-dimensional precipitation and cloud particle probes, particle probes, aerosol sampling system.
- Radiation — Sea surface temperature, radiometer, CO_2 air temperature radiometer
- Expendables — GPS dropwindsonde atmospheric profiling system, Airborne Expendable Bathythermographs (AXBT's)

[8] One wonders if the Babbage Difference Engine in the 1800's might have been more successful had Babbage sought the expertise of watch and clockmakers.

Gulfstream jet prop Commander

Used by the National Operational Hydrologic Remote Sensing Center (NOHRSC) to conduct aerial snow survey operations in the United States and Canada from October to May

Lake Seawolf

Used to monitor activity and resources, survey sanctuary users, conduct vessel traffic studies, observe the effects of shore run-off, perform aerial surveys during oil spill emergencies, and collect data on both marine mammals and the kelp forest. Photography and video will be used to record sightings.

Gulfstream IV-SP (G-IV)

In addition to a number of air chemistry measurements in the upper troposphere and lower stratosphere in the active jet stream area above the Pacific winter storms, the aircraft is on standby for hurricane surveillance missions, collecting atmospheric soundings using GPS dropwindsondes.

Rockwell Aero Commander

Utilised primarily as aerial survey platforms for verification of aeronautical charts, high-resolution aerial photography, snow water equivalent and soil moisture content measurements. Additionally, it has been used in biological algal bloom measurements, sea turtle population assessments and post-hurricane and severe flood damage assessment photography.

Cessna Citation

This aircraft is used primarily to support the Remote Sensing Division of the National Geodetic Survey by logging data in support of coastal mapping to update the shoreline and shore features on NOAA's nautical charts. The Citation also serves as an emergency responder during hurricane season by collecting digital photography of damaged areas caused by hurricane landfall.

DeHavilland Twin Otter DHC6

The NOAA Air Resources Laboratory (ARL) has developed modifications to the Twin Otter in order to measure eddy fluxes and concentration gradients through the atmospheric mixed layer. The unique nose cone accommodates infrared H2O/CO2 analyzers and net radiation sensors. The platform can also acquire air chemistry data, such as NO, NOx, Noy, SO2, O3, CO, and reactive hydrocarbons

6.2) Aircraft used for research within NERC

The information on the NERC Dornier 228 and the Facility for Airborne Atmospheric Measurements (FAAM) BAe 146 aircraft is from a visit made to FAAM 14th Jan 2009 to learn about the existing use and possibilities these NERC facilities. Information on the BAS Twin Otter and Dash 7 aircraft is from D. Blake's report [6].

6.2.1) The Airborne Research & Survey Facility - Dornier 228
This aircraft is operated by Airborne Research and Survey Facility at
NERC-ARSF Operations Centre
Firfax House
Meteor Business Park
Cheltenham Road East
Gloucester
GL2 9QL

It is managed by the NERC at Swindon, the aircraft is based at the Staverton Airport, Gloucester (Fig 6.1). This German registered aircraft being moderate size and not registered as a passenger aircraft may ease the complications if making any adaptations

Fig 6.1 ARSF Dornier 228

Technical data and science payload
The unpressurised twin-turboprop; cabin volume 14 cubic metres; crew two pilots and accommodation up to four operator/observers; up to six hours endurance at a science altitude of 20,000 feet.
Airframe modifications
Experimental power DC 28V/225A and AC via inverter 220V/50Hz92000VA), one cabin floor opening 2060mm x 515mm and one circular opening 425mm diameter; one cabin roof opening 400mm diameter and two 150mm diameter; external hard points on fuselage sides and bottom; under-wing pylons/PMS pods; internal 19” racking [16].

6.2.2) BAS Aircraft
BAS operate five aircraft:-
- Four de Havilland Twin Otters
- One de Havilland Dash 7

All of the aircraft are:
- Registered in the Falkland Islands
- Managed and operated by BAS
- Regulated by ASSI (component of UK CAA) and Falkland Islands Dept. Civil Aviation
- Maintained currently by 2 companies based in Canada.

6.2.2.1) BAS Twin Otters (DHC-6)

Known for their rugged construction, reliability and Short Take Off and Landing (STOL) performance, the version operated by BAS is the wheel/ski equipped aircraft which lands on snow, ice or any other type of hard runways. Used to transport people, fuel, skidoos, sledges, food and scientific equipment to remote camps, landing on skis on unprepared snow, the planes will also lay depots and stockpile fuel for field science parties (Fig 6.2).

Fig 6.2. BAS Twin Otter

The Twin Otters are extremely versatile and can be modified to allow airborne surveying and other scientific equipment to be fitted. Remote sensors fitted to the aircraft provide scientists with data on land, ice and sea. Radar can decipher features under the ice or layers within the ice itself. Longer-term monitoring from the air can be used to record the break-up of ice sheets or atmospheric changes.

Fact file:-

- Twin engines — Turboprop Pratt and Whitney PT-6
- Wing Span — 19.8 metres
- Length — 15.7 metres
- Take-off weight — 5670 kg (6360kg with modifications)
- Range — 1000 km (excluding reserve, possible extension to 1700km with extended range fuel tank or 6.2 hrs endurance)
- Cruise speed — 135 knots skis/150 knots wheels
- Max ceiling — 25,000ft (with crew oxygen)

There is also a launch tube to deploy instruments from the aircraft using the camera hatch on the centre line from the rear of the passenger cabin. This tube will be used during 2011/12 to deploy instrumented probes. A NERC grant has been awarded to enable a series of GPS and Iridium enabled devices to be dropped onto Antarctica to transmit ice depth measurements.

One of the aircraft is primarily configured for geoscientific measurements and another for meteorological survey. The remaining two aircraft are primarily used for logistics support. It is possible to modify the role of the aircraft should alternative deployments be required including the fitting of seats for passenger transport.

The purchase of an extended range fuel tank will increase the survey range on wheels to 1700km. The endurance (sometimes more important than absolute range) with reserve fuel would be approximately 6.2 hrs.

6.2.2.2) BAS Dash 7

A larger aircraft (Fig 6.3) with pressurised cabin the BAS version has had a variety of technical modifications;

- include the fitting of long range fuel tanks with a fuel jettison system,
- Large cargo door and strengthened cargo floor
- Enhanced avionics and navigation systems. It usually seats 12-16 people.
- BAS chose the Dash-7 for its rugged design, fuel efficiency and, crucially, short take off and landing capability.
-

Fact File:-

- Wing span 28.4 m
- Length 24.5 m
- Take off weight 21,320 kg
- Engines 4 turbo prop
- Range 4,000km (1,500km fully loaded, with required fuel reserves)
- Maximum speed 230 knots

Fig 6.3 BAS Dash 7

6.2.3.) FAAM BAe 146

The BAe 146 aircraft is unique and the most comprehensive atmospheric research aircraft in Europe. It is owned by BAe and operated by FAAM which is funded by NERC and the UK Metrological Office with funding assured up until 2014. The centre is a facility, that is to say they do not carry out engineering work themselves but project manage it on behalf of NERC and Met Office. Flight crew, maintenance and design approval is further devolved through:-

- Direct Flight Ltd — Air crew including 4 pilots
- Avalon — Aircraft maintenance
- Cranfied Aerospace — Design work
- BAe Prestwick — Certified Design Organisation Approval (DOA)

Fact File:-

- Wingspan — 26.34m
- Length — 30.99m,
- Maximum Take-Off Weight — 42184kg.
- Range — Typically 2000km without using fuel reserves at 27000 ft, 200 kts.
- Cruise speed — 400knots

The aircraft is a one off 'type A' certification and not under the European Aviation Safety Agency (EASA) which frees up to a degree the modifications permitted. The aircraft has a number of pods under-slung from the wings into which sensors may be housed, this obviously simplifies the certification logistics when fitting new sensors if they can be housed within existing pods (Fig 6.4; 6.5).

Fig 6.4 FAAM BAe 146 Atmospheric Research Aircraft

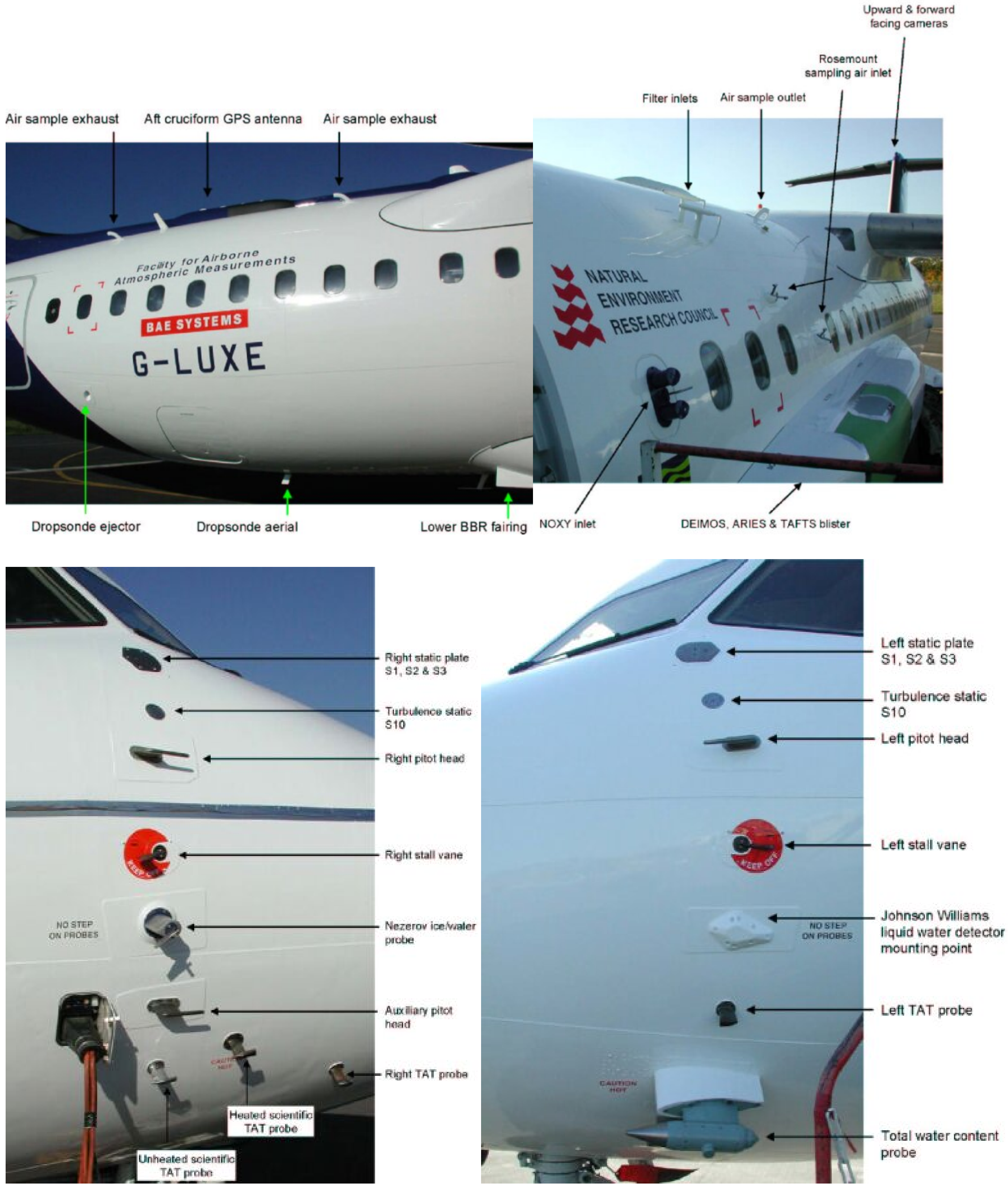

Fig 6.5. FAAM BAe 146, working clockwise; Starboard fuselage sensors and Dropsonde chute; Port fuselage sensors; Starboard nose sensors; Port nose sensors.

Fig 6.5. continued, left to right; Under wing pod mounted sensors; Example of aircraft modifications; aperture for lower lidar window under construction

FAAM personnel have broad experience of engineering new programmes into the aircraft, FAAM do not do design work or manufacture but have tried and tested companies and sub contractors (e.g. Fig 6.5). Any fitment of new equipment (inside or out but especially outside) requires Design Organisation Approval from BAe at Prestwick.

Dropsonde launch feature
The dropsonde chute is angled on the starboard side of the fuselage. After loading the dropsonde, permission to launch comes from the pilot and the person releasing the 'sonde becomes part of the air crew (i.e. under their jurisdiction) at that moment. The 'sonde free falls from the chute and there is evidence that it sometimes hits the fuselage. The safe ejection is monitored via a rear facing camera. The total number of aircraft worldwide that can launch dropsondes is only around ten, some of them being military aircraft. It has been noted by the users that some 'sondes continue to work for some depth after they plunge into the sea, this has already lead to some discussion as to whether a 'sonde could be developed to record sea data as well as atmospheric.

ARGO float launch
BAe have carried out design work to incorporate a chute for dropping ARGO floats from the 146 but because of the schedule when building the aircraft, this did not get incorporated. The work resides with BAe since, it seems, FAAM are not entitled to the IPR.

Contacts:-

- Guy Gratton Head of Facility guat@faam.ac.uk
- Steve Devereau Technical Manager stde@faam.ac.uk
- Alan Woolley Instrumentation Manager alwo@faam.ac.uk

6.3.) Other possibilities

Payloads around 7.5 kg are something of a threshold between a dropped instrument and an independent vehicle. For deployment of large vehicles, a C130 would be an obvious choice, although something of a sledgehammer to crack a walnut. At the other extreme, an option for development work is the Islander, designed and built at

Bembridge Isle of Wight. These are used by Hampshire Police, short hop passenger flights and parachuting.

7.0) Concepts and solutions

It is clear from the previous section that the number of aircraft capable of launching a gliding AUV is very limited, restricted still further if only civil research aircraft are considered and restricted again if a high altitude launch is required. Furthermore the infrastructure to carry out such an operation is restricted:-

- 82.5mm diameter dropsonde tube
- 127mm diameter sonobouy tube
- Launch from a wing pod, which also restricts the shape of the ALAUV to being tubular whilst in transit.

This section reports on concepts and solutions that would fulfil the original Oceans 2025 brief and discusses their feasibility before progressing to consider a concept design (section 8.0). Since the aircraft industry still universally measures altitude in feet, this report also adopts this convention.

7.1.0) An Unmanned Air Vehicle (UAV) becomes an Autonomous Underwater Vehicle (AUV)

The original concept was effectively to have something that begins as an UAV and becomes an AUV (Fig 1). Most UAVs are powered with the purpose of carrying out reconnaissance operations and return to base although some work on land launched UAVs to seek out thermals to extend their flight time has been done, e.g. NASA Autonomous Soaring Project UAV ‘Cloud Swift’.

Having a gliding UAV launched from a high altitude was the major investigation of Higgins MSc thesis [3]. This work gives a good background to the applications, issues and capabilities of available aircraft. The second part of the thesis proceeds to estimate the size and performance that might be expected from the ALAUV during its air gliding phase which assumes certain proportions and performance of the body and wings so parametric equations can be used to estimate the glide performance.

The assumptions made for the approximations in this section are:-

1. The lift to drag ratio of the wings does not change substantially with altitude. Although the air density changes very markedly with altitude, since both lift and drag are proportional to density, this change cancels out.
2. The lift generated by the body is negligible. Although for aircraft approximations, the width of the fuselage is considered to be part of the effective wing span, this may skew estimates when the wing span is small compared with the body diameter. This assumption has decreasing affect with increasing wing span.
3. The body has zero angle of attack while gliding, i.e. the angle of attack of the wings are set to give the optimum lift to drag ratio

Higgins estimated an ALAUV with a body diameter of 124mm required a wing plan area of:-

- 0.10m^2 to achieve a glide angle of 10 degrees (0.9m wing span for an aspect ratio of 8), giving a 17km range per 10,000ft launch height.
- 0.25m^2 to achieve a glide angle of 7 degrees (1.44m wing span for an aspect ratio of 8), giving a 25km range per 10,000ft launch height.
-

Fig 7.1 shows the asymptotic rise in wing area required to reduce the glide angle. With the shallowest, practical glide angle of say 7 degrees, wing area of c0.3m^2 (e.g. approx 1.5m wing span with an aspect ratio of 8). This still only gives a glide range of 74km from a launch height of 30,000ft. The proportion of the wings are becoming ungainly compared with the body diameter and the length of the body is likely to have to be slender and long to achieve the necessary stabilisation from the tail section.

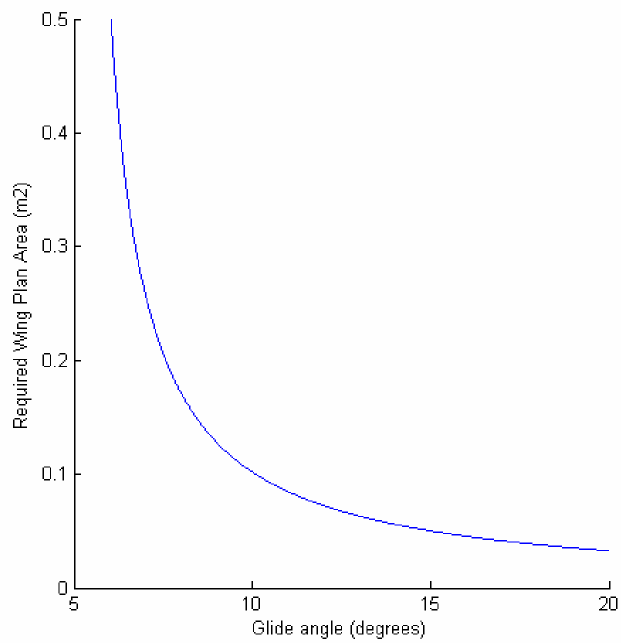

Fig 7.1. Relationship between Glide angle and Wing area (Body dia = 124mm, Cd=0.15 (frontal area of body and wings), Cl = 0.2 (wing plan area). Reproduced from E. Higgins Thesis [3]

If the restrictions of the transport and launch tube are considered, then the ALUAV is constrained to having folding wings which must fit within the launch tube diameter. If we now consider the existing aircraft infrastructure of dropsonde and sonobuoy launch tubes, this gives quite specific size constraints for the ALAUV. The following proportions of wings and body to fit into a tube have been assumed and the glide performance estimated.

- ALAUV body diameter = 80% x launch tube diameter
- Wing chord = 50% ALAUV body diameter (Fig 7.2)

These proportions are in broad agreement with the Coyote UAV discussed in section 7.1.1 and give the following sizes in table 7.1 to fit into a dropsonde and sonobuoy tube.

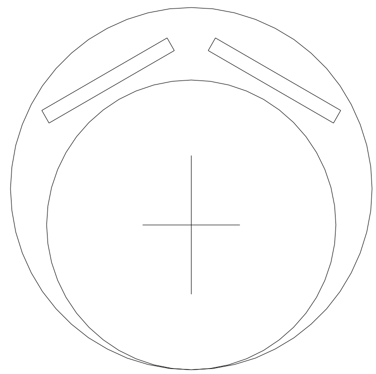

Fig 7.2. Scale schematic proportion of ALAUV fitted into launch tube with wings folded along the body. Body dia=80%tube dia; Wing chord=50%body dia; wing thickness=10% wing chord

Parameter	Dropsonde size	Sonobuoy size	Remaks
Launch tube dia (mm)	82.5	127	Given aircraft infrastructure
ALAUV dia (mm)	66	102	80% launch tube dia
Typical ALAUV length (mm)	440	670	Typical proportion based on Autosub6000
Typical ALAUV displacement (Litre)	1.1	4.0	Typical, scaled on Autosub6000
Typical ALAUV mass (kg)	.631	2.3	The ALAUV will need some flooded space for sensors; not all flooded space can be gainfully employed
Wing chord (mm)	33	51	50% body dia (see fig 6.2)

Table 7.1. Derived size for ALAUV to fit into a dropsonde or sonobuoy launch tube.

Using approximations for lift, drag, glide angle and glide speed outlined in Appendix B, the performance is estimated for varying wing span are shown in fig 7.3.

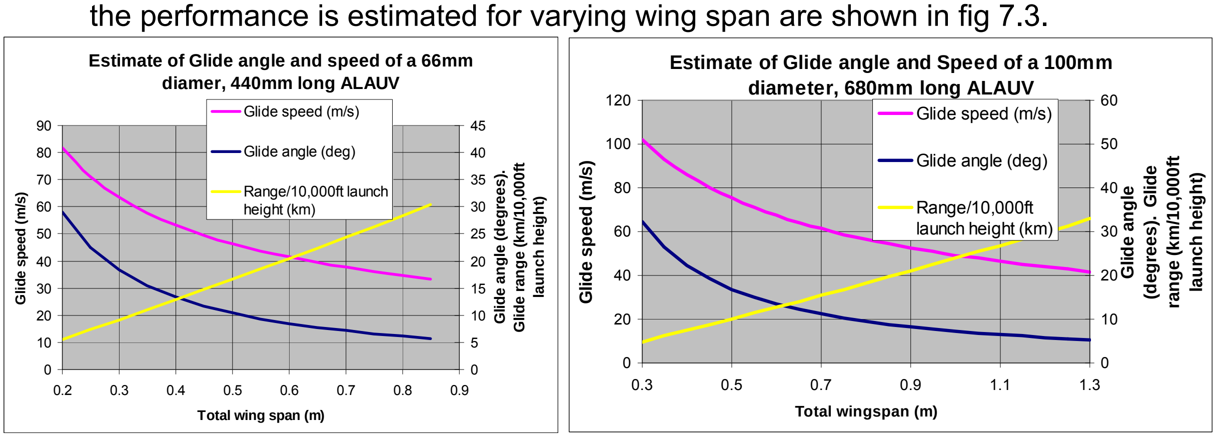

Fig 7.3. Estimate of ALAUV designed to fit into a Dropsonde launch tube

The ranges are closer to the target of 100km from 30,000ft but the half wing span is approximately equal to what would considered to be sensible overall length from an AUV viewpoint. This creates difficulties in accommodating folding wings and robust spring features to deploy them after launch.

Impact loads and frangible wings

Nature has examples of birds able to fly in air and water, for example, the guillemot. With its small, highly loaded wings, it is fast through the air (up to 80km/hr), dives and swims underwater to recorded depths of 180m but is primarily adapted to submerged foraging rather than air flight endurance. For a gliding ALAUV, the wings are required to support the weight of the vehicle in the air. Once the glide phase is finished and it dives into the water, the wings are at the wrong angle of attack and are massively oversized for any lift force that may be required to help the AUV maintain depth. Most AUVs are ballasted only slightly buoyant in water and the necessary down force in many designs is achieved by a modest pitch angle of the body (see also section 10.2). In this instance, it is assumed the wings will be jettisoned by the force of the impact with the water and only the impact force on the body section needs to be considered. For the purposes of estimating these forces and decelerations, it is assumed that the glide speed through air equals the initial speed through the water and the drag force on the body only increases by the ratio of the water density to air density (approximately 1000:1) (Fig 7.4).

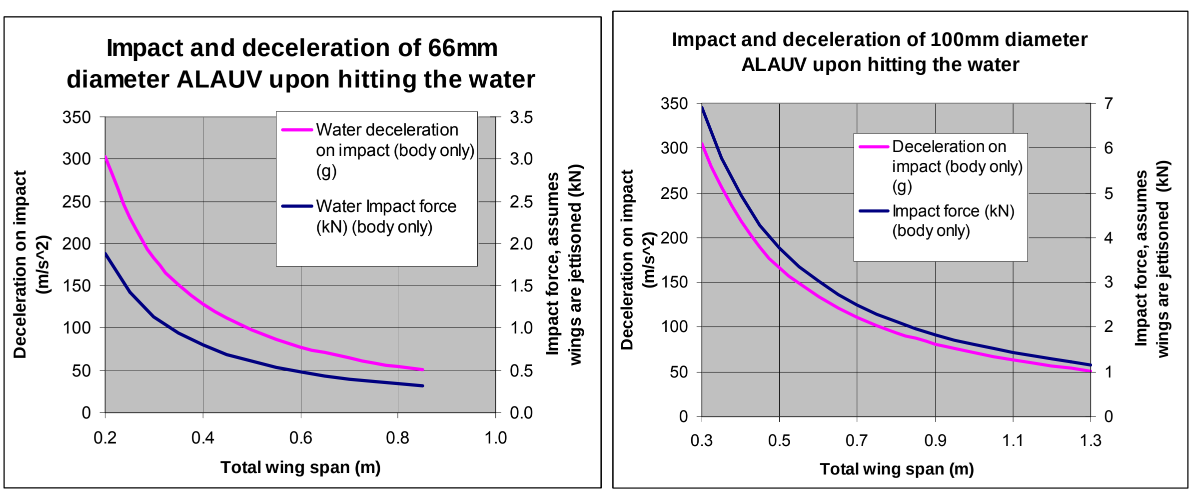

Fig 7.4. Deceleration and impact force on 66mm dia and 100mm body dia ALAUV when hitting the water

7.1.1)Practical considerations

An ALAUV being launched at high altitude has been considered with little reference so far to the engineering implications, complications or existing equipment launched in this way.

Dropsonde launch

The following paragraph has been summarised from the Airborne Vertical Atmospheric Profiling System (AVAPS) information sheet [15], (Fig 7.5). Before the ‘sonde is launched from the aircraft, it is run through a pre-flight procedure.

- The ‘sonde is connected to the aircraft dropsonde data system.
- Calibration coefficients and the sonde serial number are downloaded and the selectable telemetry transmission frequency is set in the ‘sonde.
- Calibration adjustments are made.
- Radio navigation signals are acquired via an externally mounted aircraft antenna to initiate the tracking of stations by the navigator.

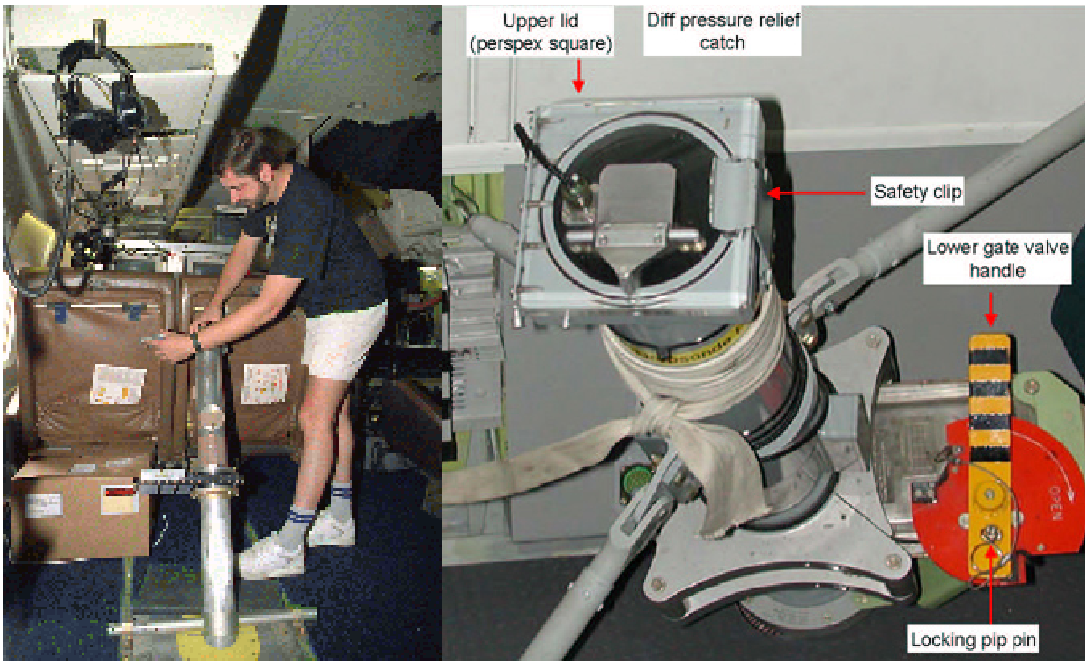

Fig 7.5 Dropsonde launch tube (picture courtesy of AVAPS)

Just after the ‘sonde is ejected from the aircraft through the launch tube, a bias tape unwraps from the ‘sonde, delaying parachute deployment by about one second to insure the parachute isn't destroyed by the forces on the ‘sonde on exit from the aircraft. Once the parachute is deployed, the ‘sonde begins to decelerate, the navaid 400 MHz telemetry antenna is deployed several seconds after launch by means of a burn line (a lanyard attached to the parachute switches on a 1 watt to 1.25 watt resistor which melts a line holding the navaid antenna release spring). The parachute inflates as it falls, taking about fifteen seconds to fully inflate. The initial streaming followed by gradual inflation reduces the overall shock load to the ‘sonde and its electronics. During the time the parachute is inflating, the ‘sonde decelerates from the speed of the aircraft to a speed on the order of 10 meters per second (Fig 7.6; 7.7).

A summary of the physical data is given in Table 7.1.

Model	NCAR – L2D2.	NCAR - LOD2
Manufacturer	*Loran Navaid Sonde*	*Omega Navaid Sonde*
Mass	*490 grams*	*490 grams*
Dimensions	*82.5mm diameter x 410mm*	*82.5mm diameter x 410mm*
Parachute size	*13 inch "Square Cone"*	*25 inch "Square Cone*
Fall velocity	*20 m/s*	*12 m/s*

Table 7.1. Physical data of a dropsonde

Fig 7.6Dropsonde (picture courtesy US Air Force)

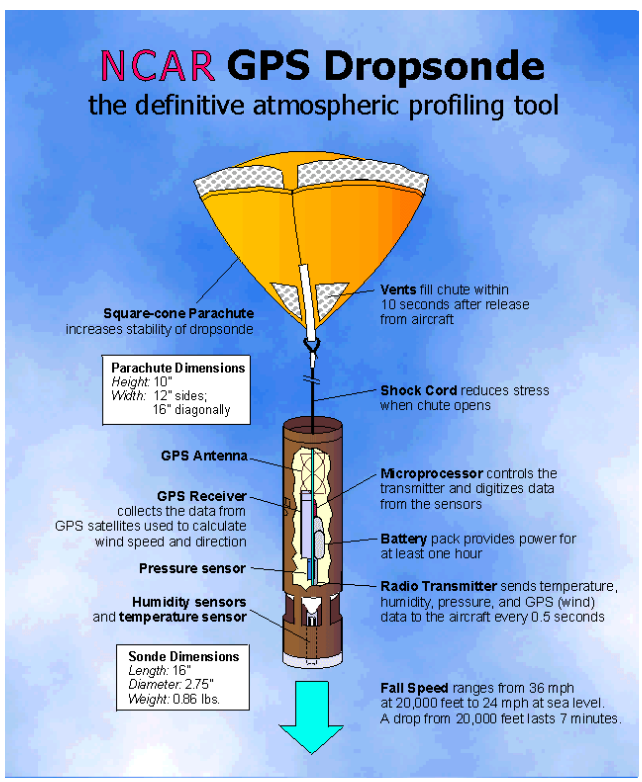

Fig 7.7. Schematic of falling dropsonde (Courtesy of National Center for Atmospheric Research[NCAR])

It has been mentioned (section 6.2.3) that the dropsondes launched from the BAe 146 sometime hits the fuselage, evidenced by the scuffed paintwork. With the cardboard casing and only weighing 0.5kg, this is not a risk to the aircraft; however, a hard cased ALAUV poses a higher risk of damage. Furthermore, the transition from falling through the launch chute to stable, slow speed fall is not trivial. One suspects a considerable amount of development has gone into the process.

UAV launch from an aircraft

Advanced Ceramics Research[9] developed the air launched UAV 'Coyote' which has been successfully deployed from a 127mm diameter sonobuoy launch tube (Fig 7.8). The rationale for the development was to enable UAVs to be carried long distances into conflict zones and deploy them from 20,000ft to avoid endangering the host aircraft. Launched from a Lockheed Orion P3 aircraft, the Coyote is seen as having environmental as well as military applications by recording data as it flies through tropical storms [17]. For the purposes of this report, table 7.2 summarises its physical data

BAe Coyote UAV	
Weight (standard payload)	5.9kg
Max take off weight	6.4kg
Maximum endurance	1.5 hours
Wing span	1470mm
Length	790mm
Tail height	305mm
Fuselage diameter	115mm
Max endurance speed	55knots
Max endurance	82 nautical miles

Table 7.2. Summary of Coyote UAV physical data

Following ejection, the tube's parachute is deployed and 5 seconds later the sleeve containing the aircraft is released. The flight surfaces are deployed, horizontal tail first, then the wing, then the vertical tails. The parachute remains attached for a further 10s after sleeve releases while the lithium polymer battery-powered pusher propeller speeds up and the global positioning system searches for satellites for navigation. By 15s after launch the Coyote's parachute is released and it begins its climb-out. After about 20s from launch the Coyote is in full flight mode. The Coyote was launched from a representative sonobuoy launcher from a Raytheon C-12 Huron in April 2007.

[9] subsequently taken over by BAe in 2009

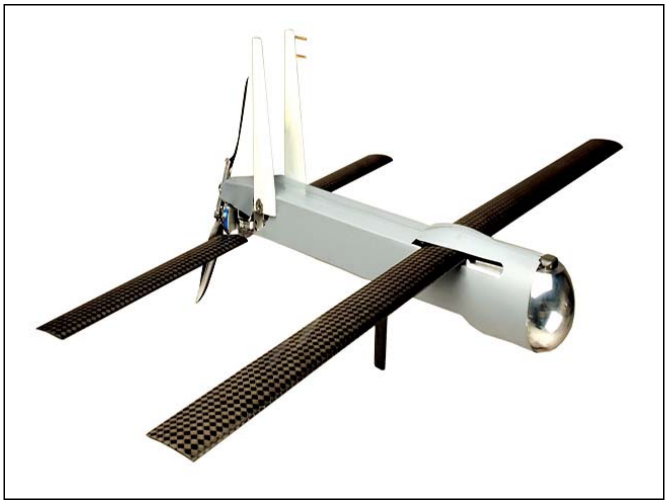

Fig 7.8. Coyote air launched UAV (ACR photo April 2008)

7.1.2 Autonomously controlled parachute

Making airdrops for military or for humanitarian reasons are well established and the military has successfully developed Joint Precision Air Drop Systems (JPADS) to land cargo with 100m accuracy using a combination of autonomously controlled parafoil and conventional circular chutes to land loads up to nearly 4.5Tonnes [18]. The initial parafoil deployment steers the load at speeds between 20 and 70 m/s, giving it the ability to penetrate a 30m/s wind. The circular parachutes open at low altitude to reduce the vertical speed to between 7 and 8m/s. For additional positional accuracy, a dropsonde is dropped first to record the wind/altitude profile. JPADS achieve a glide ratio of 3.5:1, limited by the heavy payload and requirement to cope with headwinds, giving it a glide range of some 30km when dropped from 25,000ft in zero wind. Navigation is by GPS and the control sensors include rate gyros to achieve initial steering control and prevent spinning [18]. While this solution avoids some of the difficult turbulent transition between launch (speed of the host aircraft) speed and glide speed, control throughout the glide phase is by no means simple; furthermore, it may not be as effective in covering a wide swath distance from the aircraft track.

7.1.3) Balloon launched glider

Much of the difficulty with launching a glider from an aircraft is associated with the high air speed and turbulence when the glider leaves the aircraft. An alternative may be to use a weather balloon released from a ship to give the ALAUV height for a long glide range, launching it at high altitude but in considerably more benign conditions. Thus the balloon provides the altitude and the autonomous glide provides the direction and some control over the splash down point. If the track of the balloon is predictable, the launch height (and by implication, position) could be programmable.

Although this avoids some of the technical difficulties, it restricts the capability.

- The weather balloon obviously travels with the wind direction; this may be odds with the scientific requirement.
- The initial launch position is now from a ship with its attendant ponderous nature; the concept of covering a large swath in a synoptic fashion is lost.
- The payload of a weather balloon is restricted to approximately 0.5kg
- The merit of the concept is it provides an AUV survey some 50 – 100km from the ship position (plus the distance the balloon has travelled). If there is an application that warrants the complexity of a balloon and ALAUV, a more simple and practical concept may be to launch a more conventional AUV from an UAV launched from a ship (or land for coastal work). **Indeed, this may be the dream ticket for future autonomous surveys.**

7.2) Conclusions on the feasibility of an air gliding AUV

The Coyote project illustrates the difficulties in developing a vehicle that will transition from the fuselage to free flight (whether it is powered or gliding makes relatively little difference). In oceanographic terms the predicted glide range approximately 100 km is small and may prove to frustrate rather than enhance the scientist's aspirations, and this is from a maximum launch height of 20,000 to 30,000ft. The number of civilian research aircraft available worldwide for achieving these heights is about a dozen. Of this 'dozen', some do not routinely operate or cruise at these heights (e.g the BAS twin Otters or Dash 7) and are not fitted out to launch equipment from a pressurised cabin. The advantage the high altitude launch is that of covering large distances before splash down and providing a synoptic aspect to the science but this could also be achieved by low altitude drops and using the aircraft to provide the swath width.

The practical restrictions of available aircraft severely limit the scientific programmes that could be proposed and the engineering commitment needed to overcome the technical challenges would be considerable. The combination of these difficulties makes it very difficult to conceive how a high altitude launched ALAUV development programme could be justified. The entire concept needs to be much more accessible in affordability (development and operation), range and availability of host platforms.

Subsequent sections in this report go to outline a less ambitious ALAUV which would be more simple to develop and use, thereby opening up the range applications and the modes in which it could be used. If, say such a programme was successful and there was merit in extending development for high altitude launched AUVs, there maybe interest in aeronautical fields for furthering atmospheric research. At the time of writing, University of Southampton, SES is considering preparing proposal for a small, high altitude launched glider. The development of a combined UAV and AUV would need to be a collaborative effort between those with experience and track record in both fields.

8.0) Air dropped, semi disposable AUV

If we open the possibilities of low level launch from unpressurised cabins the constraints of launch infrastructure (dropsonde or sonobuoy tubes) are nothing like as rigid and it is possible to begin a skeleton design, selecting AUV sub systems from existing technologies and seeing if the resulting whole is of any practical use and could be considered semi disposable. The following essential subsystems are considered:-

- Navigation
- Data communications
- Logging
- Propulsion
- Energy

The Autosub Long Range (ALR) project relies heavily on the sub-sytems being low average power. Fortunately, size and low power requirements often go hand in hand and so although the ALR is still a relatively large AUV, many of the subsystems are small and the completed development work proves to be immensely useful for our purposes.

8.1) Navigation

Compass

The compass module used in the Autosub Long Range (ALR) is the PNI-TCM5LT, this compact unit operates over a wide range of tilt and has been successfully integrated into the ALR. An alternative may be the Ocean Server OS5000-USD 3 Axis Digital Compass which also comes with a depth sensor input option. This module was used in the Student AUV Competition Europe (SAUCE) where there were integration problems; it was not resolved if these were due to it being unsuitable for the application or whether lack of time prevented the team getting to the bottom of the problems. The unit is also used in the low cost IVER AUV (the same as YSI AUV). Data sheets are included in Appendix C, a summary is found in Table 8.1.

Compass unit	Physical size	Weight	Accuracy	Typical Cost	Remarks
PNI-TCM5LT	33x31x13mm	12g	0.3 deg up to 70 deg tilt	£1300	Better performance at high pitch and roll angles. http://www.pnicorp.com/products/fieldforce-tcm Cheaper items are available with possibly acceptable formance, e.g. *Ocean Server nology Inc. OS5000-USD 3 Axis Digital Compass*
Ocean Server OS5000-USD 3	26x26x8	2g	0.5 deg RMS level, 1 deg RMS up to 30 deg tilt	£235	http://www.oceanserver-store.com/oscomowideop.html

Table 8.1 Possible compass module options

Speed

Speed over ground is ideally achieved by use of an Acoustic Doppler Current Profiler (ADCP) tracking the sea bed. If the sea bed is out of range, then the next best option is to measure speed through the water. Obviously this introduces error in absolute speed if water currents are present, additionally, the acoustic reflections from particulate in the water are necessarily some 10's of metres away so if any shear current is present, this will introduce further errors. There is no such instrument small enough, low enough power or affordable within the remit of being semi disposable for use in ALAUVs and so speed measurement will almost inevitably be reduced to a calibration between distance travelled per propeller revolution for a given motor torque. If the motor torque is monitored (by measuring current), it's possible the vehicle speed could be mapped for the range of propeller speeds as accurately as an ADCP speed through the water measurement[10]. The method has no way of accounting for water current other than introducing a known current vector before the mission but these short comings may be able to mitigated by more frequent GPS fixes to re-establish its absolute position and give depth averaged currents.

Depth

Measurement of depth is one of the easier parameters in the sense that there are number of options available depending on range and depth required. The OS5000-USD Digital Compass comes with an option to receive a depth signal, the Valeport CTD sensors fitted to the Sea Mammal Research Unit (SMRU) seal tags have a depth sensor operating to 2000m with an accuracy of 2m +/-(0.3+0.00035xreading)/^{o}K and a resolution of 0.5m (Appendix C).

GPS

Given that an ALAUVs heading and speed through the water is likely to be approximate (compared for instance with present Autodsub3 and 6000 which are fitted with an ADCP and fibre optic gyro heading sensor), obtaining a GPS fix to give it an accurate position at salient points during its mission will be essential. Water tight and pressure proofed GPS antennas with preamplifiers have been quite problematical to date on the Autosubs with problems of water leaks, variable performance, unreliability and bulk once they have been encased. The encapsulation and streamlined shape of the Teledyne Webb Gliders seem to have had greater success although is still relatively bulky for a small ALAUV. With GPS being routinely built into mobile phones and 'Sat Nav' navigation aids, the cost and size of these devices has reduced dramatically while the reliability and performance has improved. Fig 8.1 illustrates a Johnson Technology 7x2x0.8mm surface mount antennae (minus ground plane) and a Sparkfun Electronics receiver with antennae. While these products may serve as a good starting point for a marinised design, achieving low bulk and low production cost, reliable performance is likely to be an area of research, design and development that the NOC is likely to have to initiate. The problem is that manufacturers will not take the time to pot and tune for the change in dielectric constant and they have no interest in conformal designs for such a limited market. A further complication this is that other interested parties such as Bluefin, Teledyne Webb, Remus, iRobot, are not necessarily willing share their 'recipes', they are not interested in commercializing

[10] Since vehicle speed is proportional to motor power[3], monitoring motor power (rotational speed x torque) is a more sensitive way to calibrate vehicle speed.

antennas suitable for depth[11]. This may mean a successful design could prove to have some marketable value.

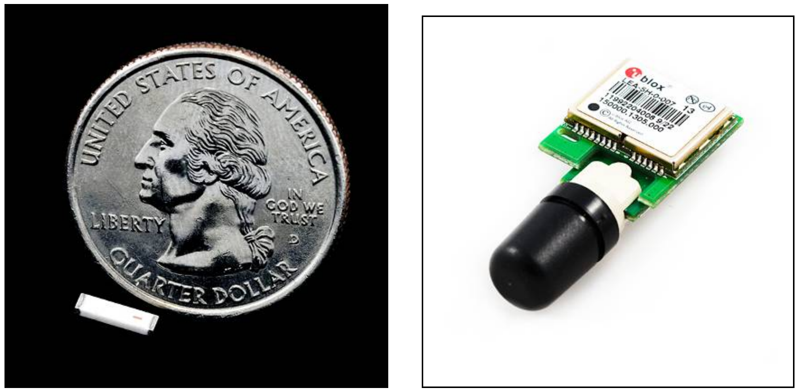

Fig 8.1. Left - Johnson Technology 7x2x0.8mm surface mount GPS antennae 1575AT43A40. Right – Sparkfun Electronics 47x22mm GS407 Helical GPS Receiver

8.2) Data Communications

Although satellite communications are relatively common place in oceanographic equipment, the technology is not routine, easy or fool proof and ALAUVs present a number of challenges:-

- The circuit board size is large relative to other subsystems[12].
- The power requirement while transmitting is significant.
- The cost of the board and aerial on board is significant relative to the overall target cost.
- Transmission, standing charges and set up fees add to the operational cost.
- The antennae size does not scale with AUV size and so presents a problem of mechanical integration and hydrodynamic drag.
- The sea wash-over the aerial interrupts transmission; this is a problem for all AUVs but especially acute for a small vehicle with negligible freeboard.

The two main contenders for satellite communications are Iridium and Argos. Until recently, Argos was only capable of transmitting from vehicle to base but with the advent of Argos-3, two communications is now possible.

A similar application to ALAUVs is the sea mammal tags developed by the Sea Mammal Research Unit (SMRU). These tags also have to be small, low power, economical in data transmission and considered disposable. They use Argos to relay data, compressing the information to maximise the transmission reliability (the time on the surface to transmit can be very short). The overall mean power consumption of the tag (including logging and CTD) is 5.3mW. A comprehensive technical description which encompasses the design, sensors, data compression/transmission, energy and field experiences is given by Boehme et al [19].

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[11] Email correspondence March 2011 with Paul Hill of JouBeh Technologies Inc, Dartmouth, NS, Canada

[12] Depending on the performance required., small board size Iridium systems are available so long as only short burst data is acceptable.

Argos-3 provides two way communications and a ‘message received acknowledgement’ which reduces the need for ‘hope for the best’ repetitive transmissions of earlier versions. Data and data rates are higher, up to 4.8kBits/sec. With suitable compression algorithms this could be usable. With the capability to obtain position fixes (within 150m?) and simple antennae arrangement, this may prove to be a practical option.

The Iridium system provides greater data rates and faster delivery times and is used in the oceanographic field of the Teledyne Webb Glider AUVs and Rapid Climate Change Programme (Rapid) with options of different providers, e.g. NAL Research[13] JouBeh Technologies in Canada[14] and AST in the UK[15]. A summary of the costs and capabilities are given in Table 8.2; a wider survey including other systems is found in Appendix C

[13] http://www.nalresearch.com/Airtime.html
[14] http://www.joubeh.com/
[15] http://www.satcomms.com/

Comparison of message-based systems

System	Message size	Airtime cost	Monthly price, 1 message/day	Monthly price, 1 message/hour	Terminal power consumption (during transmission)	Two-way comms?	Polar coverage?[16]	Data rate	Time to send one message	Delivery time
Iridium SBD	<340 bytes	$13/mo + $0.0015/byte[17]	$14.24 (30 bytes)	$31.48 (30 bytes – bulk tariff)	1.8W	Yes	Yes	2400bps?	~1s	<20s
ARGOS	32 bytes	Other stations $21/mo + $1.9/6hr slot	$81	$260	<1W	No.[18]	Yes	480bps	~1s	Up to 2hrs
		Land-based fixed stations $21/mo + $1/6hr slot[19]	$54	$151						

[16] Polar coverage means coverage beyond the reach of geostationary satellites (i.e. latitudes higher than 75 degrees).

[17] There's a minimum fee per message of $0.04, covering your first 30 bytes. SBD also has a bulk tariff, where for $16 a month you get 12,000 inclusive bytes, subject to a minimum bill per message of 10 bytes.

[18] ARGOS currently has one two-way capable ARGOS-3 satellite in orbit.

[19] This is the ARGOS JTA price for scientific applications. Marine animal tracking devices get a further discount – they're only billed for a maximum of 48 timeslots in a given month, regardless of how many they actually use. Argos is billed in Euros and the dollar prices here are based on an exchange rate of 1 euro = 1.4 USD.

		Airtime charges[20]			Monthly airtime cost for…[21]					
System	**Data rate, kbit/s[22]**	**Monthly fee**	**Charged rate**	**Equivalent cost per megabyte[23]**	**1MB**	**10MB**	**100MB**	**1000MB**	**Polar coverage**	**Marin-ised?**
Iridium dialup	2.4	$14	$1/min	$58	$72	$594	$5814	$58014	Yes	Yes
Iridium RUDICS	2.4	$14 (plus 1 off set up fee of a few $k)	$0.65/min	$37	$51	$384	$3714	$37014	Yes	Yes
Iridium Open Port	32,64,128	$32 - $1000[24]	$5 to $15/MB	$5 to $15	$47	$113	$625 (32kbit/s) $719 (64bkit/s)	$5000(32kbit/s) $5629 (64kbit/s) $6661 (128kbit/s)	Yes	Yes

Table 8.2 Summary of Argos and Iridium satellite costs and performance as of April 2010 (reproduced with kind permission from Michael Prior-Jones; updated April 2010, personal correspondence March 2011.

[20] All prices are in US Dollars and exclude taxes. Iridium airtime was priced from NAL Research. Open Port prices were quoted by AST. Fleet prices were from KVH. BGAN and Fleet Broadband, Globalstar and Thuraya (dialup/GmPRS) prices were from Satphone. ThurayaIP and ThurayaDSL prices were from X Sat.

[21] This price is the cost per month for the data used in a given month. It includes monthly subscription charges, but doesn't include initial setup costs such as activation or SIM card fees.

[22] Figures quoted here are uplink speeds – some systems have asymmetric uplink and downlink speeds.

[23] This price shows the per-minute rates converted to per megabyte, ignoring monthly fees or any overheads like minutes used whilst establishing connections.

[24] OpenPort pricing includes a data allowance as part of the monthly charge. Paying a higher monthly charge results in a lower cost per MB. 64 and 128kbit/s data rates are more expensive than the basic 32kbit/s service.

8.3) Data Logging

Given the limitations imposed by the costs and capability of the satellite communications, the data is necessarily going to have to be compressed and limited. For example, the SMRU tags only record a limited data commensurate with the total energy available and practicalities of communications. If the tag is recovered, a full data set can be downloaded regardless whether it was transmitted. A similar process may have to be adopted for ALAUVs but given that flash memory cards up to at least 16GB are readily available, logging the data on the vehicle is unlikely to be a limitation.

8.4) Propulsion and fin actuation

Mechanically powered parts on most AUVs are driven by brushless motors for longevity, reduction in the number of sliding parts (namely the brushes). If the motor is oil filled they avoid the oil becoming contaminated through brush wear. For an AUV with a working life of only approximately 200 hours, this is an area where modest cost savings may be found by using brushed motors and gearboxes readily available to the model making industry. The small brushed motor and gearbox used for life testing the Autosub6000 fin actuator potentiometers ran continuously for nearly 1300 hours before being switched off. These are available up to c20Watt for c£25 and compares with c£400 for the 120Watt brushless motor and gearbox used in the Autosub Long Range (ALR). Although these small brushed motors are only equipped with sintered bronze bushings, since they only transmit a pure couple with no side or thrust loads on the motor and gearbox bearings, the frictional losses ought to be acceptable. An alternative may be sensor-less motors similar to the type used for cooling in computers.

A magnetic coupling enabling the motor to run in air within a small pressure vessel was successfully developed for the ALR propulsion and fin actuation systems, coupled with extremely free running full ceramic bearings on the sea water side it avoids oil stirring losses, shaft seals and reduces the bearing losses. The propulsion transmission efficiency has been significantly improved and can be scaled down to suit much smaller machines.

An efficient propeller is required to complete an overall efficient propulsion system. The slow running ALR vehicle highlighted the difficulties of achieving an efficient propeller running at low Reynolds Numbers (<50,000), resulting in a one bladed propeller, effectively doubling the Re No. Similar design constraints are likely to impact the design of an ALAUV and will require significant effort to achieve an optimum vehicle range involving choice of propeller speed, vehicle speed, propeller design commensurate with hotel power (everything else which is not propulsion power).

Cost savings can be achieved in the design of the fin actuation systems by tapping into the mass modelling market. A wide range of small mechanical servo systems are available which are highly developed and competitively priced. The integration of such units, using a magnetic coupling and ceramic sea water bearings has proved to be straight forward with the demonstration exhibit built for the Oceanology International exhibition 2010 (Fig 8.2).

Miniature Fin Actuator Servo	
Size	Fits into 50mm dia tube
Max torque	0.05Nm (0.5kg.cm)
Mass	85g
Depth rating	500m
Over torque protection	Yes

Fig 8.2. Small pair of servo actuators complete with mag' coupling, sea water bearings based on small aero modellers servo motor, gear box and position feedback

8.5) Energy

With the semi disposable nature of the AUV, it makes little sense to have a rechargeable system of batteries on board. Primary batteries will have a higher energy density and a lower specific cost for a one or few off cycles. The highest energy density readily commercially available is lithium thionyl chloride with a quoted 490W.hr/kg at 4mA discharge. These cells (D size) are used for the SMRU sea mammal tags with an average current drain of 1.5mA. The energy density drops off with increasing discharge current and decreasing temperature (Data sheets in Appendix C). From the SAFT data sheets for the LS 33600 cells, the energy density for a 60mA discharge at 0^0C is approximately 400W.hr/kg.

9.0) Sensor payload

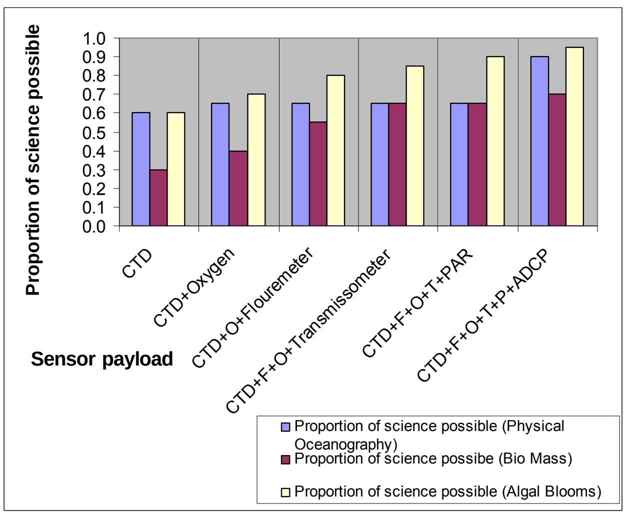
With the concept of a small, semi disposable AUV, the sensor payload is going to be limited. Informal discussions with potential users on applications and sensor load, without imposing any restrictions on size, power, weight or cost revealed a wish list:-

- CTD — All
- Fluorimeter — Oil spill Response Ltd (UV excitation for detecting hydrocarbons)[25], Prof R. Lampitt, Dr. J. Allen, Dr D. Smeed (Chlorophyll Fluorescence) (NOCs)[26]
- Oxygen — Prof R. Lampitt, Dr. J. Allen, Dr D. Smeed
- SUV Nitrate — Prof R. Lampitt, Dr. J. Allen, Dr D. Smeed
- ADCP — Prof R. Lampitt, Dr D. Smeed
- EK500 fish finder — Prof J. Watkins (BAS)[27]
- Chlorophyll — Prof J. Watkins[24]

[25] Discussions May 2010
[26] Discussions June 2008
[27] Discussion Jan 2011

Clearly there needs to be a way of sorting what is possible and still useful. For instance an ADCP is not small, light or semi disposable, similarly, the Simrad EK500 head weighing approximately 50kg, circa 400mm diameter was suggested tongue in cheek but Jon Watkins did concede in the same discussion that sensing chlorophyll would still be a useful minimum alternative. Landers, moorings, AUVs, ROVs etc have generally sprouted additional payloads throughout their lives until it is physically not possible to fit any more. In the same discussions referenced above, the author asked the scientists to judge the proportion of science in their field that could be achieved with a minimum payload compared with the full options list. Fig 9.1 shows the increasing proportion of science possible as the sensor payload becomes more comprehensive but obviously this comes at a cost, not simply of the sensors but also of a larger AUV to accommodate them. Fig 9.2 considers (albeit quite subjectively) the notion of 'specific cost' where:-

Specific Value = Proportion of Science Possible/Sensor Cost
(Cost has been normalised against the cost of a CTD, value = 1)



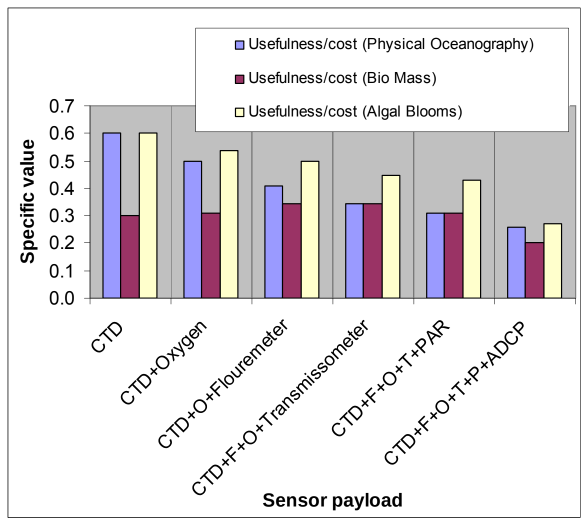


Fig 9.1 (left). Proportion of science possible with increasing sensor payload
Fig 9.2 (right). Specific value with increasing sensor complexity

Fig 9.2 shows a high specific value using only a CTD (i.e. high proportion of science at moderate cost) except for the study of bio mass. For physical oceanography, the exercise shows a law of diminishing returns for increasing complexity. When considering a programme of multiple oceanographic platforms (100's or 1000's) the most useful one we can create is not the one bristling with the most sensors, capable at great depths but the one that will deliver the most scientific knowledge. This will involve taking decisions to limit its capability in order to maximise the specific value.

Another consideration was the proportion of science possible versus the operating depth. Increasing the operating depth of an AUV increases its weight. For a given vehicle design, the balance of weight remaining after the weight all other systems have been subtracted off the displaced weight is (invariably) given over to the energy source. A deeper diving vehicle adds weight especially to items providing buoyancy which limits the weight of batteries that can be carried. Fig 9.3 is a judgement on the degree of science possible with increasing depth. If geological and geophysical sciences are excluded (which require substantially sized survey payloads) then a knee in the curve occurs at 500 to 1000m with the implication that most science in physical and biological oceanography could be carried out within this depth.

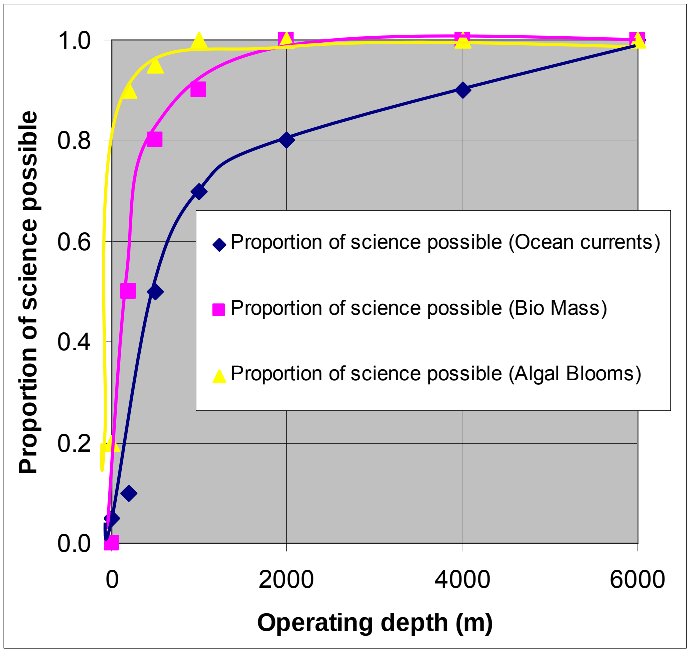


Fig 9.3. Proportion of science vs operating depth

9.1) Existing and potential sensors

The SMRU and fish tagging programmes have proved to be successful in reducing the size, power and memory requirements for sensors. These units generally include battery and logger, table 9.1 provides a performance summary.

Sensor	Manufacturer	Parameter	Accuracy	Resolution	Size	Battery Life
G5	CEFAS Lowestoft, NR33 0HT, UK	Temp	+/-0.1C	0.03C	8 dia x 31mm	10 months. 2 years 'Long life tag'
		Depth (Range options from 100 to 2000m)	+/-1% FS	0.04%		
DST CTD	Star Oddi Vatnagardar 14 104 Reykjavik Iceland *Note a large range of sensors are available, CTD and GPS picked as being the most relevant)*	Temp	+/-0.1C	Not quoted	15 dia x 46mm	4 years
		Depth	+/-0.4% FS (100 and 500m range) 0.6% (1200 and 2000m range)			
		Salinity	+/-1 PSU			
DST GPS		Temp	+/-0.1C		15 dia x 46mm	2 years
		Depth	+/-0.4% FS (100 and 500m range) 0.6% (800 and 3000m range)			
		GPS (acoustically relayed from Simrad sonar)	+/70m (Receiving radius <4km from SP270 Simrad sonar)			
Cyclops-7	Turner designs	Flourimeter	Chlorophyll *a.* 025 µg/L (Min detection level)		23 dia x 145mm (Includes pressure case and underwater connector)	Not powered, 300mW consumption
CTD Tag (used by SMRU)	Valeport Totnes TQ9 5EW UK	Temp	+/-0.005C	0.001C	105 x 70 x 40mm (complete tag with ARGOS)	1 year
		Conductivity	0.01mS	0.002mS		
		Depth	2dBar (2000dBar range)	+/- (0.3+0.035 % Temp coeff)		
Under development	NOCs Sensor group	Temp			Mounted on one small PCB	Not powered
		Conductivity				
		Oxygen				

Although the Turner Designs Cyclops-7 flourimeter is too large for the type of vehicle ideally being considered, this does include a pressure case. If the logging and power is carried within the main centre pressure case, this leaves just the sensing head needing to be fitted in the nose cone space; this is seen as being feasible.

9.2) Sensors in development at NOCs Sensor Group

The following is an indicative table of target parameters and accuracies within instruments in development.

Within a 5 year horizon

Sensor	Parameter	Accuracy	Resolution	Size	Battery Life
NOC CTD-DO v2.2 [20-22]	Temp	+/-0.003^{o} C	+/-0.0003 C	Mounted on one small PCB	Not powered 3mW when operating, ultra low power quiescent mode
	Conductivity	0.003 mS	0.0003 mS		
	Oxygen	10%	1%		
NOC LOC sensor [23-27]	Nitrate and nitrite, or phosphate, or Fe, or Mn	100 nM	15nM	Current 150mm dia x 250 mm Aim 60mm x 15mm	Not powered current 1W, aim 200mW
	pH	0.002 pH	0.001pH		
NOC methane sensor [28, 29]	Dissolved methane	2 nM	700 pM	Head 30mm x 15mm x 25mm + PCB	Not powered current 500 mW
NOC optical carbonate system sensor	pH CO_2	0.015 pH 10μM	0.005pH 2μM	Head 30mm x 15mm x 25mm + PCB	Not powered current 2 W, aim <200 mW

4-10 years to deployment on miniature AUV (without additional investment)

Sensor	Parameter	Accuracy	Resolution	Size	Battery Life
Micro Cytometer [30, 31]	Phytoplankton population (discriminated by functional group)	Counts – 1 cell, functional taxonomy	1 cell	Current 250mm x 300mm. Aim 60mm x 15mm	Not powered 3W when operating
NOC nucleic acid sensor [32, 33]	Quantitative counting of phytoplankton with species level discrimination	10 cells	1 cell	Current 300mm diam x 250 mm Aim 60mm x 15mm	Not powered currently 5W, aim 500mW

10.0) Size, mechanical design and performance

Based on the conclusions that the ALAUVs need to be within the size of a dropsonde (82mm diameter) and a sonar buoy (127mm diameter), it is possible to begin to make estimates of performance based on some of the sub-systems described in section 8.

10.1) Hotel power, propulsion power and range

A model based on the dropsonde 82mm diameter with an operating depth of 500m is shown in figure 10.1. Table 10.1 lists the estimated hotel power (everything that is not propulsion power). Using estimated propulsion efficiencies and the drag coefficient from Polyart [34], the range can be estimated for varying vehicle speed and hotel power (Fig 10.2). The maximum range increases as the hotel power decreases but the cruise speed at which maximum range occurs also decreases. Ultimately, there is a minimum speed below which the vehicle is impractical, e.g. the speed is insufficient to overcome water currents.

Fig 10.1. Outline design of 82mm diameter ALAUV. The cut away nose section is the space for the sensor payload, the cut away tail shows the pair of fin actuators and propulsion motor.

	Continuous power (W)	Duty cycle	Average power (W)	Remarks
Rudder and stern-plane actuation	Approx 2.3 at max speed	0.05	0.115	Data sheet value
Logging, sensors and data transmission	-	-	0.0035	Based on average SMRU tag performance[28]
Mission management	0.3	1	0.3	Based on Autosub Long Range PXA270 and Persistor modules
Heading sensor	0.048	0.05	0.0024	TCM5LT 3 axis compass module (see Appendix B)
Total Power (W)			**0.4209**	

Table 10.1. Estimation of hotel power

[28] Note, Sea Mammal Tags use ARGOS for transmission of data. If Iridium is adopted, this will us more power

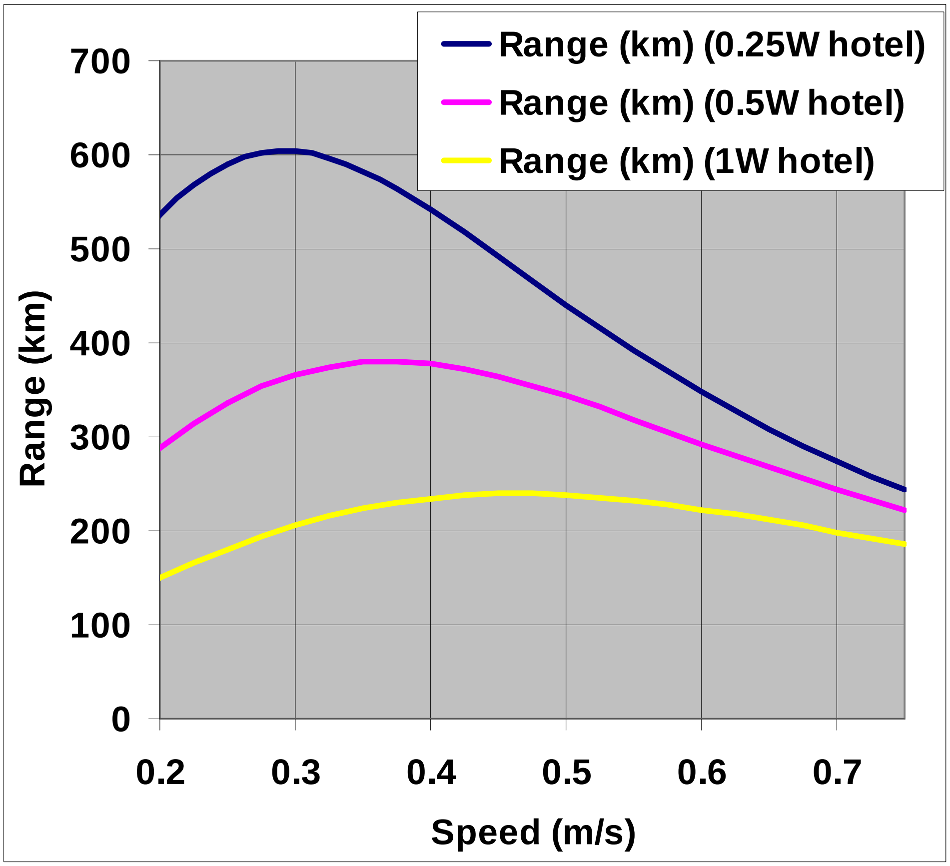


Fig 10.2. Estimated range vs speed for 82mm diameter ALAUV (see Fig 10.1) Based on 2.3 Litre form displacement, Cd=0.17 ($V^{2/3}$), powered by 6 Lithium thionyl chloride 'D' cells (0.54kg, 216 W.hrs) with an overall propulsion efficiency of 30%. The 0.5W curve is representative of the condition in Table 10.2. The lower 0,25W hotel is indicative of what might be achieved with yet-to-arrive low power technologies.

10.2) Creation of down force to overcome buoyancy

Autosub3 (7m long), when operating at a speed of 1.5m/s overcame the buoyancy forces (c100N) by adopting a pitch down attitude of approximately 3 to 5 degrees. When Autosub3 was required to operated at slower speeds (0.5m/s), short 'winglets' were added as a more efficient means of creating down-force and avoiding excessive pitch angles. Using simple scaling laws, an estimate can be made whether wings would be required for ALAUVs for the cruise speeds envisaged. Assuming the practical value for buoyancy scales with vehicle form displacement (i.e. Length^3), for a 0.5m long ALAUV the buoyant force is estimated to be:-

$$Buoyant\ force_{ALAUV} = Buoyant\ force_{Autosub3} x\ (L_{ALAUV}/L_{Autosub3})^3$$

$$i.e.\ 100\ x\ (0.5/7.0)^3 = 0.04N$$

If we assume the down force for a given pitch angle scales with L^2 and velocity^2 then

$$Down\text{-}force_{ALAUV} = Down\text{-}force_{Autosub3}\ x\ (L_{ALAUV}/L_{Autosub3})^2\ x\ (v_{ALAUV}.v_{Autosub3})^2$$

For an ALAUV cruise speed of say 0.5m/s, the estimated down force will be

$$100\ x\ (0.5/7)^2\ x\ (0.5/1.5)^2 = 0.06N$$

The down force is similar in value to the buoyant force and it is reasonable to assume the vehicle will control without the need for additional wings. If slower speeds are required or more detailed analysis shows wings are necessary, then schemes of folding wings which deploy when launched from the aircraft will have to be investigated.

10.3) Construction

The main pressure hull provides the source of buoyancy and dry space for all dry subsystems. The relatively shallow operating depth (500m) puts the failure mode of the housing firmly in buckling mode as oppose to material failure [35]. In order to create a weight efficient design this entails ring stiffening the cylinder to resist buckling. If the stiffening rings are integral with the cylinder, this reduces the useable dry space but if the stiffening rings could be made as part of the internal chassis work which withdraws when the chassis is removed this helps release the annular spaces between the rings to be used by electronic assemblies (fig 10.3).

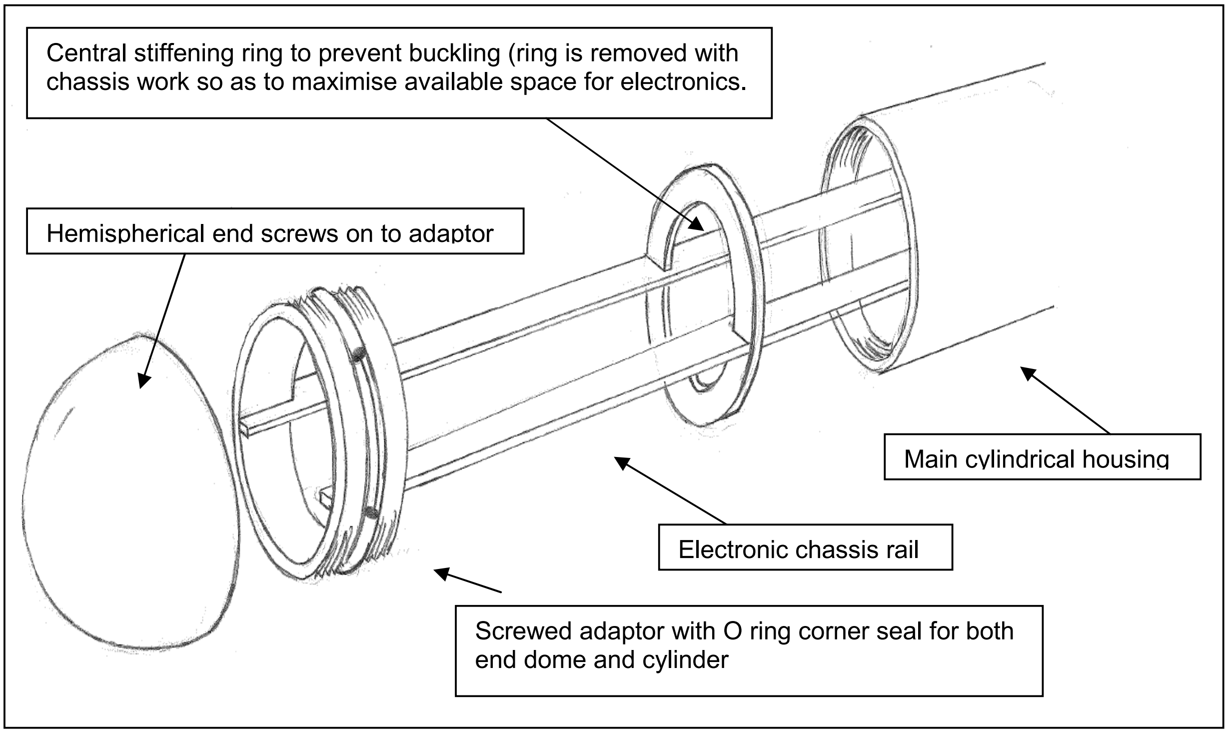


Fig 10.3. Sketch of retractable stiffening rings from pressure cylinder to provide more useable space for internal assemblies

A significant cost and volume of an AUV is taken up with cabling and underwater connectors. Autosub3 at one stage weighed 2.4Te in air while its form displacement was 3.5 Te, thus its flooded volume was approximately 1Te, or 1000 litre. The flooded sections of the vehicle were considered to be full of sensors, in practice, much of the space was taken up with cables and connectors. This inefficient use of space, expense and source of unreliability needs to be addressed, the most obvious approach being to see if underwater connectors can be designed out. The full size model (fig 10.1) shows the fin actuators bolted to the end hemisphere of the pressure vessel, sealed with a face seal, through which the wires can pass.

10.4) Antennae

Some features of an AUV do not scale with vehicle size, communication antennae are an example. While the size of antennae with preamplifiers is reducing, it remains a technical challenge to produce something compact, water tight, pressure tight and operates with wave wash over. The problem is compounded by practical difficulties:-

- The potting (to provide the pressure proofing) reduces the antennae performance and making the antenna more bulky.
- AUV developers are sometimes unwilling to share their invested knowledge.
- Some proprietary marinised products have proved to be flawed
- Companies mass producing antennae for commercial markets are unwilling to invest in equivalent products for such a limited oceanographic market.

Wave wash over can seriously diminish performance where some continuity of satellite access is required (e.g. GPS). With such a small vehicle with minimal freeboard this could pose a significant problem. A solution may be to configure a moving mass within the pressure hull to move the BG position from above the Centre of gravity (CoG) (which provides level trim) to forward of the CoG such that the vehicle floats vertically in the water. With a thin antenna on the nose, this then clears the water surface, the vehicle behaves like a miniature spar buoy, following the wave action and the drag of the 'spike' antennae on the nose is negligible during flight.

10.5) Cost

The economics of producing ALAUVs such that they are affordable to be considered semi disposable is crucial to the success of the concept. While scientific research centres do not necessarily have the skills, experience or knowledge in reducing production costs and marketing high volume devices, it is possible to lay the groundwork in having a conceptual design which lends itself to low production costs by designing around mass market sub systems and using the small vehicle size to simplify the design. The production cost of the SMRU sea mammal tag has been taken as a foundation since this is a compact unit sealed to a similar depth operation and contains:-

- CTD sensors
- Data logging
- Battery
- Data transmission

In addition to the functionality of a sea mammal tag, an ALAUV needs:-

- Propulsion
- Fin actuation
- Stern-planes and rudder
- Stabilising fins
- Mission management
- Pressure housing (to house electronics and provide requisite buoyancy)
- Faired nose and tail sections

An indication of production cost of the overall vehicle is given in Table 10.2. This does not include the design and development costs or profit.

Sub-system	Indicative production cost (£ ex VAT)	Remarks
Sensors, logging, satellite transmission	3500	Based on present cost of SMRU Seal tags *(note reduction made since seal tag is potted, a process not required for ALAUV)*[29]
Heading, compass and Mission management hardware	500	Proprietary hardware costs *(Direct insight control processor. Ocean Server Tech Inc Attitude and heading sensor)*
Nose and tail cones	10	Spun or pressed from thin aluminium or plastic moulding.
Central pressure vessel and electronic chassis work	300	• Extruded aluminium tube • Spun or pressed aluminium hemisphere ends with O ring seals • Electronic chassis doubles as ring stiffening for the cylinder and anchorage for end dome fixing/sealing *NOTE, prototype model for wind tunnel tests including nose+tail cone and stabilising fins cost £770*
Stern-plane and rudder actuation	120	Prototype twin actuator cost £480. *NOTE £450 of this cost was one off machined pressure case, magnetic coupling and final bearing ass'y*
Stabilizing fins	5	Die cut polyethylene, stamped to form 'living' hinges for stern-planes and rudders
Propulsion motor, gearbox, magnetic coupling.	120	• Proprietary brushed motor with gearbox • Small pressure case • Magnetic coupling transmits output power to propeller. • Propeller mounted on stainless ball races or full ceramic ball races for longer corrosion life
Propeller	10	Single plastic moulding
Parachute systems	150	Based on dropsonde design
Assembly and test	350	Approx 1 day labour
Batteries	95	6 x Lithium thionyl chloride D cells
Miscellaneous	774	15% of above costs
Total	**5934**	**Indicative cost**

Table 10.2. Indicative production costs for an ALAUV produced in their 1000's

[29] Note. Sea Mammal Tags use ARGOS for data transmission. If Iridium is adopted, this will be more expensive

Another bench mark cost is the cost of an ARGO float which contains similar sensors and data transmission at approximately £10k. An ARGO float has additional costs not associated with sea mammal tags or the envisaged ALAUV:-

- Buoyancy engine to control its depth profiling
- Substantially larger (25kg cf envisaged 2kg weight in air for ALAUV)
- A 2000m operational depth, together with its larger size, its construction entails a substantially larger pressure vessel.

When bench marked against the existing technologies of Sea Mammal tags and ARGO floats, both of which are considered disposable, the costs in Table 10.2 would not seem unreasonable. If costs could be further driven down, to say £5k, the vehicle would be considered semi disposable given other operational and scientific overheads of collecting oceanographic data.

11.0) Performance comparisons with other technologies

In order to check the distinctiveness of the concepts, ideas will be compared against a range of other low cost AUVs which vary greatly in the way they work; namely

- ARGO float programme
- Teledyne Webb Research Gliders
- Liquid Robotics Inc Wave glider
- YSI Eco Mapper propeller driven AUV.

If the ALAUV programme is to succeed it must deliver something which is significantly more distinctive or economic.

11.1) ARGO Floats

ARGO floats are, in the main, deployed from ships (although some have been air deployed), they carry a Sea Bird or FSI CTD to record profiles which are transmitted to base via ARGOS (Fig 11.1). The programme began in 2000 and by Oct 2007 had reached its target of deploying 3100 floats around the world. The population is now considered to be complete. In broad terms, their performance is as follows:-

- Cost — Approx £10k each
- Battery life — 5 years
- Endurance — Target of 150 x 9 day cycles
- Weight — 25kg
- Operational depth — 2000m profile
- Premature failure rate — Target of 5%.
- Cost/profile — circa $200/profile [36]

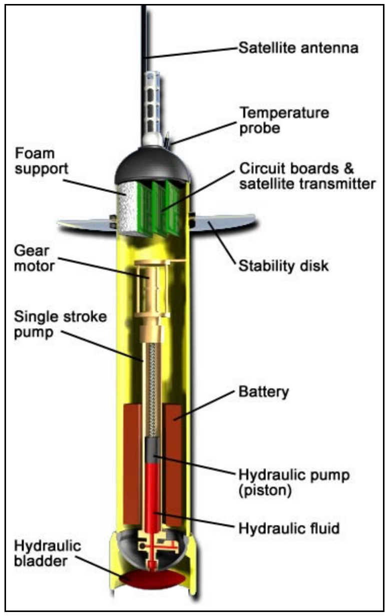


Fig 11.1 ARGO float schematic (courtesy of British Oceanographic Data Centre [BODC])

The main limitation of the vehicle is that they drift and so the survey is largely uncontrolled and this is made good by the sheer weight in numbers. The programme could not meet the demands of the applications described in section 4. Notably, ALAUVs would have the following advantages:-

- Air launched from aircraft[30]
- Capability for controlled swath surveys independent of currents
- Under ice oceanographic surveys
- Cheaper to produce
- Their smaller size means they can be launched from smaller aircraft which in turn means
    - Cheaper to operate
    - Faster to mobilise

The ARGO programme provides some useful experience on the implementation of wide scale surveys using many vehicles and possible limitations. At the 1st Euro-Argo Users Workshop, Gould presented the case that present measurements of CTD are considered generic enough to be permitted in international waters without needing permission [37]. This may change if other measurements are added e.g. the measurement of oxygen could be considered to have some economic interest if it is considered to give some measure of potential marine stocks. This is pertinent since scientists supportive of the ALAUV concept caveat their support with considerable shopping list of sensors they would *ideally* like to see on board. Additional sensors have been considered for ARGO floats, e.g. oxygen, which have not been implemented mainly on economic grounds but there could be wider issues in carrying a large number of sensors unless the surveys are in local waters or appropriate diplomatic clearances are obtained. The creation of multi sensor ALAUVs, which at

[30] Although ARGO floats are air launched, this is not routine and their larger mass (potentially 10x) makes them less convenient

the same time are still required to be semi disposable, present a considerable (insurmountable?) economic challenge and possible political headaches if fleets of them are to carry out ocean-wide surveys.

Some observations on the 1st Euro Argo Users group workshop

It is an exciting but sometimes daunting prospect when considering a new way of carrying out oceanography that will call for a quite different infrastructure. It is some comfort to observe how scientists morph into special interest groups and organise workshops, seminars conferences etc. For example, King presented a brief explanation on Delayed Mode Quality Control (DMQC), the process of quality control methods to sift bad data, potentially bad data, corrected data and upgrades of float design [38]. The message to the user was ‘be careful to understand what it is you think you are measuring’. This is a huge subject and creates its own circuit of working groups to ensure all the data centres are working consistently but:-

- The workshop did not involve engineers, their work is essentially done. The scientists arrange the conferences, workshops etc as demand requires.
- The Argo infrastructure of Data Centres and QC management could make an excellent starting point for demonstrating that data from ALAUVs can be used and can tap into a ready made and functioning structure.

11.2) Teledyne Webb Research Gliders

Glider AUVs are proving to a popular choice for Autonomous oceanography (Fig 11.2). Typically with a 1000m operational depth, they descend by means of changing their buoyancy with a buoyancy engine, as they descend they glide forward by means of wings. Once at their programmed depth, oil is pumped from the main pressure vessels into a bladder to increase the displacement (buoyancy), as they float back to the surface, again, it glides forward. Fitted with Iridium satellite transmission, the data is sent back to a land base where it can be examined, engineering data can be checked to see the vehicle is operating properly and the mission can be modified if required. Since these vehicles travel slowly, their energy consumption is low and missions can last up to many months

Fig 11.2. Fleet of three NOC Teledyne Webb gliders (courtesy of NOC)

Their range and the ‘at sea’ adaptability made possible through the Iridium connection and relatively low cost make gliders formidable instruments for basic profiling data. But ALAUVs would have the following distinctions:-

- An ALAUV would be capable of constant depth survey *(a glider must be continually profiling up and down to maintain forward motion)*. This would give ALAUVs an advantage for near surface phenomena (pollution spills, algal blooms) as well as more exotic applications such as under ice surveys.
- Able to be air launched providing the possibility of deploying several vehicles over a wide area as well as faster mobilisation.
- Better control over the vehicle’s track and heading *(the inherent slow speed of the glider makes it a little susceptible to ocean currents; a conventionally propelled vehicle provides the option of a faster survey speed to minimise the effects of currents)*
- Cheaper to produce *(present cost of a glider is circa £75k)*

11.3) Liquid Robotics WaveGlider

The Wave Glider AUV produced by Liquid Robotics (Sunnyvale, CA, USA) is unique in its operation, the propulsion is by means of wave power with a sub surface vane assembly (known as the glider) suspended deep enough beneath the floating vehicle to be largely unaffected by the wave action. As the top float heaves with the wave action, the upwards pull on the vanes produces a forward force to propel the vehicle. The sensor package (part of the submerged assembly) is solar powered from the float. (Fig 11.3)

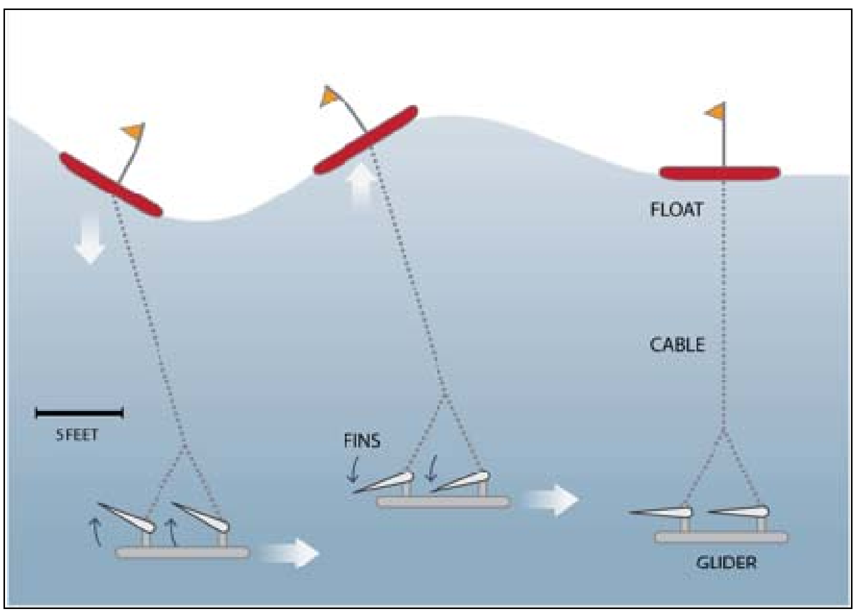


Fig 11.3. Liquid Robotics Wave Glider schematic

With the entire vehicle powered by the environment, the endurance limited only by system failure or degraded performance due to marine growth. To date some 10,000 accumulated miles have been covered by the fleet. Because Wave Glider is essentially a surface vehicle, ALAUVs would hold a number of advantages:-

- An ALAUV would be capable of surveys (profiled or at constant depth) down to its operational depth (typically 500m).
- Under ice surveys are a possibility *(Wave Glider needs open water and waves to operate)*
- Able to be air launched providing the possibility of deploying several vehicles over a wide area as well as faster mobilisation.
- Better control over the vehicle's track and heading *(the Wave Glider speed is between 0.05 and 1m/s and so has similar limitations to the Teledyne Webb glider)*
- Cheaper to produce, making an ALAUV semi disposable.
- More convenient to handle, operate and mobilise *(the Wave Glider weighs 90kg in air, 150kg displacement).*

11.4) YSI Eco Mapper AUV.

The Eco Mapper (YSI Integrated Systems and Services, Marion, MA, USA) is a more conventional AUV with propeller, rudder and stern-planes and has been chosen as being probably the most economic to procure amongst AUVs of its type. With a speed of up to 2m/s and a range of 50km, it is possible to equip it with a wide range of sensors including side scan options. Fitted with radio WiFi link and rechargeable lithium Ion batteries, it is a comprehensive package.

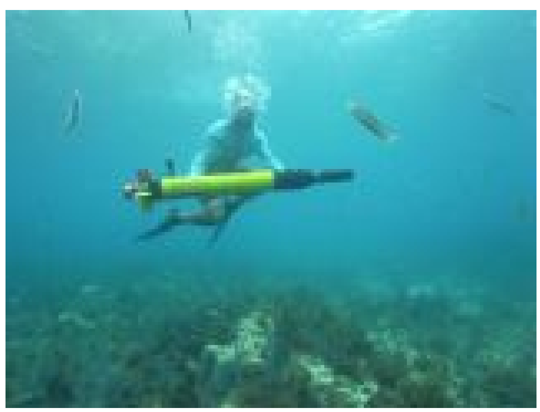


Fig 11.4. YSI Eco Mapper (courtesy of YSI Integrated Systems and Services)

The idea of the ALAUV is for it to be a stripped down AUV with limited capability (except range) so as to open up new ways of operating them. The ALAUV contrasts in the following ways:-

- Cheaper to produce by virtue of size and simplicity *(Eco Mapper is thought to be in the region of £40k although costs of AUVs are hard to come by; given the present limited sales, manufacturers prefer to quote against a specific enquiry).*
- Smaller *(Eco Mapper is 147mm diameter, 1530mm long, weighing 20.4kg in air in standard form).*
- Longer endurance *(300-400km for an ALAUV vs 50km for the Eco Mapper)*
- Semi disposable.
- ALAUVs will be designed very specifically to be simple.

12.0) Legalities

Considerable work has been done on establishing the legal status, codes of practice for the design and operation of UAVs [Appendix D and Ref 39]. While this sometimes ventures beyond the boundaries of engineering, the legal work, especially in finding precedents, help the acceptance of new technologies and their operations into the infrastructure of research centres. A preliminary report specifically for ALAUVs has been written by Dr Tsimplis, included in Appendix D. The context of this report centres mainly on the UAV phase of the operation and was written during the time when high altitude launch was being investigated. If ALAUVs are to be launched at low level from unpressurised aircraft in remote regions the risk to the operator or a third party is much reduced.

For the purposes of research and development of ALAUVs and establishing some baseline of performance, a practical approach would be to work with the aircraft operators committed to environmental research (e.g. BAS and FAAM) and be guided by their present codes of good practice and experience.

13.0) Environmental impact

If ALAUVs prove to be successful and useful in oceanographic research, there is a possibility they will be produced in their thousands. The environmental impact of these vehicles being semi disposable has to be factored into the feasibility of such a venture. There are at least two present day precedents for semi disposable instruments. The ARGO floats, much larger than the size of an ALAUV being proposed, are seldom recovered but at the end of their life are designed to work until there is no more battery life to power them back to the surface. At this point they drift in mid water until pressure case corrodes, leaks and sinks. Similarly, Sea Mammal Tags are very seldom recovered. While we cannot simply fall back on these precedents and be complacent, they do provide a good starting point. The environmental impact can be mitigated to be acceptable with appropriate design and policy at the start of the design.

- **The use of ALAUVs should result in a net gain to the environment** through providing data which helps society better understand and manage its stewardship of the oceans. This should be the primary consideration when assessing environmental impact.
- **A proportion will be recovered for refurbishment**. The approach should be to recover all ALAUVs where it is easy to do so, this could be assisted through a reward system in case they are found by fishermen. Non recovery should be because it makes little or no economic sense to recover it which invariably links in with the environmental impact. I.E. if it financially costly to recover, it is highly likely that it is also environmentally costly and the minimum impact will be to ditch it.
- **Materials will be chosen that either corrode back to their natural oxides** (e.g. aluminium, steel) or do not create a pollution hazard (including, as far as possible, the batteries). Ultimately, a design decision could be made not to anodise aluminium to encourage its degradation or use mild steel in place of stainless steel. In practice, this is likely to jeopardise the reliability too much (e.g. some corrosion would start to take place while they are in stock). In practice, soft anodised 6082 grade aluminium (a good yet cheap grade which has adequate corrosion resistance) does not present a pollution hazard. Materials considered to be pollutants should be avoided or kept to a minimum, e.g. the use of lead for trim ballast weights can and should be avoided.
- **Use of bio degradable, bio based epoxy resins for printed circuit boards and potting of electronic components**. This is of interest to the electronics industry as a whole with concerns over electronic consumer goods creating long term landfill pollution [40].
- **The vehicles are small**, much smaller than most oceanographic equipment (XBTs excepted where their impact of the copper wire and lead ballast weight has been called into question). A sense of perspective should always be held, e.g. five hundred unrecovered ALAUVs scattered over a wide area would be roughly the equivalent mass of an unrecovered mooring.

14.0) Conclusions and challenges

The advances made in the electronic sub system technologies since AUVs were first considered in the 1980s have been considerable. The size, weight, cost and power consumption (both in operation and quiescient) has dramatically reduced while their performance (especially in the realms of logging and control) has increased. In parallel with advances in commercial products, progression has been made in propulsion efficiencies and weight efficient construction, such that there is now an opportunity to make a radical reduction in size of an AUV while enhancing its usefulness through being more economic to produce, deploy and operate and retain a useful range.

14.1) Engineering challenges

This report has made the case for low level air launched AUVs but there remains a number of technical challenges which have proved to be beyond the scope of this study to resolve:-

Miniaturised, low power, low cost sensors are a prerequisite for the success of ALAUVs. While there are existing products for recording CTD which fit closely to the requirements (cost being possibly the largest hurdle), research and development for other sensors have some way to go before being considered ready. Should the development of ALAUVs continue, success with ongoing research work on sensor development, at NOCs and elsewhere will be crucial (see also section 9)

Satellite communication systems do not scale with vehicle size and remain a significant cost in the list of proprietary items. In particular, the size and performance of the antennae for GPS and data transmission present problems not only for transmission performance (degraded through being potted and effects of wash-over) but also hydrodynamic performance with the size of antennae relative to the small overall size of the vehicle. On the Autosub programmes to date, these problems have been tackled in a 'needs must' way, future development needs a more focussed effort.

Parachute descent. The technical feasibility of a low level launch has been based on a simple parachute being deployed to control the descent rate before reaching the sea which then needs to become unattached. The parachute deployment is part and parcel of existing dropsonde instruments but the description of timed unravelling of bias tapes etc (section 7.1.1) suggests an element of trial and error in their development. Indeed, the rigging of the recovery lines on each of the Autosub Vehicles has been a similar process. The effort taken to get such apparently simple systems to work reliably should not be underestimated. Given that reliable deployment and jettisoning of the parachute is crucial and is outside the experience of the NOCs Autonomous Systems Group, it would be easy to underestimate the effort required for this subsystem. Approaches have been made to Dropsonde manufacturers during this phase of work to see if there is interest in collaborating on this aspect. So far the responses have been luke warm.

The fit of the dry subsystems in the pressure vessel for a dropsonde diameter ALAUV (82mm) is likely to be tight especially given that a ring stiffened vessel is required if it is to have a good mass/displacement ratio. If a system of moving battery mass is adopted to change the BG of the vehicle, it will require dry space in addition to the volume of the battery pack. The concept of an electrical chassis forming the ring stiffening structure needs to be tested, a small permanent set of the cylindrical section could irretrievably lock the chassis work inside the cylinder after it has been pressurised. **Given that the diameter, length and weight of the vehicle is the most important and an early mechanical design decision, it is important to ensure feasible values are derived**.

Economic production

Low cost production is essential to the success of ALAUVs. Industry has shown an interest in the project so far and will be an important contribution during all the development and proving phase to ensure what is being developed can be cheaply produced and marketed

The conclusion of this study is that the ALAUV concept is feasible and opens the way for new applications, new ways of working with AUVs. Avenues for funding hardware development and marketability should be actively explored to address the challenges described and embark on a programme to produce a prototype system.

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Appendix A

Civilian Aircraft used for research in Europe and the USA
(Summary reproduced from E Higgins MSc thesis High Altitude Air-Deployed AUVs August 2007).

	Aircraft	Operator	Payload (kg)	Range (km)	Ceiling (m)
	De Havilland Twin Otter	BAS (British Antarctic Survey)		1437	8100
	De Havilland Dash 7		5280	4000	6700
	DASSAULT FALCON 20 E-5	DLR (Deutsches Zentrum für Luft- und Raumfahrt) (German Aerospace Centre)	1400	2780	12800
	CESSNA C-208 B Grand Caravan		500	1000	5500
	Cessna Citation II	NLR (Nationaal Lucht- en Ruimtevaartlaboratorium) (National Aerospace Centre)	1300	3000	13100
	Learjet 35A	Enviscope GmbH	1000	3400	13700
	BAe146-300	FAAM (Facility for Airborne Atmospheric Measurements)	4000	3700	8800

	Aircraft	Operator	Payload (kg)	Range (km)	Ceiling (m)
	ATR42-320	Service des Avions Francais Instruments pour la Recherche en Environnement	100	2200	7600
	Dornier 228-101	NERC (Natural Environment Research Council)	500	1600	7600
	CASA C-212-200	Instituto Nacional de Técnica Aeroespacial	2800	1760	7600
	Caravan I 208	Geological Survey of Finland	1196	1710	7700
	Cessna Beechcraft C-90	Tel Aviv University	1000	2235	8800

	Aircraft	Operator	Payload (kg)	Range (km)	Ceiling (m)
	Lockheed WP-3D Orion		28000	7000	8200
	Gulfstream Jet Prop Commander 1000		350	3200	10700
	Lake Seawolf LA-27	NOAA (National Oceanic and Atmospheric Administration)	181 (under wing)	2800	6000
	Gulfstream IV-SP (G-IV)			7000	13700
	Rockwell Aero Commander (AC 500 S)			1600	5500

Appendix B

Derivation of ALAUV Airborne Gliding Estimates

From the equilibrium of forces in FigB.1 at a normal to direction of flight

$$D = mg.\sin\alpha \qquad \text{(Eqn 1)}$$
$$L = mg.\cos\alpha \qquad \text{(Eqn 2)}$$

Dividing (1) by (2)

$$\tan\alpha = D/L = Glide.Angle \qquad \text{(Eqn 3)}$$

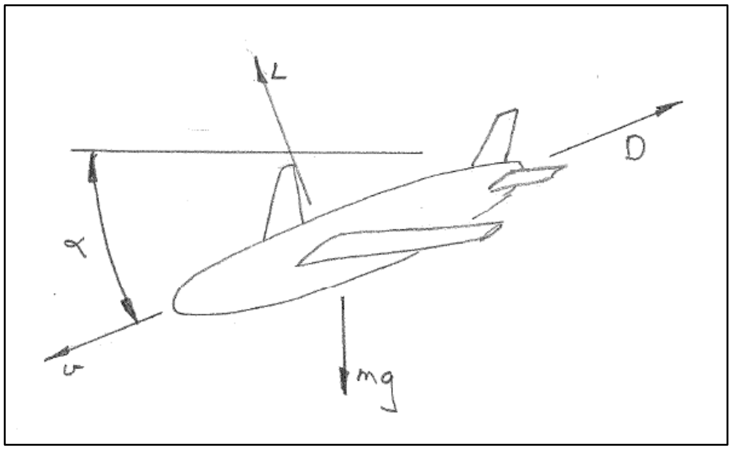

Fig B.1 Essential forces on air vehicle during gliding

From the scaling equations for lift and drag using empirical Coefficient of lift (Cl) and Coefficient of drag (Cd)

$$D = \frac{1}{2}.\rho.CdV^{2/3}.v^2$$
$$L = \frac{1}{2}.\rho.Cl.A_w.v^2$$

D	= Drag
L	= Lift
ρ	= density of air
Cd	= Coefficient of drag
V	= Volume of vehicle
v	= velocity
Cl	= Coefficient of lift
A_w	= Plan area of wings

suffix b = body
suffix w = wing

For the purposes of estimating the glide of a small winged vehicle, we will split the drag into components of body drag and wing drag. It is convenient to scale the body drag to $V^{2/3}$ with the appropriate coefficient of drag for the body Cd_b

For the wings, the commonly accepted scaling area for both Cd_w and Cl_w is the plan area of the wing, so, the total drag is expressed by

$$D = \frac{1}{2}.\rho.v^2.(Cd_b.V^{2/3} + Cd_w.A_w)$$

And glide angle α is given by

$\alpha = \tan^{-1}[(Cd_w.A_w + Cd_b.V^{2/3})/Cl_w.A_w]$ **Used in section 6 to estimate glide angle and range.**

Resolving forces in the vertical plane:-

$$\frac{1}{2}\rho.v^2.[Cl_w.A_w.\cos\alpha + (Cd_w.A_w + Cd_b.V^{2/3}).\sin\alpha] = mg$$

Rearranging to solve for v,

$$v = \sqrt{\frac{2.mg}{[(Cl_w.A_w.\cos\alpha) + (Cd_w.A_w + Cd_b.V^{2/3}).\sin\alpha]}}$$

Used in section 6 to solve for glide speed

Appendix C

μSub Data sheets of potential sub-systems

PNI – TCM5LT

360˚ Tilt Compensated 3-axis Compass Module

General Description

The TCM5LT uses advanced algorithms, with hard iron and soft iron corrections, to provide highly accurate heading information, in **any orientation**. This is accomplished by integrating 3-axis magnetic field sensing, 3-axis tilt sensing, and compass heading into a single module. The output information of the unit will indicate accurate attitude position (X, Y and Z coordinates) of the module and can be used in systems requiring full 360° rotation. Advanced electronics and built in algorithms counter the effects of hard and soft iron interference, making the TCM5LT accurate in most any environment. PNI's patented Magneto-Inductive (MI) sensors and pioneering processor technology combine to provide all this performance under a low power budget that extends mission duration.

The magnetic sensors and accelerometers are calibrated to operate from -40 to 85°C; hence the measurement is very stable over temperature and inherently free from offset drift

Features

- Tilt compensated compass heading over full 360° rotation
- High accuracy compass heading: 0.3°
- Ultra low power (sleep) mode: 85-220 µA
- High resolution: 0.1°
- High repeatability: 0.05°
- Multiple measurement modes: Compass heading, magnetic field and tilt
- Calibrated field measurement range: ±125 µT (± 1.25 Gauss)
- High resolution field measurement: 0.05µT (0.0005 Gauss)
- Advanced calibration: Hard and Soft Iron
- Compact size: 3.3 x 3.1 x 1.3 cm
- Calibrated magnetic field intensity in 3 dimensions.
- Data output via logic level using a binary high performance protocol for superior data integrity and scalability
- Improved start-up time over the TCM5L: 40-70 mSec from power down for valid measurement; 10-25 mSec from power down to power up acknowledgement.
- Simplified calibration routine requiring only 12 calibration points available for difficult to maneuver applications

Ordering Information

NAME	Part Number	Package
TCM5LT	12720	Each

133 Aviation Blvd., Ste. 101; Santa Rosa CA 95403-1084 USA

For more information, please call PNI Corporation direct at (707) 566-2260, email: sales@pnicorp.com, or visit PNI's website at http://www.pnicorp.com

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PNI – TCM5LT 360˚ Tilt Compensated 3-axis Compass Module

Parameter	TCM5LT	Units
Heading Specifications		
Accuracy with <70° of tilt	0.3°	Deg RMS
Accuracy with >70° of tilt	0.5°	
Resolution	0.1°	
Repeatability [1]	0.05°	
Max Dip Angle w/ accuracy	85°	Deg
Magnetometer Specifications		
Calibrated Field Measurement Range	± 125	µT
Magnetic Resolution	± .05	
Magnetic Repeatability	± 0.1	
Tilt Specification		
Pitch Accuracy	0.2°	Deg RMS
Roll Accuracy	0.2° for Pitch < 65° 0.5° for Pitch < 80° 1.0° for Pitch < 86°	
Tilt Range	± 90° pitch ± 180° roll	Deg
Tilt Resolution	< 0.01°	
Tilt Repeatability [1]	0.05°	Deg RMS
Calibration		
Hard Iron Calibration	Yes	
Soft Iron Calibration	Yes	
Mechanical Specifications		
Dimensions (L x W x H)	3.3 x 3.1 x 1.3	cm
Weight	12	grams
Mounting Options	Screw mounts/standoff Horizontal or Vertical	
Interface Connector	4-pin	
I/O Specifcations		
Latency from power-down to valid measurement	≤ 70	mSec
Latency from power-down to power-up	≤ 25	
Maximum Sample Rate	20	samples/sec
UART Communication Rate	300 to 115200	baud
Output Formats	Binary High Performance Protocol	
Power Specifications		
Supply Voltage	3.3 to 5.5 (unregulated)	VDC
Current Draw – Poll mode	11.5 RMS	mA
Current Draw – Push mode	7.2 RMS	
Idle Mode	7.2 – 11.5	
Sleep Mode	85 – 220	µA
Environmental Specificaions		
Operating Temperature	-40° to 85°	C
Storage Temperature	-40° to 85°	
Shock	Up to 2500 G's per MIL-STD-810F	
Vibration	Qualified to MIL-STD-810F	
Humidity	Non-condensing/Qualified to MIL-STD-810F	

[1] Repeatability is based on statistical data at ±3 sigma limit about the mean

PNI 133 Aviation Blvd., Ste. 101; Santa Rosa CA 95403-1084 USA

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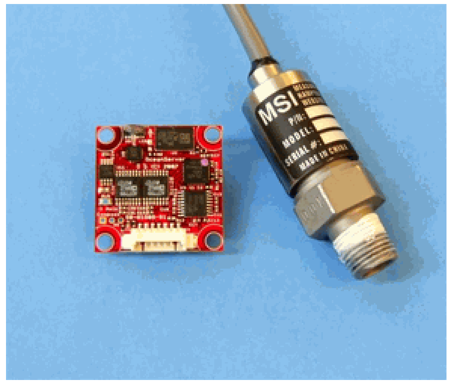
PNI-TCM5LT Compass module used in the Autosub Long Range

Ocean Server Technology Inc. OS5000-USD 3 Axis Digital Compass data sheet



OS5000-USD 3 Axis Digital Compass, shown with depth sensor (not included)

The OS5000-USD is an extremely small form factor (1.0” x 1.0”) 3 axis, tilt compensated digital compass. The flexible design allows customers to use either a USB or RS232 Serial connection for system integration. The OS5000-USD provides precise heading, roll and pitch data ideal for rapid attitude measurement. The compass offers an easy to use ASCII interface which includes hard-iron and soft-iron calibration and simple data configuration for your application. In addition, the OS5000-USD can be used calculate depth using an off the shelf pressure transducer (for example MSI MSP-340 not included)

Tiny size, 1” x 1”x 0.3”; weighs less than 2 grams weight.
Precision compass accuracy, 0.5 deg RMS Level Heading, 1° Typical RMS accuracy at < ± 30°tilt, 1.5° at < ±60° tilt. 1 Degree Resolution.
Roll & Pitch full rotation operation.
Typical 1° accuracy < ± 30° tilt.
Tilt-compensated (electronically gimballed).
Low power consumption, <30ma @3.3V, 35ma running in USB.
Hard and soft-iron compensation routines.
Support for a high resolution depth or altitude sensor (24 bit A/D).
Serial Interface: RS232 or USB.
50 MIPS processor supporting IEEE floating point math.
Baud rate programmable: 4,800 to 115,000 baud.
Rugged design (10,000 G shock survival).

Operating temperature: -20C to 70C (Specified accuracy for OC to 50C).
ASCII sentence output in several formats; NMEA checksum.
High data update rate to 40HZ.
Support for True or Magnetic North output.
Precision components: 3 Axis magnetic sensors from Honeywell, 3 Axis accelerometers from ST Microelectronics, 24 bit differential Analog to Digital converters from Analog Devices.
USB to Serial Driver or Direct Serial Connection. USB using the Silabs CP210x chip.
USB drivers for Windows, Linux, Apple OS X.
RoHS Compliant, OS5000-USD is the next generation replacement for OS3500 and OS1500 compass boards.
Software also Downloadable from Website.

***Comparison of message-based systems** (reproduced with kind permission from Michael Prior-Jones; Annual Science Meeting 1-3rd June 2009, updated April 2010, personal correspondence March 2011)*

System	Message size	Airtime cost	Monthly price, 1 message/day	Monthly price, 1 message/hour	Terminal power consumption (during transmission)	Two-way comms?	Polar coverage?[31]	Data rate	Time to send one message	Delivery time
Iridium SBD	<340 bytes	$13/mo + $0.0015/byte[32]	$14.24 (30 bytes)	$31.48 (30 bytes – bulk tariff)	1.8W	Yes	Yes	2400bps ?	~1s	<20s
IsatM2M	25 bytes	$0.06 for 10 bytes or $0.120 for 25 bytes	$5 (25 bytes – minimum spend)	$89.28 (25 bytes)	9W	Yes	No		10s?	30s
ARGOS	32 bytes	Other stations $21/mo + $1.9/6hr slot	$81	$260	<1W	No.[33]	Yes	480bps	~1s	Up to 2hrs
		Land-based fixed stations $21/mo + $1/6hr slot[34]	$54	$151						
DCP	650 chars (roughly 400 bytes)	Free	$0	$0	50-100W	No	No	100bps	75 seconds	<1 hr
Orbcomm	<2000 bytes?	Unlimited for $60/mo	$60	$60	24W	Yes, in theory!	Sporadic	2400bps	~1 s	Up to 6hrs?
Globalstar simplex	<36 bytes	$10 - 77/mo $0.2 - /msg[35]	$30 (includes 100 9-byte messages)	$860	2.5W	No	No	100bps	<1s for 9 bytes, ~3s for 36 bytes.	< 30 minutes

[31] Polar coverage means coverage beyond the reach of geostationary satellites (i.e. latitudes higher than 75 degrees).
[32] There's a minimum fee per message of $0.04, covering your first 30 bytes. SBD also has a bulk tariff, where for $16 a month you get 12,000 inclusive bytes, subject to a minimum bill per message of 10 bytes.
[33] ARGOS currently have one two-way capable ARGOS-3 satellite in orbit, but the ARGOS-3 terminals are not on the market yet.
[34] This is the ARGOS JTA price for scientific applications. Marine animal tracking devices get a further discount – they're only billed for a maximum of 48 timeslots in a given month, regardless of how many they actually use. Argos is billed in Euros and the dollar prices here are based on an exchange rate of 1 euro = 1.4 USD.
[35] Globalstar simplex pricing by Blue Oceans. Cheaper tariffs bill in 9 byte units, bulk tariff ($77/mo) bills in 36 byte units

		Airtime charges[36]			Monthly airtime cost for…[37]					
System	**Data rate, kbit/s[38]**	**Monthly fee**	**Charged rate**	**Equivalent cost per megabyte[39]**	**1MB**	**10MB**	**100MB**	**1000MB**	**Polar coverage[40]**	**Marinised**
Iridium dialup	2.4	$14	$1/min	$58	$72	$594	$5814	$58014	Yes	Yes
Iridium RUDICS	2.4	$14	$0.65/min	$37	$51	$384	$3714	$37014	Yes	Yes
Iridium OpenPort	32,64,128	$32 - $1000[41]	$5 to $15/MB	$5 to $15	$47	$113	$625 (32kbit/s) $719 (64bkit/s)	$5000(32kbit/s) $5629 (64kbit/s) $6661 (128kbit/s)	Yes	Yes
Fleet MPDS	28,64,128[42]	$0	$34/MB	$34	$34	$340	$3400	$34000	No	Yes
Fleet 33 dialup	9.6	$0	$3/min	$43	$43	$430	$4300	$43000	No	Yes
Fleet 55/77 ISDN	64	$0	$7/min	$15	$15	$150	$1500	$15000	No	Yes
Fleet 77 ISDN2	128	$0	$12.50 /min	$14	$14	$130	$1300	$13000	No	Yes
BGAN	492[43]	$50	$7/MB	$7	$57	$120	$750	$7050	No	No
FleetBroadband	432[44]	$0[45]	$13/MB	$13	$30	$130	$1300	$13000	No	Yes
Thuraya dialup	9.6	$36	$1/min	$15	$51	$186	$1536	$15036	No	Yes
Thuraya GmPRS	15	$60[46]	$5.50/MB	$5.50	$60[47]	$88	$582.5	$5533	No	Yes
ThurayaIP	444	$550[48]	$4/MB	$4	$550	$550	***$550***	$3770[49]	No	No
ThurayaDSL	144	$0[50]	$6/MB	$6	***$6***	$60	$600	***$2400***[51]	No	Yes
Globalstar #777	9.6	$14 - $49	$1.12/min	$16	$30	***$49***[52]	$49	$49	No	Yes

[36] All prices are in US Dollars and exclude taxes. Iridium airtime was priced from NAL Research. OpenPort prices were quoted by AST. Fleet prices were from KVH. BGAN and FleetBroadband, Globalstar and Thuraya (dialup/GmPRS) prices were from Satphone. ThurayaIP and ThurayaDSL prices were from X Sat.

[37] This price is the cost per month for the data used in a given month. It includes monthly subscription charges, but doesn't include initial setup costs such as activation or SIM card fees. The figure shown in ***bold italic*** is the lowest price for that quantity of data.

[38] Figures quoted here are uplink speeds – some systems have asymmetric uplink and downlink speeds.

[39] This price shows the per-minute rates converted to per megabyte, ignoring monthly fees or any overheads like minutes used whilst establishing connections.

[40] Polar coverage means coverage beyond the reach of geostationary satellites (i.e. latitudes higher than 75 degrees).

[41] OpenPort pricing includes a data allowance as part of the monthly charge. Paying a higher monthly charge results in a lower cost per MB. 64 and 128kbit/s data rates are more expensive than the basic 32kbit/s service.

[42] MPDS operates at 28kbit/s on Fleet 33, 64kbit/s on Fleet 55 and 128kbit/s on Fleet 77. Airtime prices are the same for all three systems.

[43] Only the larger, more expensive BGAN terminals offer 492kbit/s. Cheaper, smaller ones offer lower speeds, but the airtime price doesn't change.

[44] There are currently two FleetBroadband terminals on the market. The smaller, cheaper unit offers 284kbit/s data rate. Airtime pricing is the same for both units.

[45] FleetBroadband has no monthly fee, but there's $30/month minimum spend.

[46] The $60 monthly fee includes the first 5MB of data allowance

[47] Includes the first 5MB of data allowance

[48] Entry-level ThurayaIP plan is $550 for 148MB

[49] Second-level ThurayaIP plan - $1570 monthly including first 450MB of data. Subsequent data at $4/MB. An unlimited plan is available for $9999/mo!

[50] This is the cheapest "basic" pre-pay plan.

[51] Unlimited data plan available at $2400/mo

[52] Globalstar Europe offer an unlimited burst data plan for €34.99 (=$49). This deal only applies for service within Europe.

Primary lithium battery

LS 33600

3.6 V Primary lithium-thionyl chloride ($Li\text{-}SOCl_2$)
High energy
D-size bobbin cell

Benefits

- High voltage response, stable during most of the lifetime of the application
- Wide operating temperature range *(-60°C/85°C)*
- Easy integration in compact system
- Low self-discharge rate *(less than 1 % after 1 year of storage at + 20°C)*

Key features

- Stainless steel container
- Hermetic glass-to-metal sealing
- Built-in safety vent
- Finish with or without flat positive end
- Non-flammable electrolyte
- Compliant with IEC 60086-4 safety standard and IEC 60079-11 intrinsic safety standard
- Underwriters Laboratories *(UL)* Component Recognition *(File Number MH 12609)*
- Restricted for transport *(Class 9)*

Main applications

- Utility metering
- Automatic meter readers
- Buoys
- Measuring equipment
- Industrial applications
- Professional electronics
- Marine equipment

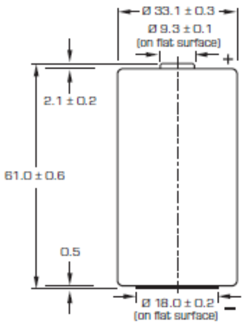
Optional upon request

- Low magnetic version

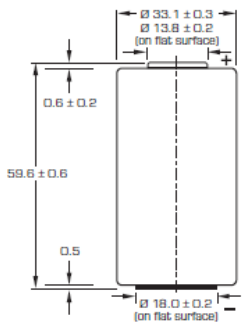
Cell size references		D
Electrical characteristics		
(typical values relative to cells stored for one year or less at + 30°C max.)		
Nominal capacity *(at 5 mA + 20°C 2.0 V cut-off. The capacity restored by the cell varies according to current drain, temperature and cut-off)*		17.0 Ah
Open circuit voltage	(at + 20°C)	3.67 V
Nominal voltage	(at 0.7 mA + 20°C)	3.6 V
Nominal energy		61.2 Wh
Pulse capability: Typically up to 400 mA *(400 mA/0.1 second pulses, drained every 2 mn at + 20°C from undischarged cells with 10 µA base current, yield voltage readings above 3.0 V. The readings may vary according to the pulse characteristics, the temperature, and the cell's previous history. Fitting the cell with a capacitor may be recommended in severe conditions. Consult Saft)*		
Maximum recommended continuous current *(to maintain cell heating within safe limits. Battery packs may imply lower level of maximum current and may request specific thermal protection. Consult Saft)*		250 mA
Storage	*(recommended)* *(for more severe conditions, consult Saft)*	+ 30°C (+ 86°F) max
Operating temperature range *(Operation above ambient T may lead to reduced capacity and lower voltage readings at the beginning of pulses. Consult Saft)*		- 60°C/+ 85°C (- 76°F/+ 185°F)
Physical characteristics		
Diameter (max)		33.4 mm (1.32 in)
Height (max)		60.2 or 61.6 mm (2.37 in or 2.42 in) depending on finish type
Typical weight		90 g (3.2 oz)
Li metal content		approx. 4.5 g
Available termination suffix	CN, CNR	radial tabs
	CNA (AX)	axial leads
	FL	flying leads... *etc.*

July 2010

LS 33600



Finished version with protruding positive end cap



Finished version with flat positive end cap

Dimensions in mm.

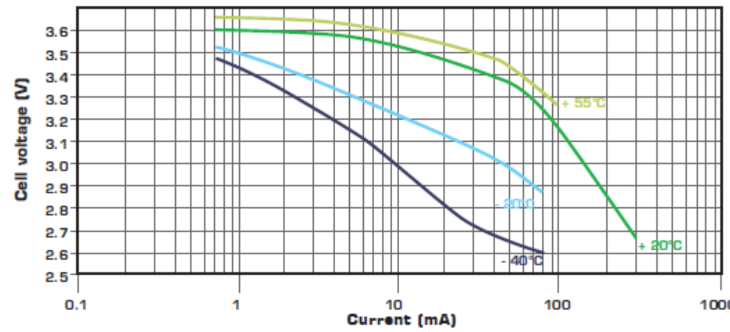
Storage

- The storage area should be clean, cool *(preferably not exceeding + 30°C)*, dry and ventilated.

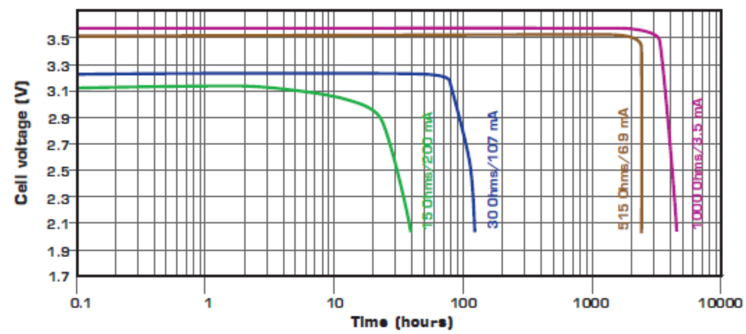
Warning

- Fire, explosion and burn hazard.
- Do not recharge, short circuit, crush, disassemble, heat above 100°C *(212°F)*, incinerate, or expose contents to water.
- Do not solder directly to the cell *(use tabbed cell versions instead)*.

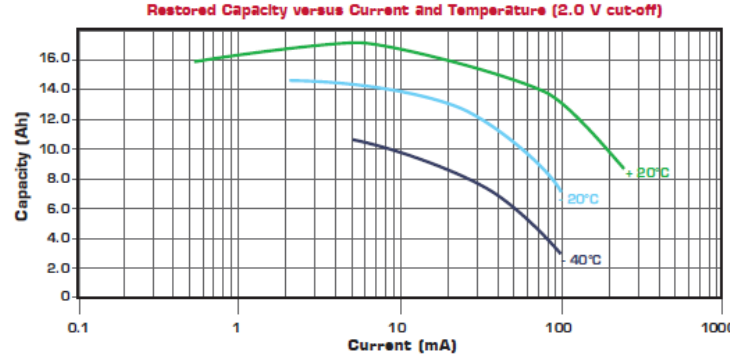
Voltage plateau versus Current and Temperature (at mid-discharge)



Typical discharge profiles at + 20°C



Restored Capacity versus Current and Temperature (2.0 V cut-off)



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Doc. N° 31007-2-0710

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For more details on primary lithium technologies please refer to Primary Lithium Batteries Selector Guide Doc N° 31048-2.

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Appendix D

Preliminary report on the Legal issues related to the release of unmanned air vehicles (UAV) from aircraft carrying autonomous oceanographic instruments.

Mikis Tsimplis and Alexander Sandiforth, Institute of Maritime Law, University of Southampton

Introduction

This preliminary report provides a general background on the legal issues that need to be explored in order to assess the feasibility of the use of UAVs for marine research. The report does not resolve in detail the legal issues but will hopefully assist in deciding whether there is a need for a scoping study in the legal aspects of the use of UAVs.

There are a number of legal issues that can be identified in relation to the proposed activity. These can be categorised into issues related to the operation of the UAVs in the air and in the marine environment. The operation of the UAVs in the air raises issues related to:

1. The legal character of a UAV.
2. The launching requirements
3. Potential civil and criminal liability arising from collision with an object on land or at sea.
4. Potential civil and criminal liability arising from collision while descending through the air,
5. Their operation as measuring devices while descending through the air.
6. The environmental impacts.

The operation of the UAVs after they reach the ocean surface includes:

7. The legal character of the marine part of a UAV.
8. Potential civil and criminal liability arising due to their navigation/drifting in the various sea areas.
9. Their operation as measuring devices in the sea.
10. To their environmental impacts.

These categories of issues identified above involve aspects of national as well as international law.

In particular the operation of UAVs raise questions of international law in respect of:

a. the character of these objects under international law
b. the existence of a right or a prohibition to launch such objects over the EEZ and the High Seas,
c. the existence of a right to conduct scientific research in the air space and the various oceanic jurisdictional zones.

1. The legal character of a UAV.

Whether a UAV can be considered an aircraft suitable or capable under present provisions for registration would determine a number of issues[53]:

-First whether the construction standards of UAV should be consistent with those prescribed for kites, sailplanes or other aircraft.

-Second whether a certificate of airworthiness would be required.

-Third whether permission for a flight would be needed for each UAV separately.

-Fourth in identifying the person to whom liability for damages may attach.

Under EC Regulation 1592/2002 Annex II (b) aircraft "specifically designed or modified for research, experimental or scientific purposes, and likely to be produced in very limited numbers;"[54] are excluded from the application of the EC Regulation 1592/2002 and from the requirements for certification. However this particular provision probably refers to manned aircraft. For unmanned aircraft and gliders there is a list of further exclusions which suggests that provided the weight of the UAVs kept within the limits specified (less than 75kg) they would arguably not be under the requirements of the EC Regulation 1592/2002. [55]

2. Launching of objects from aircraft.

Art.8 of the Chicago Convention on International Civil Aviation states:[56]

> *No aircraft capable of being flown without a pilot shall be flown without a pilot over the territory of a contracting State without special authorization by that State and in accordance with the terms of such authorization. Each contracting State undertakes to insure that the flight of such aircraft without a pilot in regions open to civil aircraft shall be so controlled as to obviate danger to civil aircraft.*

Thus UAVs cannot be flown without permission by any of the contracting States and the responsibility for safety is with each contracting State.

The permission requirements are regulated through national and European law. In the UK the Air Navigation Order 2005[57] regulates the operation of aircraft as well as

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[53] The legal basis is (EC) Regulation No 1592/2002 on common rules in the field of civil aviation and establishing a European Aviation Safety Agency.
[54] It is unclear what "very limited numbers" means.
[55] (EC) Regulation No 1592/2002 Annex II (g) unmanned aircraft with an operating mass of less than 150 kg; (h) any other aircraft with a total mass without pilot of less than 70 kg.
[56] Signed 7 December 1944.
[57] SI 2005/1970

kites. European Law directly applicable in the UK[58] also provides restrictions and requirements on the operation of aircraft.

If the UAVs characteristics do not permit their exemption from the EC regulation 1592/2002 then permission for flying would be required and this would be subject to the existence of a airworthiness certificate. Requirements under the 1944 Chicago Convention, related to navigation in air would need to be fulfilled.[59]

If the UAVs are exempted from the application of EC Regulation 1592/2002 then they could[60] be considered as articles dropped from an aircraft. Article 66(1) and (2) of the Air Navigation Order 2005 prohibit the dropping of articles from aircraft.

In particular Art 66(1) states:

> *Articles … shall not be dropped, or permitted to drop, from an aircraft in flight so as to endanger persons or property.*

This by itself is not a total prohibition of dropping of articles but must not endanger persons or property when dropping of an article takes place.

Art. 66(2) prohibit, subject to some exceptions, the dropping of articles from aircrafts flying over the UK. Presumably this would include the UK territorial waters. Special activities like the dropping of articles for the purposes of public health or as a measure against weather conditions, surface icing or oil pollution, or for training for the dropping of articles for any such purposes, and of wind drift indicators for the purpose of enabling parachute descents are permitted provided that these articles are dropped with the permission of the Civil Aviation Authority (CAA).[61]

The restrictions will apply for launches of any aircraft registered in the UK anywhere in the world[62] and to aircrafts taking off from UK. Aircraft overflying the UK will be subject to the restrictions if they launch UAVs while overflying UK territory.[63]

Thus launching of UAVs is not permissible at the moment in the UK. It is also clear from the structure of the Civil Aviation Act that prior authorisation from CAA would be necessary for such launches and that the CAA does have authority to permit such launches.[64]

---

[58] Commission Regulation (EC) No 1702/2003 of 24 September 2003 laying down implementing rules for the airworthiness and environmental certification of aircraft and related products, parts and appliances, as well as for the certification of design and production organisations.

[59] These would include requirements of construction, safety of navigation, including navigation lights communications as well as licensing of the "pilots" of the UAVs.

[60] If the UAV are self-propelled and weight more than 7 kg they would probably fall under the definition of "small aircraft" and be subject to s. 98 of the Air Navigation Order 2005. Permission by the Civil Aviation Authority (CAA) would in that case be needed if the flying height is in excess of 400 ft.

[61] The Air Navigation Order 2005, s. 66(3)(f,g).

[62] The Air Navigation Order 2005, s. 149(1).

[63] Even if they are just passing through the UK airspace s. 150 of the Air Navigation Order 2005.

[64] The Air Navigation Order 2005, s. 153.

If the aircraft takes off from somewhere other than the UK the law of the country where the plane took off would apply unless it is a UK registered aircraft in which case the Air Navigation Order 2005 would also apply. It is expected that similar to the UK restrictions will be in force in other countries a public policy/safety point of view.

There is a report by CAA titled "CAP 722- Unmanned Aircraft System Operations in UK Airspace – Guidance" which provides information for the users of UAVs and the requirements for registration and operation of such instruments.

3. Potential civil and criminal liability arising from collision with an object on land or at sea.

In the UK civil liability for surface damage caused by aircraft is currently governed by the Civil Aviation Act 1982. This includes liability for objects that have been dropped from an aircraft. The CAA 1982 introduces a regime of strict liability to the owner of the aircraft.[65] A claimant, therefore, only needs to prove that the damage suffered on the surface and that the damage itself has been caused by an aircraft in flight or by an object falling from it. There are no financial limits which attach to this liability. The liability regime applies to incidents in the UK territorial waters.[66]

Internationally, the liability regime which governs damage caused by aircraft to third parties on the surface finds its basis in the Rome Convention of 1952. [67] This introduces strict liability[68] on the aircraft operator.[69] Thus there is no need to prove negligence on behalf or the aircraft owner operator or crew. The Convention only applies to damage caused on the surface of one Contracting State by an aircraft in flight registered in another Contracting State.[70] However the Convention specifies that ".. a ship or aircraft on the high seas shall be regarded as part of the territory of the State in which it is registered".[71] The liability under the Convention is limited. The 1978 Montreal Protocol introduces maximum liability in respect of personal injury or loss of life was limited to 125,000 SDRs.[72] The liability for property damage depends on the size of the aircraft.[73] Thus, if the UAV is considered as an object falling from an aircraft limitation of liability in respect of property damage would depend on the size of the launching aircraft. If the UAV is, due to its physical characteristics subject to independent registration and therefore an independent aircraft, limitation of liability may be apply to each of them and the registered owner will face strict liability.

[65] Civil Aviation Act 1982 s. 16
[66] Civil Aviation Act 1982 s. 106
[67] CONVENTION ON DAMAGE CAUSED BY FOREIGN AIRCRAFT TO THIRD PARTES ON THE SURFACE, SIGNED AT ROME, ON 7 OCTOBER 1952 (ROME CONVENTION 1952) and its Montreal Protocol 1978. The Protocol entered into force in July 2002.
[68] Rome Convention 1952 Art.1.
[69] Rome Convention 1952 Art.2. There is a presumption that the registered owner is the operator under Art. 2(3).
[70] Rome Convention 1952 Art. 23(1).
[71] Rome Convention Art. 23(2).
[72] Montreal Protocol, 1978 art. 11(2).
[73] Montreal Protocol, 1978 art. 11(1)

At this stage we do not consider criminal liability. Note though that breaches of the Air Navigation Order are punishable by fines and, of course loss of life or personal injury may incur criminal charges under criminal law.

The applicable criminal law would most likely be that of the country in which the aircraft is registered.

4. Potential civil and criminal liability arising from collision while descending through the air.

Neither the 1952 Rome Convention[74] nor the Civil Aviation Act 1982[75] will apply to collision of an object dropped by an aircraft with another aircraft. However s. 66(1) of the Air Navigation Order, 2005 could potentially be the basis for civil liability where there is the release of an object from an aircraft.

The common law principles of negligence could be an alternative basis for claiming damages. There has been one recorded case where a release of an aerial torpedo hit a yacht. In that case liability was admitted.[76]

Criminal liability has not been dealt with at this stage. Note though that breaches of the Air Navigation Order are punishable by fines and, of course loss of life or personal injury may incur criminal charges under ordinary criminal law.

5. Issues related to the operation of atmospheric or oceanic measuring devices while descending through the air.

If the UAVs are equipped with measuring through the atmosphere or the atmospheric boundary layer they will need permission for measuring if they are released over the territorial sea. However outside the territorial sea waters research is effectively unregulated.

6. Environmental impacts.

Environmental laws will be applicable. However, unless the UAVs do not have a self-propulsion system and do not release materials in the atmosphere their operational environmental impacts are not expected to be important.

Notably is to be expected that some environmental impact assessment will need to take place in view of the risks and liabilities arising from collisions with aircraft or ships.

Environmental impacts are better discussed in respect of the marine environment.

[74] Article 24.
[75] There is a specific requirement in Art. 76(2) that the "damage is caused to any person or property on land or water".
[76] *Piper v Darling* (1940) 67 Ll L Rep 419.

7. Issues related to the operation of UAVs after they land on the sea surface and become AUVs or ocean gliders.

A comprehensive report on legal issues related to AUVs has been provided in Brown and Gaskell (1999).[77] There have been some small changes in relation to the legal problems posed by the use of ARGO floats, however the major parts of the analysis and conclusions of that report remain robust. Thus it is considered that only a small part of re-analysis is required for this respect.

8. Conclusions

The development of a marine (or air/sea) observational system deployed through gliders or UAVs from an aircraft involves several legal issues related to permits, licensing and operation of the systems.

In addition issues related to liabilities arising from the deployment of such a system have been identified. Whether the liability will attach to the owner of the UAVs or to the launching aircraft or both depends on the applicability of the various conventions and on the legal character of the UAV which, in turn may depend on its physical characteristics and in particular its weight.

Finally the requirements and the liability provisions may vary depending on the area of the oceans were deployment will take place.

[77] REPORT ON THE LAW RELATING TO AUTONOMOUS UNDERWATER VEHICLES, NOC.