

Design Considerations of Submersible Unmanned Flying Vehicle for Communications and Underwater Sampling

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I. ABSTRACT

This study examines considerations for a submersible unmanned flying vehicle (SUFV) capable of collecting water samples from seas and rivers, and providing unique operational communications capabilities. The chosen design, the Cormorant, a quadrotor capable of operating in both air and water, is sized to meet the anticipated mission profiles. The proposed proof of concept design shows potential at delivering sensor data more quickly and reliably than current approaches. Also presented are details on the propulsion system design options, configuration, and adaptability of the components to both air and underwater environments. Critical to the proposed design is the capability of the vehicle to quickly submerge at different depths and maintain location while measurements take place. A ballast system is proposed for depth control, while rotors provide propulsion to maneuver and change attitude. Once measurements are collected, the vehicle is capable of surfacing and taking off to fly to a new target location, communicate and/or relay data, or fly back to deliver the data to base. Delivering the sensor data can be accomplished by communicating via both acoustic and radio frequency (RF) communications, and flying to heights and ranges where RF attenuation effects due to atmospheric conditions are minimized.

II. INTRODUCTION

Taking water samples along rivers and lakes may be an arduous process and can take extended lengths of time and manpower. Current technology may also hinder what is attainable for an oceanographer. To sample water along a river, certain methods are currently used as noted in Ore et al. [1], grab sampling (technician grabbing sample), statically deployed systems, autonomous surface vehicles (ASVs), and autonomous underwater vehicles (AUVs). These methods are not ideal for many scenarios due to additional manpower required, slow speeds, and/or spatial restrictions. For instance using an AUV along a river might be restricted if changes in depth restrict its motion or if obstructions block the waterway. It would be very beneficial to be able to accommodate these instances but not this is not readily possible with current technology. Using aerial vehicle technology could help improve riverine and other water sampling methods and is a current research topic for others as well.

Ore et al. [1] used an unmanned aerial vehicle (UAV) to sample water at high spatial frequency in rivers and lakes by tethering a small pump about a meter long to collect

water. Ore et al. were mainly interested in sampling water at different points in a river and or lake(s). The tethered method restricts sampling water to relatively shallow depths. If one is interested in how water quality or properties changed over depth it would require another system.

Young [2] and Yang et al. [3] present different options that could offer the benefits of aerial coverage and water sampling. Young presents an air launched vehicle that can impact the water and then submerge as a typical AUV. This system was meant to be launched from a larger aircraft and was not meant to takeoff out of the water. Yang et al. studied a system very similar to how a Gannet bird plunges into the water. The system studied flies as a typical aircraft does but to transition into the water, much like the bird, it dynamically changes shape which allows it to plunge deeper into water. Their system was meant to be able to take-off out of the water and repeat transitions. This system has the benefits of the speed and range of an aircraft with more aerodynamic shape underwater. However the system needs to change configuration drastically which could be difficult to robustly design, resulting in a relatively complicated system.

Drews-Jr et al. [4] came up with a different hybrid water-air system which combined the propulsion systems of both UAV and AUV systems. They conducted trade studies on the efficiencies of different vehicle types in both air and water. Their conclusions pointed to a system that consisted of both drive train systems of UAVs and AUVs. When in the air, the UAV propulsion system is used. Once on the water the AUV thrusters allow downward forces to pull the vehicle under and also allow underwater navigation. From a complexity point of view this system is very good as both UAV and AUV systems are not overly complex and are rather robust. The main issue with including both is the weight penalties in the air. Carrying around additional payloads can drastically affect flight time.

In the realm of maritime, open sea environments, current remote underwater object detection and classification is typically performed by unmanned underwater vehicles (UUVs) or ASVs which either need to communicate the sensor data via acoustic or radio frequency (RF) systems. However, acoustic communications underwater affords relatively low bandwidth and is greatly affected by noise [5]. RF Signal propagation in the troposphere, the lowest layer of the Earth's atmosphere, is affected by many parameters of which the index of refraction is the most influential [6]. In maritime environments, ocean water evaporation results in the occurrence of atmospheric trapping layers. The modified refractivity profile of these trapping layers varies sharply,

as shown in Fig. 1. Evaporation duct height changes on a scale of tens of minutes to hours in coastal regions and on a scale of hours in the open ocean. These evaporation ducts result in a wave-like conduction of electromagnetic (EM) waves which can generate signal skip-zones where a signal cannot be received [7]. In [8] the benefits of unmanned

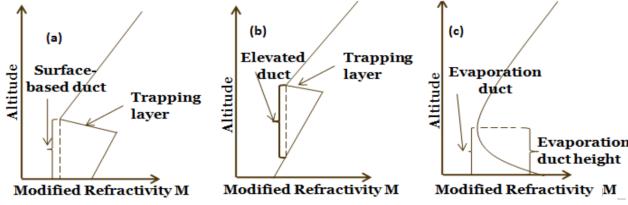


Fig. 1. Refractivity profile representations for (a) surface-based ducts, (b) elevated ducts, and (c) evaporation ducts.

surface vehicles (USV) communicating using RF from the surface to ships with higher antenna heights, as opposed to communicating with other USVs with lower antennas and within a 24 meter evaporation duct, were demonstrated. Therefore, a possible solution to RF attenuation due to maritime atmospheric evaporation duct conditions is to have an airborne unmanned flying vehicle (SUFV) that is able to relay communications between a UUV and a main ship.

For this proposed work, the main considerations were being able to quickly and effectively measure water properties along a river at different depths, and being able to fly up in the open ocean and hover to relay RF communications from a UUV to a main ship in an evaporation duct maritime atmospheric environment. It was also desired for the vehicle to be able to cover ranges on the order of 10-20 miles. This work combines both UAV and AUV technology, as Drews-Jr et al. [4] considered, but slightly different. Instead of carrying both drive-train systems, the proposed "Cormorant" submersible SUFV utilizes a buoyancy system to change depth in the water.

III. MOTIVATIONAL CASE STUDIES

In this effort we focus on two application case studies for the proposed SUFV design. The first case study involves a scenario where the vehicle needs to collect vertical columns of data from a river within a given range. The second case study involves using the proposed vehicle to help relay communications in a multi-vehicle operational environment, where underwater unmanned vehicles (UUVs) relay communications via the Cormorant vehicle back to the main ship. In each case, the benefits of the proposed Cormorant SUFV design in terms of its capability to operate underwater, on the surface, and fly and hover above the surface will be demonstrated and compared to current approaches.

For the first case study, assume the requirements are to collect data for a given range R , at some depth D . In order to collect the samples, the vehicle needs to submerge every S distance, collect water data such as temperature, salinity, and bathymetry as a function of 3D position. The mission profile for a typical UUV will involve submerging, collecting

data at different depths, moving forward to a distance S , surfacing and so on until the range R is covered as is depicted in Fig. 2 (a). For our proposed SUFV vehicle, the mission profile involves submerging, collecting data at different depths, surfacing and flying to next measurement location a distance S away and so on until the range R is covered, as is depicted in Fig. 2 (b).

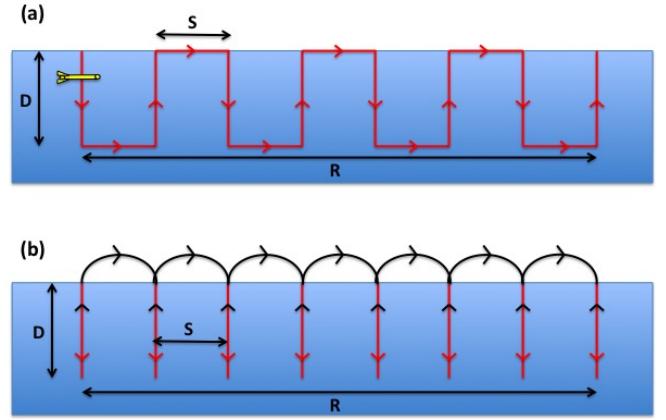


Fig. 2. Case 1 sampling scenario for (a) a typical UUV, and (b) for the proposed SUFV design.

For the second case study, the requirements are to provide underwater detection and classification of objects of interest at depths of 60 ft, representative of shallow-water regime [9]. This is also about the order of magnitude for the depth of the area of interest of river/ocean mixing. A target area (TA) is assigned to a UUV for conducting detection and classification of objects using sonar. While sweeping through the TA, the vehicle needs to communicate the sonar data back to the main ship via RF communications. However, due to an evaporation duct, there are skip zones where the UUV cannot communicate. A depiction of this case study is shown in Fig. 3. We consider a scenario where the proposed SUFV helps

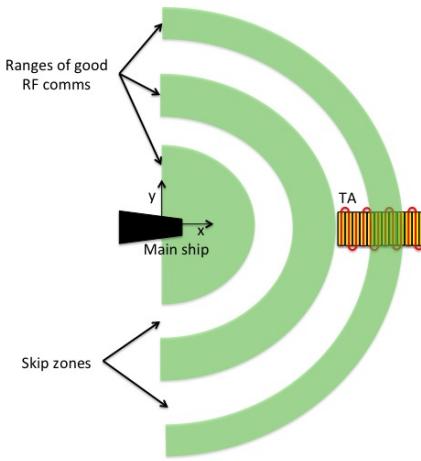


Fig. 3. Top view of case 2 scenario with ranges of good communications and skip zones between main ship and UUV.

relay communications between UUV and main ship, as is

depicted in Fig. 4. We compare the ability to communicate sonar data back to the main ship by a direct link from the UUV and using our proposed Cormorant vehicle design as a communications relay. In the next section, we consider these

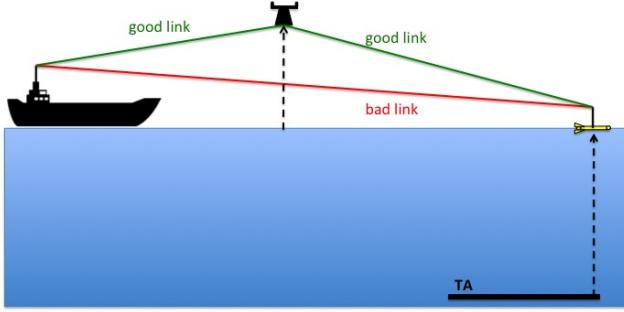


Fig. 4. Side view of case 2 scenario with main link between UUV and main ship and relay link using proposed SUFV.

two case studies for determining design considerations for a physical design that can be sized and tested.

IV. OVERALL DESIGN CONSIDERATIONS

A. Vehicle

We performed a trade study for the selection of the overall vehicle design. Among those studied were multirotors, single main rotor (SMR) and coaxial helicopters, and freewheeling vehicles [10]. The quadrotor configuration was chosen as it has the major advantage of propulsive system simplicity as compared to the other concepts. For example, the generally smaller blade diameter as compared to that of the SMR and coaxial helicopter design has operator-safety advantages. In addition, these smaller rotors may be turned underwater if needed to apply forces and moments to the vehicle in a way that would not be possible with a traditional helicopter. Also, the obvious complexity advantages in the linkage between the power plant and the propeller make the multirotor a reasonable choice. The use of a multirotor with homogenous rotors for aerial and underwater propulsion comes with several complications, including increase in power required to turn a propeller under water, which has three orders of magnitude higher density than air. Another albeit more complicated possibility is to use variable pitch propellers to lower the load when operating underwater. This of course adds the mechanical complications of such a system.

B. Sensor placement

While it is possible to do sampling with a detachable and/or slung-loaded sensor suite as referenced, the complexities associated with such a system are not attractive. The subsystem also needs to have an navigation solution

and potentially control (if imaging sonar is required, for example), adding another level of complexity. A slung-loaded sensor has additional requirements, such as a winch mechanism if depth control is desired. These may be heavy (mechanism plus tether), may jam, and may also become tangled on underwater obstructions. Slung load dynamics also may need to be considered if the load is not rigidly attached to the vehicle during use, adding further complications to such a system.

Operationally, submerging the entire vehicle has several advantages. For example, a vehicle squatting several inches below the surface may be more immune to wave action and/or environmental effects (wind, sun) than one on the surface. This may be of value for stabilizing a vehicle with a sonar imager sensitive to platform movement, or cooling motors on a hot day. Another advantage is the ability to negotiate obstacles should a complicated mission be required, such as inspecting an underwater structure where maneuvering might be required to reach areas of interest. Submerging may also allow the vehicle to operate in areas with heavy surface traffic, submerging to a safe depth while scanning or loitering to avoid collisions.

C. Depth Control

For depth control, several strategies were considered including positive buoyancy with propulsion, dive planes, compressed gas and bladder, as well as different types of pumps (peristaltic, diaphragm, stepper/piston) moving air, water, or oil. Using a positively buoyant vehicle with propulsive control for diving [11] is ruled out due to its inefficiency in required power. Making multiple measurements down to tens of feet (up to 60 ft as required for some missions to model river/sea mixing) require a more efficient depth control system. This decision also rules out the use of dive planes, as these rely on relative water velocity to function. Compressed gas and bladder (with the bladder on the external part of the vehicle) is useful in case of emergency ascent but having to replace gas canisters is undesirable for normal operation. The main disadvantage of this system is it may become the limiting factor for mission endurance. That is, it may limit the number of dives possible with the vehicle should a dense desired dive grid be required and/or an efficient propulsion system be used [12]. Different pumps moving different media are also considered. Other systems, including oil pumps may be considered in the future as well due to the relatively better incompressibility of oil, which is useful at greater depths. A stepper with a piston is also good for heavy vehicles, but has disadvantages for a SUFV. First, it tends to be heavy, requiring a rigid container and a stepper motor with associated electronics. This is not beneficial for flight endurance. Second, a stepper motor continuously draws power even if not in use, further reducing flight endurance.

D. Waterproofing

The Brushless DC motors selected are waterproof but not corrosion resistant. If they are to be used in a salty environment, they should be cleaned with fresh water and

sprayed with an anti-corrosion lubricant after each use. Motor damage may result from debris sticking between these two during operation. Salt water also presents electrical complications for exposed electronics. Silicon is used to seal through-holes and exposed terminals and electronics.

E. Submersible Prototype

For the Cormorant, the primary goal of the prototype was to test the depth control system, so the flight time was limited to only 10 minutes of hover endurance. The propulsion system was optimized using the methods described in [12]. The optimizer outputs are shown in Table I. We chose the 17 inch diameter 5.5 inch pitch propellers for additional payload capacity in case predictions were incorrect. Carbon fiber is chosen for the blade material so that, in case it is desired to turn them as underwater screws, they will not deform along or around their radial axis. In Fig. 5, the Cormorant SUFV vehicle design is shown operating underwater.

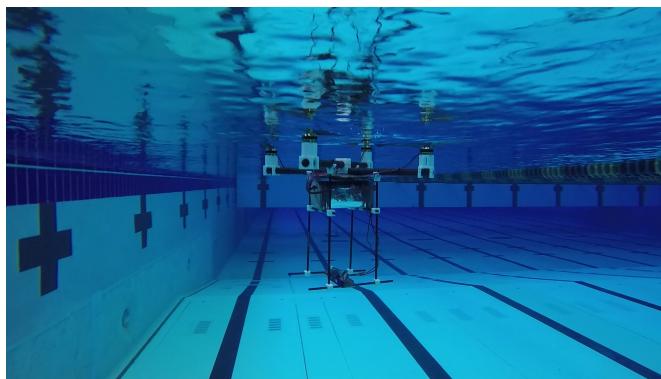


Fig. 5. Cormorant proof of concept SUFV design operating underwater. Still from <https://www.youtube.com/watch?v=U7vl7uqwN4I>

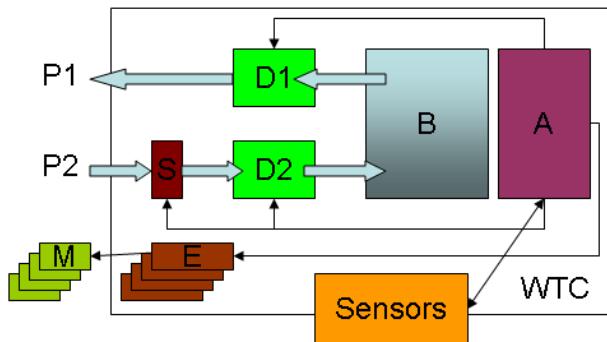


Fig. 6. Schematic of Cormorant. D1, D2 are pumps, B is a bladder, A is the avionics suite, S is a solenoid, E are ESCs, M are rotors. P1 is the ascent pathway and P2 is descent. Most electronics are contained inside the water tight compartment WTC.

Inside the water tight compartment (WTC), the avionics (box A in Fig. 6) control the vehicle's electronics. It interfaces with a receiver for manual mode, and is capable of autonomous operation. A hobby-grade 72 MHz receiver is used to allow operation in several feet of water. A more

recent hobby-grade 2.4 GHz receiver may also be used but due to the attenuation in water, its efficacy is limited to about one foot. The prototype Cormorant employs an ArduPilot (APM) with custom code. The next version will interface with a Gigabyte Brix computer for more complicated sensor processing. To fly, the APM commands the motors (M) via electronic speed controllers (E) in the standard multirotor configuration. As the vehicle lands on the water, the APM spools down the rotors. To descend, the APM commands the solenoid (S) and the diaphragm pump D2 to activate, pulling water into the bladder (B). This increases the weight of the vehicle, causing it to sink. As the vehicle descends, the APM interacts with a barometer which is modified to measure water depth. When it detects a pre-set depth, the APM closes S and D2 and waits for the next pre-set depth to enable D1 to begin ascending. If the descent rate exceeds a particular value, the rotors may be used to arrest it. As D1 empties the bladder, buoyancy overwhelms weight, and the vehicle begins to ascend.

TABLE I
OPTIMIZER OUTPUT FOR RUBBER PROPULSION SYSTEM REQUIREMENTS
FOR CORMORANT PROTOTYPE, 10 MINUTE HOVER

Parameter	Value (rubber)	Value (built)
Battery configuration	4S	4S
Battery capacity	4322 mAh	4000 mAh
Propeller diameter	16"	17"
Propeller pitch	3.5"	5.5"
RPM_{hover}	2700 RPM	2520 RPM
K_v	364 RPM/V	390 RPM/V
P_{hover}	252 W @ 14.8 V	263 W @ 14.8 V

The first system for depth control tested uses air to inflate/deflate a bag attached outside the WTC. To surface, the air is compressed from inside the WTC using an air pump, and forced out into the bag. This increases the buoyancy of the vehicle which causes it to surface. To dive, the opposite happens. In this case, a solenoid is energized, dumping the compressed air in the bag back into the WTC. This system has the drawback that should the pump fail, the vehicle may be lost. Peristaltic pumps were found to be functional to about 6-7 ft of depth in this design. It is possible to increase the efficiency of the system by allowing the WTC to have more air (less electronics) but this increases the weight of the vehicle in trimming it to be near neutrally buoyant. The second system tested uses a water bladder inside the WTC. To descend, a diaphragm pump pulls water from the environment into the bladder, and the opposite to ascend. A solenoid is required to keep water from leaking backwards through the diaphragm pump into the bladder, slowly sinking the vehicle. If this happens and the vehicle surfaces, the extra pressure inside the WTC will likely cause a blowout or a leak once the vehicle surfaces and experiences lower external pressure. One advantage of this system is that greater depths are attainable, although two diaphragm pumps and at least one solenoid are required to operate it. Another advantage of this system is no extra ballast needs to be carried, and the vehicle can trim itself to be nearly neutrally buoyant using

the water surrounding it. The Cormorant prototype was tested successfully down and back up from 21 feet of chlorinated water in this configuration, limited by the depth of the pool that was used to test it. The test was done untethered and a barometer was used to automatically detect depth and reverse the pumps to surface. The static margin, which may change as vehicle submerges due to water filling the bag inside the WTC, depends on the depth control system. The cormorant has a low-mounted battery to keep it statically stable in an upright attitude, although this may be adjusted a priori or propellers may be used underwater if necessary to change attitude.

F. Endurance prototype

As described above, the Cormorant prototype was built to refine the depth control system for a flying submersible vehicle. A larger vehicle named Eagle [12] has been built to test the "long" endurance aspect of the final Cormorant configuration; a combination of the Eagle and Cormorant prototype capable of long-endurance and diving. The Eagle is designed to have a hover endurance of over two hours. Table I shows optimization output of the two configurations. The difference between the Eagle and the final configuration is the payload/battery tradeoff. The Eagle flies a 40.8 Ah battery, while in the final configuration, half of the battery is removed and replaced by about 1.8 kg of sensors, avionics, and depth control equipment. This drops the calculated hover endurance from about 140 minutes to around 50-60 minutes.

TABLE II
OPTIMIZER OUTPUT FOR RUBBER PROPULSION SYSTEM REQUIREMENTS
FOR CORMORANT, 140/60 MIN HOVER, 0/1.8 KG PAYLOAD

Parameter	Value (rubber)	Value (built)
Battery configuration	6S	6S
Battery capacity	44378 mAh	40800/20400 mAh
Propeller diameter	30"	30"
Propeller pitch	10.5"	10.5"
$RP M_{\text{hover}}$	1400 RPM	1390 RPM
K_v	112 RPM/V	100 RPM/V
P_{hover}	417 W @ 22.2 V	409 W @ 22.5 V

V. CASE STUDIES RESULTS

For the first case study, consider a specific scenario in which a river needs to be sampled with the following dimensions and requirements: $R = 8$ mi (half of the maximum range of the Cormorant to allow for a return trip), $D = 15$ ft, and $S = 300$ ft, corresponding to 141 samples required. Next we make a comparison between time to complete the river sampling using a Remus 100 and our Cormorant design. Specifications of the Remus 100 are given in Table III [13].

Sizing the Cormorant vehicle for maximum range, replacing 1.8 kg of batteries with avionics and sampling sensors, leads to the performance metrics shown in Table IV. The sink/ascend rate varies between 1-3 ft/sec, therefore a conservative 1 ft/sec rate was chosen for analysis. The

TABLE III
REMUS 100 SPECIFICATIONS [13]

Parameter	Value
Max. depth (m)	100
Max. endurance (hr)	22
Max. range (mi)	74
Cruise speed (m/s)	1.5
Sink/ascend rate (m/s)	1

power required to dive and surface is very minimal, since it only requires inflating/deflating the ballast system with a small amount of water, and the brushed DC motors in the diaphragm pumps use very little power (on the order of 500 mA at 7 m). This accounts for about 2% of hover power, and a conservative value of 5% is used for analyses. Therefore, the maximum range for the Cormorant was for the most part restricted to power required to fly to subsequent sampling locations, and the power available from the batteries.

TABLE IV
CORMORANT SPECIFICATIONS (CALCULATED UNLESS OTHERWISE
SPECIFIED) [13]

Parameter	Value
Max. depth tested (m)	7
Dive/surface rate tested (m/s)	0.3-1
Max. range (mi)	16
Max. endurance (min)	56
Cruise speed, max. range (m/s)	7.6
Cruise speed, max. endurance (m/s)	3.1

Results show that to sample the river it would take the Remus 100 about 4.9 hr, where as it only takes 2.1 hr with our proposed Cormorant design. The better performance by our Cormorant design is mainly due to its ability to get to traverse S faster than a UUV with its ability to fly. Note however that if the mission profile requires horizontal water columns instead of vertical, the UUV clearly has the upper hand.

For the second case study, consider a specific scenario in which a TA needs to be completely covered by a UUV to detect and classify objects of interest using sonar. Assume the TA is at 60 ft deep, and the UUV needs to be able to surface at any point during the detection and classification phases to communicate sensor data to a main ship. The atmospheric conditions are such that a standard 24 m evaporation duct is present at any azimuth within 100 miles from the ship.

Lets also assume the UUV carries an RF FreeWave radio communicating at 900 MHz, with antenna height of 1.5 ft. Also assume the main ship antenna is located 70 ft above the surface of the water. For our Cormorant vehicle, assume it also communicates at 900 MHz using a FreeWave radio, and can communicate above the evaporation duct at 30 m.

Using the advanced propagation model to calculate the signal propagation loss as a function of range and height above the surface of the water, as is described in [14] and [15], the resulting propagation loss profiles for both UUV-to-Ship and Cormorant-to-Ship links are shown in Figures 7 and 8, respectively. It can be seen that greater propagation loss

is experienced when the transmitter and receiver are within the evaporation duct for UUV-to-Ship links, since the duct acts as a wave-guide for the links that are trapped within the duct, bouncing between the ocean surface and the upper layer of the duct.

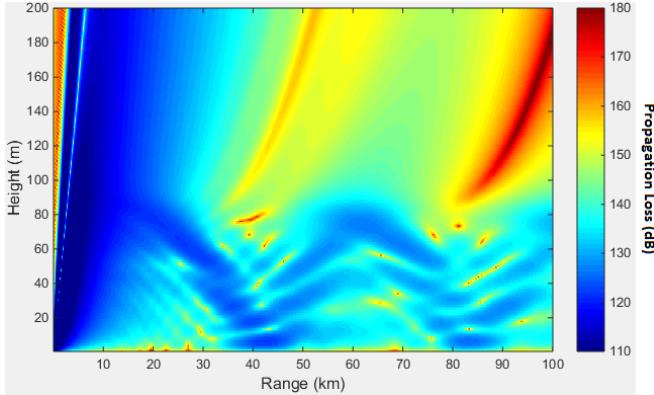


Fig. 7. Propagation Loss profiles for (a) UUV-to-Ship link in a 24 m evaporation duct.

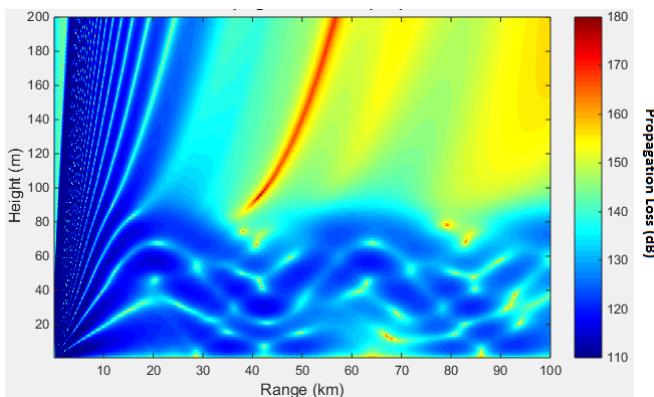


Fig. 8. Propagation Loss profiles for Cormorant-to-Ship in a 24 m evaporation duct.

We assume the receiver sensitivity to be $RS = 130$ dB of propagation loss, which is used as a threshold of communications where signal levels experiencing more than RS propagation loss are considered bad links. Using a Rayleigh distribution for the signal-to-noise (SNR) ratio of the signal, as described in [15], we can define the probability of communications as the probability that the SNR falls below the threshold value. The propagation loss at the receiver, with corresponding probability of communications for UUV-to-Ship, UUV-to-Cormorant, and Cormorant-to-Ship cases are shown in Figures 9, 10, and 11, respectively.

Assuming ranges of good communications as those for which there is $\geq 60\%$ probability that the SNR falls below the threshold value, we can calculate locations between transmitter and receiver at which good communications ranges and skip-zones are located. Shown in Figures 12, 13, and 14 are the ranges of good communications for UUV-to-Ship, UUV-to-Cormorant, and Cormorant-to-Ship links, respectively.

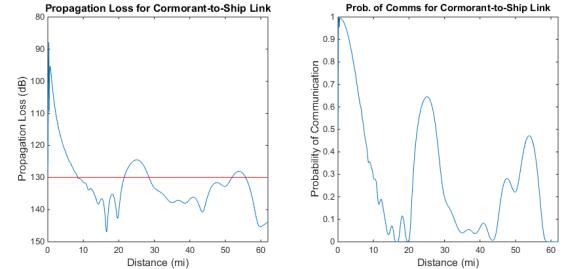


Fig. 9. Propagation loss at the receiver height and probability of communications for UUV-to-Ship link.

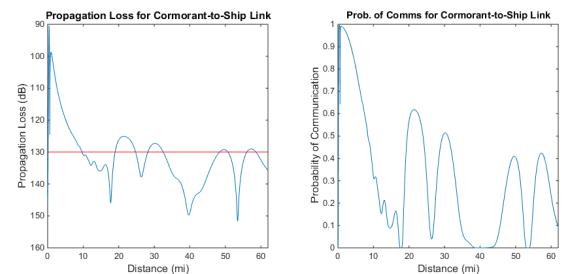


Fig. 10. Propagation loss at the receiver height and probability of communications for UUV-to-Cormorant link.

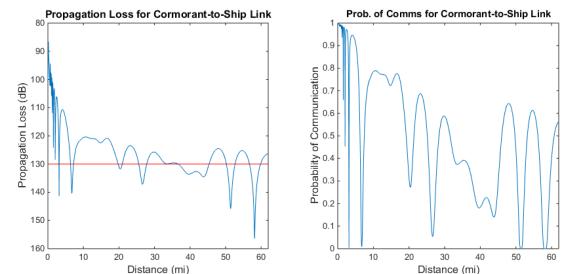


Fig. 11. Propagation loss at the receiver height and probability of communications for Cormorant-to-Ship link.

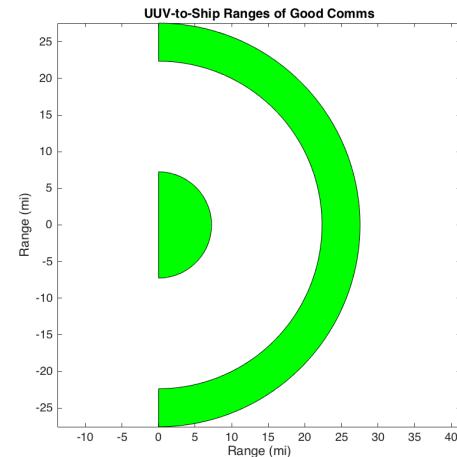


Fig. 12. Ranges of good communications and skip zones for UUV-to-Ship links.

As can be seen from Fig. 12 for the UUV-to-Ship good

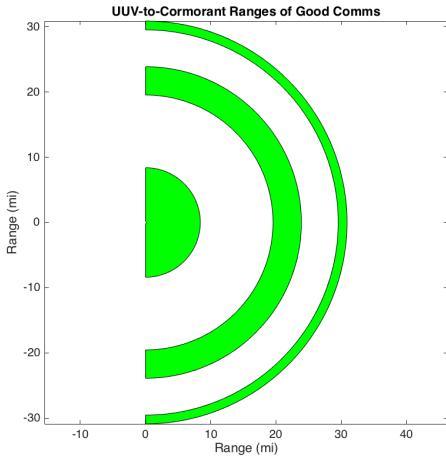


Fig. 13. Ranges of good communications and skip zones for UUV-to-Cormorant links.

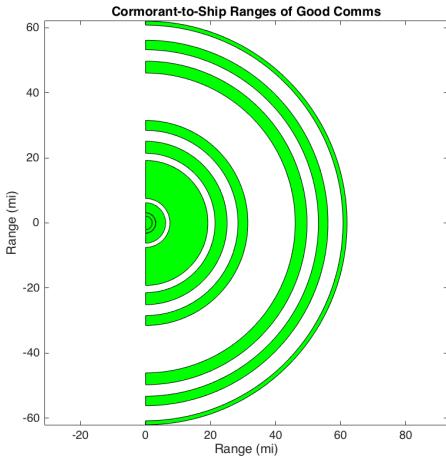


Fig. 14. Ranges of good communications and skip zones for Cormorant-to-Ship links.

communication ranges, the location of the TA is limited to lie within 8 miles from the main ship, or between 23 and 27 miles from the main ship, which highly restricts the TA ranges and UUV RF communications as it sweeps through the TA. From Figures 13, and 14, it can be seen the benefit of having Cormorant as a communications relay above the 24 m evaporation duct by allowing the TA to be at multiple ranges from the main ship, as long as the TA is within good communications ranges with the Cormorant, and as long as the Cormorant is in good communications ranges from the main ship. As a simple specific example, a TA at 20 miles from the main ship will not allow the UUV to communicate back to the ship while it sweeps through the TA. However, the same TA at 20 miles from the main ship can be located using the following configuration: place the TA 8 miles from the Cormorant vehicle, and make sure the Cormorant is 12 miles from the main ship. As the threshold of probability of communications is increased, the

ranges of good communications start to shrink, and UUV-Cormorant-Ship placement configuration possibilities start to decrease, but still provide more options than not having the Cormorant as a communications relay. The Cormorant design can also be sized for greater hover endurance for cases where the UUV needs to relay communications during further classification of objects of interest, and for cases with more than one TA.

VI. CONCLUSION AND FUTURE WORK

A design for a SUFV capable of hovering around an hour is presented. The SUFV enables riverine and maritime operations in situations not possible by using solely a UAV, ASV, or UUV by leveraging the benefits of each type of vehicle. For some conditions, the SUFV also outperforms traditional sampling methods. We show how the Cormorant design outperforms a typical UUV while sampling a river for a given range, by completing the sampling more than two times faster. We also show the benefits of the Cormorant's long hovering endurance while relaying communications between a UUV and a main ship for a given evaporation duct atmospheric environment.

In terms of vehicle design, once endurance of the system is confirmed, the depth control system and avionics/sensors will be added to the vehicle. This will allow for autonomous sampling of approximately 16 miles of water. Testing will also be done to test the depth control system beyond the 7 m limit currently imposed by depth limit of the pool used for testing.

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