Ship-Based UAV Measurements of Air-Sea Interaction and Marine Atmospheric Boundary Layer Processes in the Equatorial Indian Ocean

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A Proposal to ONR Code 322
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ABSTRACT

Just as the development of aircraft carriers in the early twentieth century revolutionized the role of the Navy by extending the reach of the surface fleet, or “projecting force”, the addition of unmanned aerial vehicles (UAVs; also known as “unmanned aerial systems”, UASs) to the oceanographic research fleet can extend the reach of research vessels and enable scientific measurements well beyond the immediate vicinity of the vessel. The basic platform capability for ship-launched and recovered UAVs already exists in the InSitu (Boeing) ScanEagle UAV which may be launched by a portable catapult system and recovered by flying into a vertical wire suspended from a “cherry-picker” crane (the “SkyHook” recovery system) over the side of the vessel (Figure 1). Developed for the military, the typical payload for the ScanEagle includes electro-optical sensors (visible and IR) or radar, which are used for detection and targeting. However, the vehicle can also be equipped with scientific payloads that can address marine atmospheric boundary layer (MABL) processes and, more generally, air-sea-wave interaction research. It is the use of these platforms and scientific payloads to enhance the capabilities of research vessels in the Coupled Air-Sea Processes DRI that is the subject of this proposal. Specifically, these capabilities include the measurement of air-sea fluxes, marine atmospheric boundary layer (MABL) variables, and surface signatures of ocean boundary layer (OBL) processes.

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VOLUME I: TECHNICAL PROPOSAL

Project Period: 2/1/11 – 1/31/13

APPROACH

We propose to deploy ScanEagle UAVs from the R/V Revelle during the Cochin-to-Cochin cruise (November 3-23, 2011, Rob Pinkel, SIO, Chief Scientist) as part of the joint field program with NOAA/NSF (DYNAMO) and International partners (CINDY 2011: Japan, India, Australia).

Air-Sea Fluxes and the Marine Atmospheric Boundary Layer

The UAVs will be used to extend the air-sea flux and MABL measurement capabilities of the R/V Revelle. For this program, flight control and data communications are limited to line-of-sight, which for a minimum altitude of 350 m above sea level (ASL) would give a 50 nm radius and for 100 m ASL a 30 nm radius. These flight zones are given as A and B, respectively, in Figure 1a, along with two sample flight plans on the right. Figure 1b shows a “sounding” flight plan with soundings to 1 km above sea level (ASL) bounding profiling to lower altitudes, while Figure 1c shows a “fluxes” flight plan with soundings to 1 km bounding a series of constant altitudes flight tracks along which eddy fluxes of momentum, sensible heat and water vapor will be measured. In keeping with the constraints on communications, the initial minimum flight altitudes will be limited to 100 m, but as experience in the field evolves during the experiment, flights to lower altitude will be conducted closer to the vessel. In particular, we will be concerned to measure the flux divergence as a function of elevation above sea level to determine the altitude bounds and errors in the constant flux assumption in the lower MABL, and the validity of Monin-Obukov scaling.

Depending on the payload (see Table 2) we expect that the UAVs will have a flight endurance of up to 6 hours at 50 knots, thus being able to cover up to 300 nm in one flight. This range will permit the aircraft to measure the spatial decorrelation scales of the air-sea fluxes and related MABL variables relative to the research vessel. One of the greatest constraints on the accuracy of predictions of air-sea fluxes and surface wave processes is the sparseness of *in situ* wind and related MABL data. The ship-based UAV capability will permit us to directly measure these decorrelation scales and place the ship-based measurements in the larger context.

Quantification of these decorrelation length scales is also important for determining the required resolution of numerical models or prediction schemes. With only time-series data at a point, or from a slowly moving platform (e.g. research vessel), spatial decorrelation scales are usually estimated from the temporal scales and mean wind speeds. Access to UAV data which can directly measure spatio-temporal scales will significantly improve the estimates of the spatial decorrelation scales, and thus the required resolution for numerical models and predictions.

Atmospheric Convection & Precipitation

While the UAVs can be programmed to fly fixed patterns for air-sea fluxes and MABL measurements as described above, one of the great opportunities for the planned cruise is the ability to use the output from the weather radar on the research vessel to determine flight tracks for the UAV in real time. For example, the weather radar will show patterns of atmospheric convection and precipitation, including the aggregation of isolated convective systems having scales of O(1-10) km into larger convective systems of scales O(100) km. Associated with these systems are patterns of precipitation leading to shallow pools of initially cooler fresh water at the ocean surface. One of the most important processes governing the growth of the convective systems is lateral entrainment, measured by horizontal entrainment velocities approaching the perimeter of the convective cell. The UAV will be able to accurately measure these velocities with its gust probe and GPS/IMU system as it circumnavigates isolated convection cells under direction from the weather radar data and the on-board (the UAV) video stream. While the UAV does not have the ability to remotely sense sea surface salinity (SSS), it can measure sea surface temperature (SST) radiometrically, either from the pyrgeometers or the IR camera. This will permit correlation of recently precipitated pools of cooler fresher water at the surface with the convective activity.[1]

The Diurnal Surface Layer

During this cruise, researchers Rob Pinkel and Jerry Smith plan to measure the evolution of the diurnal surface layer (DSL) using a tethered array of wirewalkers profiling the DSL out to approximately 2 km from the vessel, while a vessel-mounted phased-array Doppler sonar measures the vertical structure of the DSL. The DSL is a warm layer that grows to a few meters deep while it is warmed by the sun during the day and cools at night, leading to a diurnal cycle. Given the strong thermal stratification during the day much of the direct coupling of the atmosphere to the ocean may be confined to this layer for significant periods, but this can be modulated by interactions with internal waves leading to entrainment of cooler water from below and straining and mixing of the DSL (Walsh *et al.*, 1998). While the high-resolution measurements of the tethered array will be limited to horizontal scales of a few km from the vessel, the UAV measurements of air-sea fluxes, SST and surface waves related to DSL processes can extend out to ~50 km (see Figure 1). Thus flight patterns will be designed to fly out along the array and beyond in directions along the principle axis of the array and orthogonal to it.

[1] It should be stressed that due to payload limitations the full suite of instruments described in this proposal can not be flown on any one flight but would be distributed across flights. See Table 2 for examples of specific payloads.

Surface Wave Processes and Mixing

It is by now well accepted that surface wave breaking can directly and energetically mix the surface layers of the ocean down to depths of the order of the wave height, and dissipate significant turbulent kinetic energy in the process. Over diurnal surface layers (DSLs) of only a few meters deep, this means that surface wave breaking may play a significant role even for breaking waves of only a meter in height. This presents the possibility of a negative feedback mechanism. Consider a DSL that has been heated by the sun and contributes to the instability of the atmosphere. With the onset of atmospheric convection there will be surface winds associated with the entrainment into the convective cell, sometimes becoming squalls. These winds generate surface waves that grow and break, thus mixing down the warmer surface layer of the DSL and entraining cooler water from below. This would lead to a reduced SST and thereby a more stable atmospheric boundary layer. Therefore, in the context of the dynamics and thermodynamics of the DSL, we expect surface wave processes to be important. The fixed nadir looking LIDAR on the UAV will be able to measure the development of the surface wave field and visible or IR imagery will be able to identify and quantify the kinematics of the breaking. Using recent laboratory results (Drazen *et al.*, 2008) that are the basis of a breaking model, the dynamics of the breaking and its role in near-surface turbulence and mixing can be inferred.

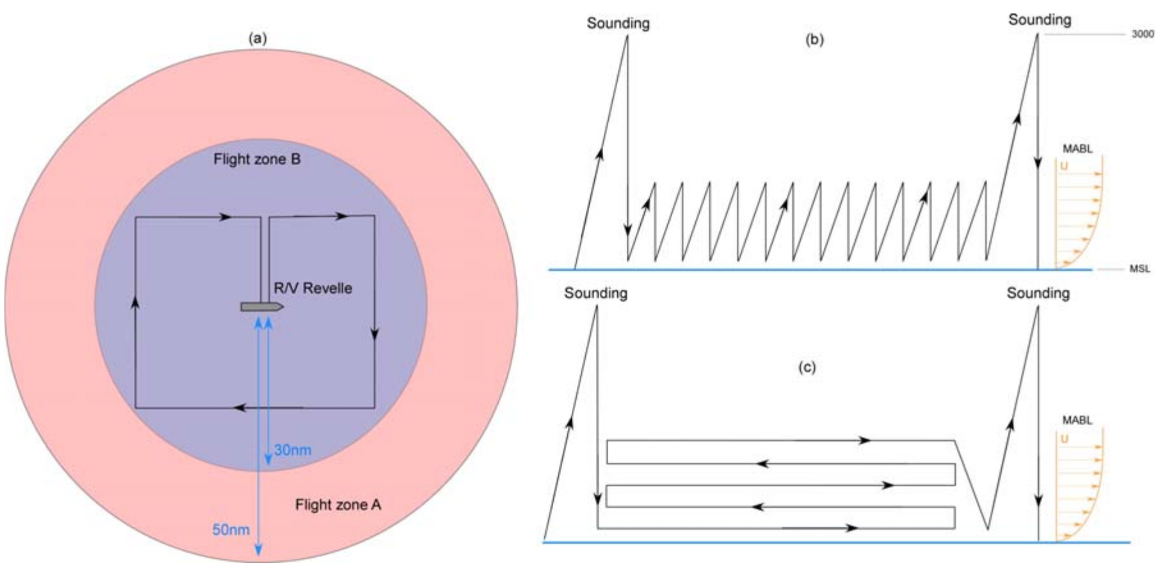

Figure 1: (a) Flight zones of the ScanEagle based on line-of-sight communications for minimum altitude of 350 m, (A), and 100 m, (B); (b) vertical section of atmospheric profiling flight plan; (c) vertical section of air-sea fluxes flight plan.

PLATFORMS & INSTRUMENTATION

In support of this proposal, Robert Bluth, the director of CIRPAS (NPS), will be submitting a proposal to ONR to provide three ScanEagles and spares from the NPS inventory, along with pilot services and launch, recovery and flight control equipment for this project.

The ScanEagle UAVs would be launched and recovered from the R/V Revelle. Figure 2a shows two elevation views of the launch equipment. Figure 2b shows potential installation sites on the R/V Revelle. The SkyHook recovery system can be suspended from a crane over the side of the Revelle. The launch and recovery equipment, designed to be installed and de-installed in the field, will take up limited deck space on the Revelle: approximately one 20’ container. Pictures of past deployment and recovery are shown in Figures 3a and 3b.

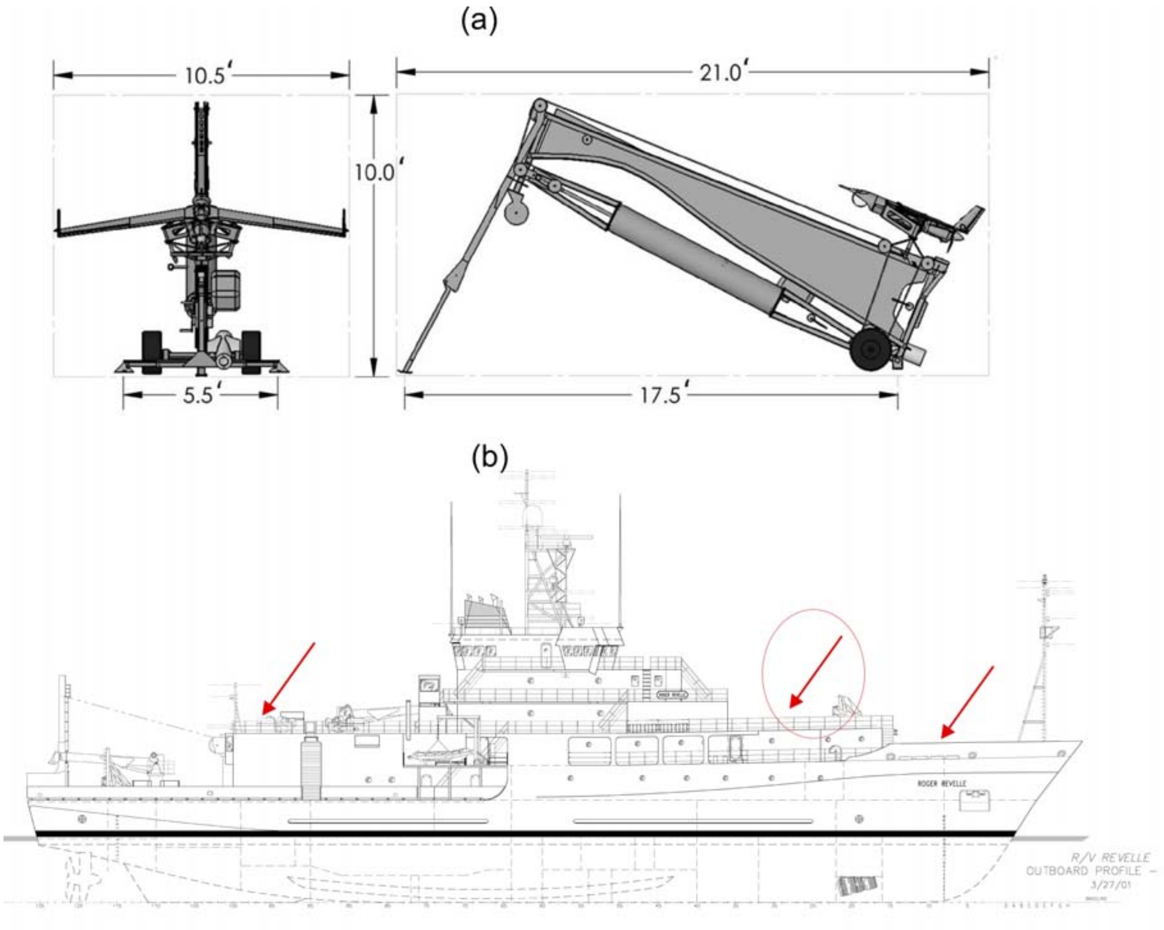

Figure 2: (a) InSitu SuperWedge Launcher and (b) its possible installation locations on the R/V Revelle – Optimal location is circled in red.

In a previous DURIP (N00014-08-1-1024) PI Melville has been funded to purchase and equip two BAE Manta C UAVs with the same class of instruments and develop a nine-port turbulence probe mounted on the nose of the UAV (Figure 4). The turbulence probe and the supporting GPS/IMU unit are the heart of the system for the measurement of air-sea fluxes. The turbulence probe measures the wind vector relative to the aircraft and by accurate measurement of the aircraft position and orientation with the GPS/IMU system permits the measurement of the wind vector in an Earth frame. The vertical fluxes of momentum, heat and moisture can then be measured using so-called “eddy correlation methods”, the average of the product of the vertical velocity with the appropriate variable (e.g. temperature for sensible heat).

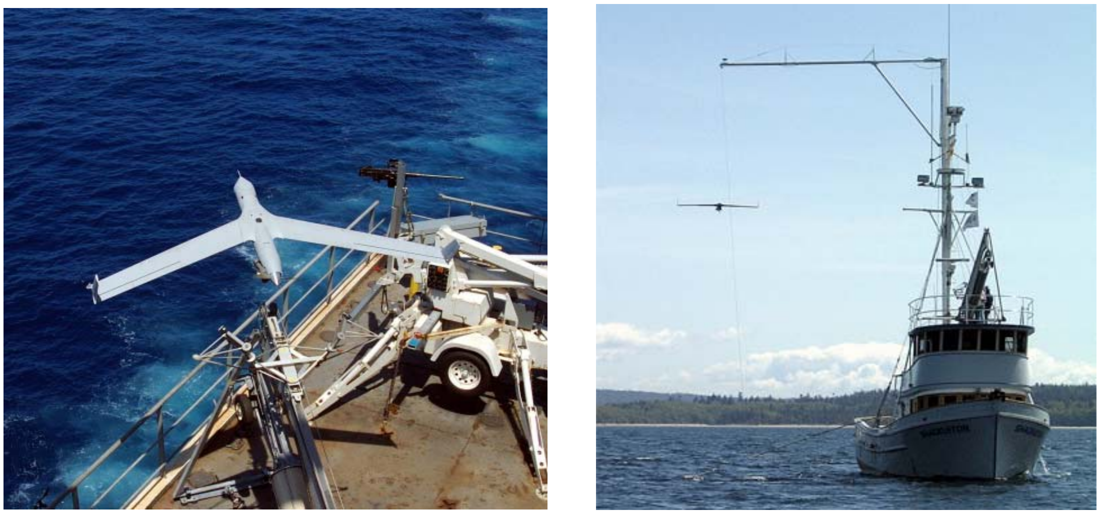

Figure 3: (a) ScanEagle launched from vessel (photo credit: Boeing) (b) ScanEagle approaching a ship for its autonomous landing. The UAV is recovered using Boeing InSitu's SkyHook system, in which ScanEagle catches a cable hanging from a 50 ft-high pole (Photo credit: Evergreen).

Figure 4: Krypton hygrometer collocated with 9-port turbulence probe mounted on a BAE Manta C UAS.

To make measurements in the lower constant flux layer of the MABL a laser altimeter is used to accurately measure both the height above the surface, and, in combination with the GPS/IMU measurements, the surface waves. The accuracy of these raw altimeter measurements, O(1) cm, is such that the system can be used to also measure the sea surface height (SSH) and in extra-tropical regions infer geostrophic currents in the same way as satellite radar altimetry is used to measure SSH. Upwelling and downwelling radiation can be measured by radiometers as can the sea surface temperature (SST). Imagery of the SST signature of OBL processes, including fronts and internal waves can be captured with an infrared (IR) camera. In addition to low level flights in the MABL, the

UAV can also be used to measure vertical profiles of atmospheric variables (e.g. pressure, temperature, humidity, winds) up to the ceiling of the UAV, which is ~ 5 km.

Table 1: Boeing InSitu ScanEagle specifications

	Boeing Insitu ScanEagle
Mission Endurance	Up to 24 hours
Fuel Type	Gasoline (100 octane unleaded non-oxygenated gas) or Heavy fuel (JP5, JP8, Jet-A)
Mission Airspeed	48 kts
Dash Speed	80 kts
Stall Speed	36 kts
Navigation System	Insitu
Service Ceiling	5 km
Command and Control Radio	900 MHz UHF datalink
Control Radio Range	20 nm LOS / "unlimited" with Satellite
Payload Capacity	2 kg (<8 hrs endurance) 6 kg total fuel and payload combined (24 hrs endurance with 5.4 kg fuel)
Power available for payload	Battery (included in payload)
Fuel Capacity	N/A
Engine	1.9 hp (1.4 kw), 2-stroke engine
Wing Span	3.11 m
Fuselage length	1.37
Tail Height	N/A

Without the shipboard recovery system the Manta is restricted to shore-based operations over the coastal oceans; however, it has a substantial scientific payload (6.8 kg) with enough fuel for 5 hours endurance at a mission speed of 50 kts (See Table 1).

On the other hand, the ScanEagle has ship-board recovery capability, a 2-kg (scientific) payload and approximately 6 hours endurance at the same mission speed. Thus the ScanEagle can operate up to 150 nm from a vessel, using line of sight (LOS) communications up to 50 nm and satellite communications for larger ranges.

The trade-off for this greater range is a relatively small payload (2 kg). In anticipation of this proposal, PI Melville recently submitted a DURIP proposal ("Instrumentation for a Ship-Based ScanEagle UAV System for Air-Sea Interaction Research") to purchase and modify the instrumentation for the ScanEagle scientific payloads for this project.[2] Table 2 lists the instruments that will be available as scientific payloads on the ScanEagle aircraft, also shown in Figure 5.

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[2] For the longer term, InSitu has already developed a larger UAV, the Integrator, which shares the same catapult launch and SkyHook recovery system, but a much larger payload of up to 35 lbs. With a wingspan of 16 ft and length of 7.2 ft, the Integrator is significantly larger than the ScanEagle (wingspan 10.2 ft, length 4.5 ft), but still small enough to be launched and recovered from all but the smallest research vessels.

The common essential elements of the measurement of many air-sea fluxes from the atmospheric side are the measurement of the wind velocity vector and the measurement of the distance from the surface. Along with temperature, humidity and pressure measurements to give air density, this capability will permit the measurement of the momentum, sensible heat and water vapor fluxes.

Table 2: Scientific and Flight Instrumentation Payload

PAYLOAD #1

Instrumentation	Weight (kg)	Power (W)	Data type	Measurement
9-port Turbulence/Gust Probe	0.118	<0.2	Analog	Winds, momentum fluxes, other fluxes
Laser Altimeter	0.307	5	RS232/AO	Surface waves, a/c control
Humidity/Temperature	0.050	<0.1	Analog	H/T profiles and bulk fluxes
Fast Response fiber Thermistor	<0.050	0.01	Analog	T, sensible heat flux
Krypton Hygrometer (including electronics)	0.318	<0.09	Analog	H_2O covariance fluxes
DAQ system	0.200	<10	N/A	Data acquisition
DGPS	0.077	2.1	RS232	georeferencing, winds, a/c control
IMU – LN200	0.780	12	Digital	georeferencing, winds, a/c control
TOTAL	**<1.900**	**<30**		

PAYLOAD #2

Instrumentation	Weight (kg)	Power (W)	Data type	Measurement
Laser Altimeter	0.307	5	RS232/AO	Surface waves, a/c control
Digital Video Camera	0.100	<3.2	GigE	Ocean surface processes, wave kinematics and breaking
Humidity/Temperature	0.050	<0.1	Analog	H/T profiles and bulk fluxes
FLIR A325 LWIR Camera	0.700	<24	GigE	SST, fronts, ocean surface processes
DAQ system	0.400	<20	N/A	Data acquisition
DGPS	0.077	2.1	RS232	georeferencing, winds, a/c control
TOTAL	**<1.650**	**<54**		

PAYLOAD #3

Instrumentation	Weight (kg)	Power (W)	Data type	Measurement
Humidity/Temperature	0.050	<0.1	Analog	H/T profiles and bulk fluxes
Radiometers	0.200	<0.1	Analog	SST, radiation budget
KT19.85 II	0.240	<2	RS232	SST
DAQ system	0.200	<10	N/A	Data acquisition
DGPS	0.077	2.1	RS232	georeferencing, winds, a/c control
TOTAL	**0.770**	**<14.5**		

The vertical velocity measurement along with the measurement of the relevant variable (e.g. humidity, temperature) will permit so called “eddy flux” or covariance measurements of the flux of the corresponding quantity (water vapor, sensible heat, gas flux).

Turbulence Probe: This system measures the three components of wind velocity relative to the aircraft, and is currently in final testing under ONR funding (9-port system). Current gust probe technology is based on arrays of pressure ports mounted either on a sting ahead of the nose of the aircraft or on the nose of the aircraft itself. In the former case, the nose of the sting must be ahead of the free-stream flow distortion by the aircraft. Here a 9-port nose array plus static pressure ports along the side of the fuselage will give the three components of wind velocity relative to the UAV. The velocity field in an Earth frame is then determined by adding the motion of the aircraft from DGPS/IMU measurements to the velocity field relative to the aircraft. We expect the (1 sigma) errors from the DGPS/IMU velocity measurements using the LN200 IMU combined with DGPS receiver to be no more than O(0.02) m/s.

The differential pressure transducers to be used in the gust probe array will have an accuracy of 3 Pascals at 100 Hz - 1 kHz. For incident velocities in the range 20-40 m/s, the airspeed range of the aircraft, this will permit resolution of the velocity relative to the aircraft with errors of O(0.01 - 0.001)U, where U is the speed of the aircraft relative to still air. This will permit resolution of pitch and yaw with errors of better than O(0.01 - 0.001) radians, or vertical and cross-track velocities with errors of O(0.01 - 0.001)U. The turbulence probe will be equipped with an additional reservoir to mitigate any water intake during low level flights[3] and will be structurally reinforced to withstand lateral loads and SkyHook cable friction during difficult landings.

[3] This method is currently used on a number of gust probe systems, including the one mounted on the CIRPAS Twin Otter and Controlled Towed Vehicle, CTV, system.

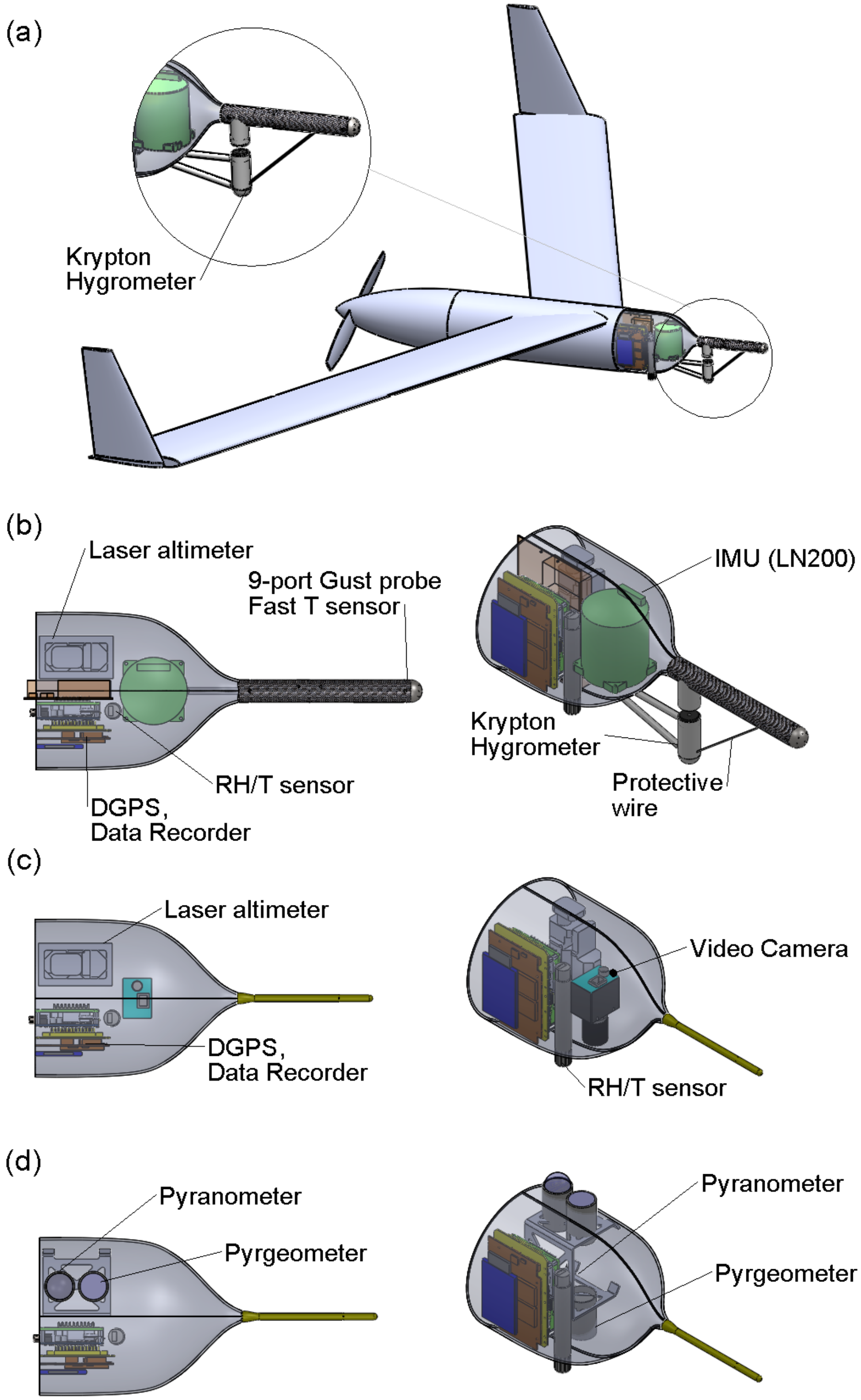


Figure 5: (a) ScanEagle UAS equipped with one of the air-sea interaction payloads. (b) example of proposed payload, for MABL lower altitude that includes 9-port turbulence probe, laser altimeter, fast response fiber optic temperature sensor, water vapor, RH/T. Upper altitude packages are shown in (c) equipped with laser altimeter and digital camera and (d) with a set of downward/upward looking pyranometers and pyrgeometers for SST and net radiation measurements. (In (b) to (d), plan views of payloads are in the left column.)

Figure 6: Turbulence probe and sonic anemometer comparisons from a pickup truck. (a)-(b) Experiments with the turbulence probe mounted on the Manta fuselage, which is attached to a full length roof rack with a rigid aluminum pipe structure. Two sonic anemometers (Campbell Scientific CSAT3s) are positioned such that the measurement volumes are 27~cm laterally and 5~cm forward of the turbulence measurement volume.

The turbulence probe is the heart of the covariance flux measurement system for all variables since the vertical velocity measurement is common to all. The turbulence probe evaluation has been accomplished by mounting the probe next to the measuring volume of two CSAT3 sonic anemometers mounted above the cab of a pickup truck (Figure 6). The pickup truck was then driven at speeds up to 28 m/s along the road and data from all three instruments recorded simultaneously.

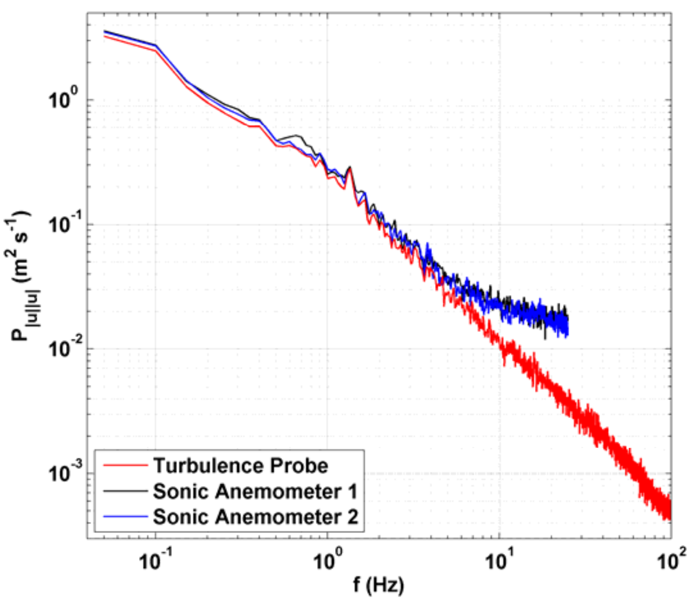


Figure 7: Comparison between sonic anemometers and turbulence probe spectra of the relative horizontal wind. The entire record length is 975s.

Figure 7 shows direct intercomparisons of spectra of the streamwise (horizontal) velocity. The agreement is very good up to frequencies of 5-7 Hz, corresponding to a roll-off in the spectrum of the horizontal wind speed measured by the ultrasonic anemometers. Figure 8 shows the comparison between the measurement of the friction velocity u* by the ultrasonic anemometer and the turbulence probe friction. Again, the agreement is very good with the turbulence probe measurements slightly less than those of the sonic anemometer.

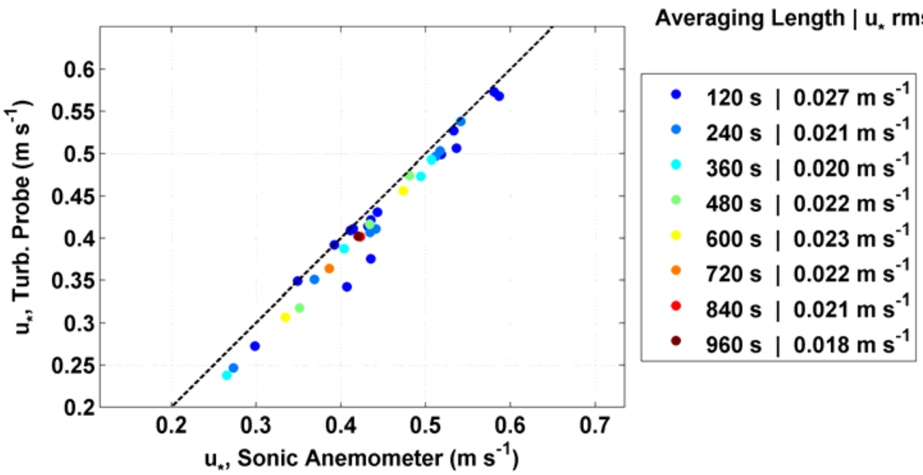


Figure 8: Comparison between sonic anemometer and turbulence probe friction velocity u, calculated from the measured wind. Marker colors represent different averaging lengths, from 120~s (blue) to 960~s (red).*

Laser Altimeter: The instrument is a repackaged, modified version of the Pacer ILM500 sensor. Once the aircraft motion is removed from the laser altimeter measurements using the onboard DGPS/IMU unit, we obtain the surface-wave profile along the aircraft track. Raw vertical accuracy is approximately 5-10 cm, with a maximum range over the ocean of approximately 200-300 m while sampling at 1kHz. For measurements of SSH, the 1 kHz data can be averaged over say 60s for 1 nm horizontal resolution, beating the measurement error down to less than 1 mm.

Radiometers: Upwelling and downwelling solar and long-wave radiation measurements from Kipp & Zonen pyranometers and pyrgeometers, respectively, at 0.3 to 2.8μm and 4.5 to 42μm (CGR3 and CMP3). The sea surface temperature Ts can be measured from the long-wave upwelling and downwelling fluxes, Q_{lu} and Q_{ld} (Katsaros, 1990). The solar radiation fluxes are used for cool skin temperature corrections in the TOGA-COARE algorithm, and for giving the solar albedo.

KT19.85 II: The Heitronics KT19.85 II is an infrared pyranometers used to measure sea surface temperature. The instrument will be repackaged to reduce its weight from 1.5 kg to 240 g.

Nadir Video Camera: The nadir-looking video camera serves several purposes. Following techniques developed in the GOTEX experiment (Melville et al., 2005), we will use the video for imaging wave breaking (whitecaps) and seek correlations with the modulation of air-sea fluxes. In addition to imaging breaking, the video will also capture ocean fronts, Langmuir circulations and other ocean surface phenomena that have visible signatures, including internal waves. We have selected a 12-bit, 2448 X 2050 pixel nadir-looking video camera (Prosilica, Model GC2450). We plan to operate the camera at 15 frames per second for 5 minute records, which will be recorded and stored on board the aircraft.

FLIR A325 LWIR Camera: This instrument will be used to capture ocean temperature fronts and other phenomena that have a thermal surface signature. The camera is equipped with an uncooled Microbolometer sensor array (7.5-13μm), 320x240px, for a NETD <50mK.

Humidity and Temperature: The sensor (HMP45C Vaisala) will provide RH and T measurements with accuracy of ±2% (RH) and ±0.2°C (T), with a response time <10sec.

Fast Response Fiber Optic Thermistor: The OTG-F sensor uses the temperature-dependent bandgap of GaAs crystal as the temperature transduction mechanism to provide fast response atmospheric T measurements, with accuracy of ±0.3°C, resolution of 0.05°C and response time of 0.005s.

Krypton Hygrometer: The KH20 sensor (Campbell Scientific) is used to measure fluctuations of water vapor around the mean value. Combined with the HMP45C sensor described above, we will calculate water vapor fluxes using direct covariance techniques. The placement of the Krypton hygrometer, shown conceptually in the insert of Figure 4a, will be finalized after testing in collaboration with InSitu/Boeing, to exclude the possibility of the instrument fouling on the SkyHook cable during recovery.

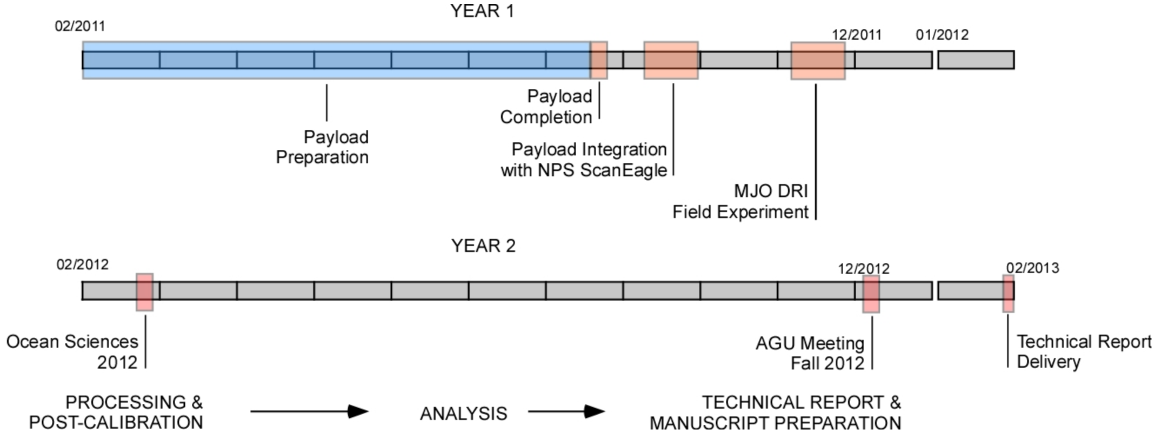
IMU-LN200 and DGPS receiver: The Novatel LN200 is a state of the art inertial motion unit. Combined with a high accuracy DGPS module (Novatel Propak), post-processed using Waypoint Inertial Explorer Software, we expect horizontal position accuracy of approximately 10 cm (this will vary based on distance from GPS ground station or Omnistar availability), horizontal velocity accuracy of 0.02m/s (rms), attitude (pitch, roll) accuracy of 0.005° (rms), and heading of 0.008° (rms).

FUTURE NAVAL RELEVANCE

For the future, one important area of ship-borne UAV-based research is the effect of water vapor fluxes and spray on electromagnetic (EM) or electro-optical (EO) propagation in the marine atmospheric boundary layer. By using a precisely and dynamically positioned UAV as both an instrument platform and target, issues of EM and EO propagation and refraction in the lower MABL may be resolved.

In addition, at the request of Terri Paluszkiewicz and Scott Harper (ONR, Physical Oceanography) PI Melville, along with colleagues Al Plueddemann and Eric Skyllingstad, is currently preparing a white paper in support of a potential future ONR DRI focusing on understanding the role of surface waves in OBL processes. Should such a DRI go forward, ship-borne UAV capabilities would greatly improve spatio-temporal observations of the coupling between the marine atmospheric boundary layer and the marine boundary layer, Langmuir circulations/turbulence, surface waves, wave breaking, sub-mesoscale processes, including fronts and related processes.

PROJECT SCHEDULE AND MILESTONES



INTERFACE WITH EXISTING FACILITIES

PI Melville's Air-Sea Interaction Group at SIO is in the forefront of research devoted to exploiting and developing modern electro-optical techniques for studying surface waves and other processes of air-sea interaction. We currently use LIDARS from airborne, fixed and floating platforms to measure the spatio-temporal structure of surface wave fields. This ship-based UAV project would complement our ongoing efforts in this area by significantly expanding the platforms available to do air-sea interaction research.

FFATA Regulations
UCSD will comply with FFATA regulations.

CURRENT AND PENDING PROJECT PROPOSAL SUBMISSIONS

PI Melville is currently supported by ONR (Physical Oceanography) in the Hi-Res DRI (N00014-07-1-0210) in a project which is focused on airborne and *in situ* measurements of ocean wave processes including breaking using electro-optical and imaging techniques.
PI Melville recently submitted a DURIP proposal ("Instrumentation for a Ship-Based ScanEagle UAV System for Air-Sea Interaction Research") to purchase and modify the instrumentation for the ScanEagle scientific payloads to be used in this project.
A complete list of Melville's current and pending projects is provided as an attachment to the grants.gov proposal package.

QUALIFICATIONS

While PI Melville has spent most of his professional career in ocean-related research, his training up to and including his PhD was primarily in aeronautical engineering. This education included aerodynamics, propulsion, stability and control, aircraft structures, and aircraft instrumentation at a level consistent with the technology to be used and developed in the proposed effort. While this was some time ago, the fundamentals in all these areas have not changed in the intervening period. In the GOTEX and HIRES DRI experiments Melville's group also developed considerable experience in developing new airborne instrumentations and novel techniques to analyze airborne measurements.

Thus Melville's background in both aeronautics and oceanography is well suited to the use of the equipment described in this proposal.

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