Development of Instrumented UAS for Air Sea Interaction Research & Ship-Based UAS Measurements of Air-Sea Interaction and Marine Atmospheric Boundary Layer Processes in the Equatorial Pacific

Update on the AGOR / UAS Scientific Demonstration Integration

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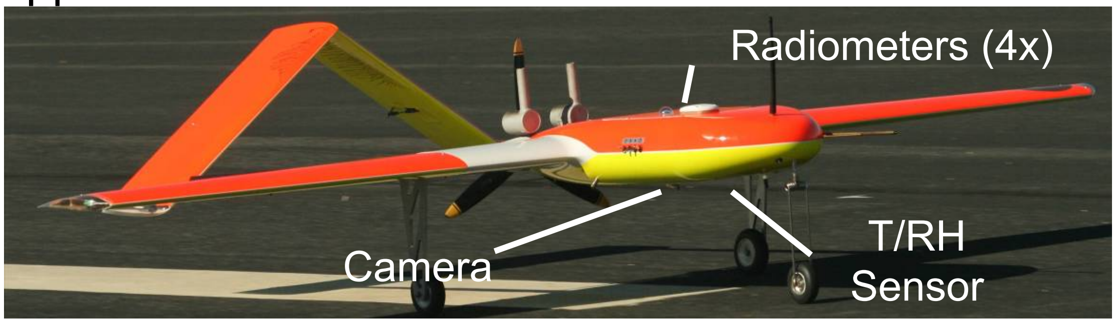
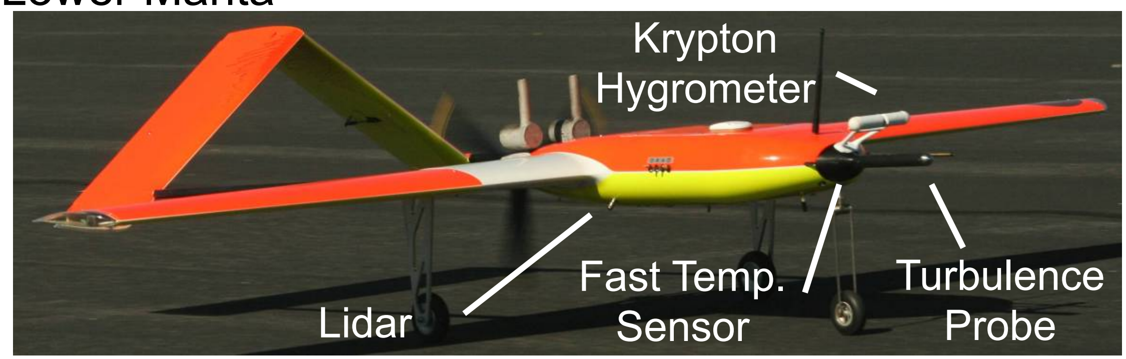
SE Flight Support: NSWCDD (POC: Lorenz Eber)

SIO Manta UAS for Air-Sea Interaction Research

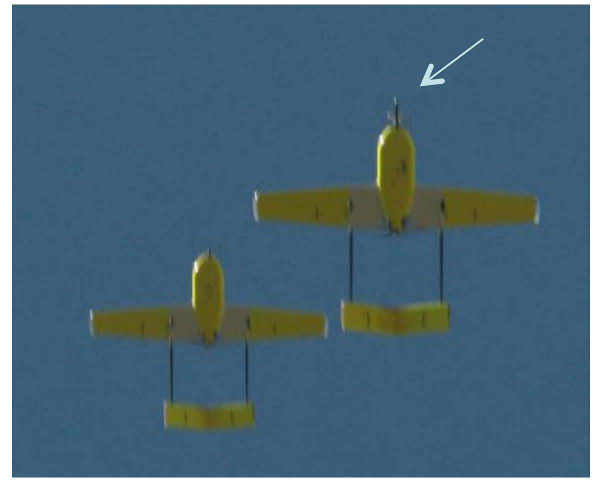
Upper Manta



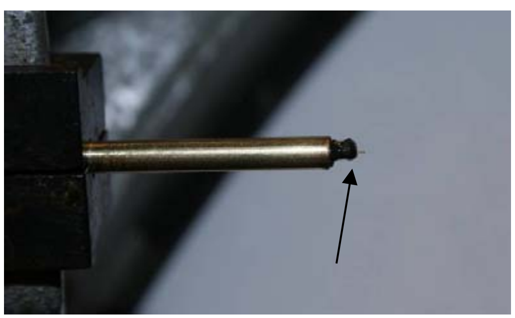
Lower Manta

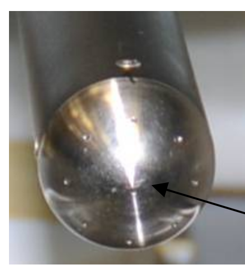


Automated
Stacked flight)

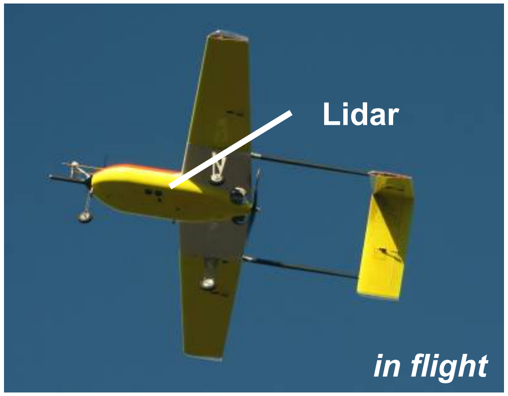


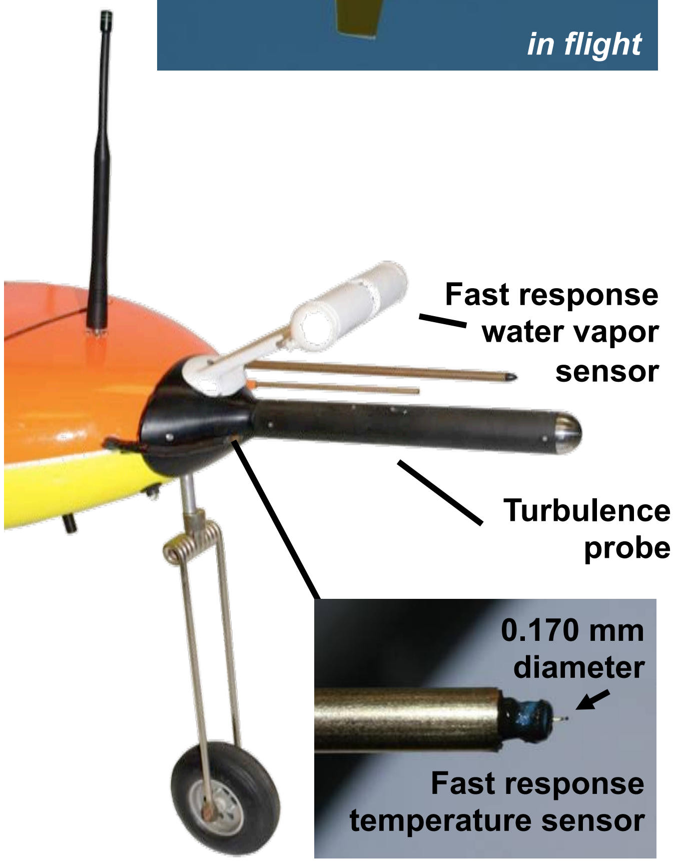
Fast response
T-sensor
(fiber optic)





SIO Manta UAS for Air-Sea Interaction Research

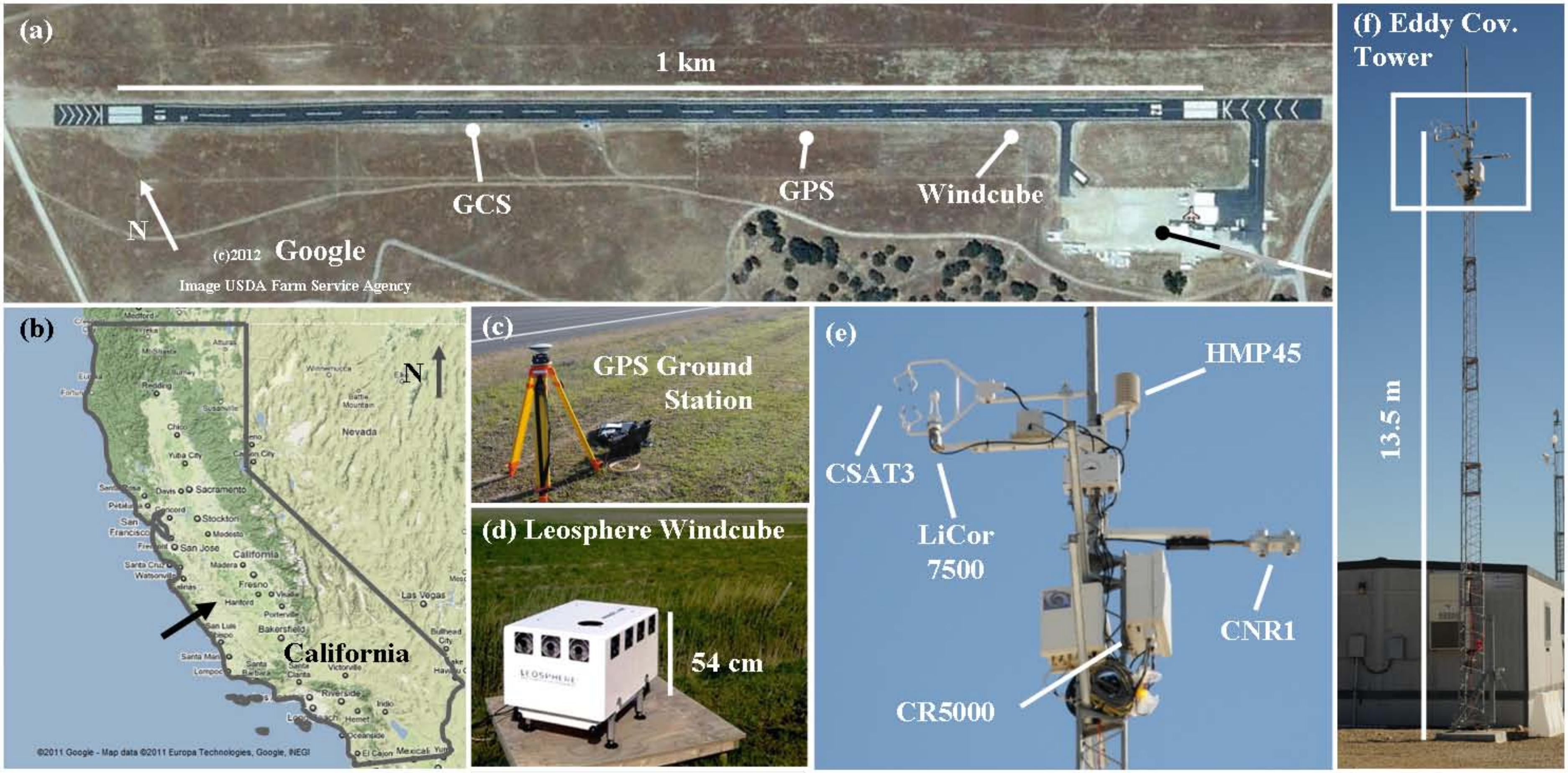




- 5 hrs endurance, ~7 kg payload, 2.7-m wingspan
- Capable of stacked flight configuration
- Measures mean and turbulent wind (turbulence probe), surface topography, standard meteorological variables and air-sea fluxes

Instrumentation	Measurement (accuracy)
Prosilica Camera	Ocean surface processes, wave kinematics and breaking
Pyranometers, pyrgeometers	Up-/down-welling, long-/short-wave radiation, SST
SIO turbulence probe	Relative wind, momentum and other fluxes (**georeferenced horiz./vert.: 5.5 cm s^{-1} / 2.6 cm s^{-1}**)†
Honeywell HG1700 IMU	Georeferencing (with DGPS, roll/pitch: 0.013°, yaw: 0.031°, horiz./vert. velocity: 0.020/0.020 m s^{-1})
Opsens fiber optic temperature sensor	Temperature (0.3 °C at 50 Hz), sensible heat flux
Krypton hygrometer	Moisture, latent heat flux
Meas. Devices Ltd. Nadir lidar	surface waves, topography, aircraft control (**georeferenced vertical rms: 8.6 cm**)‡
Novatel DGPS	Georeferencing, winds, aircraft control
H/T sensor	Humidity/temperature profiles and bulk fluxes

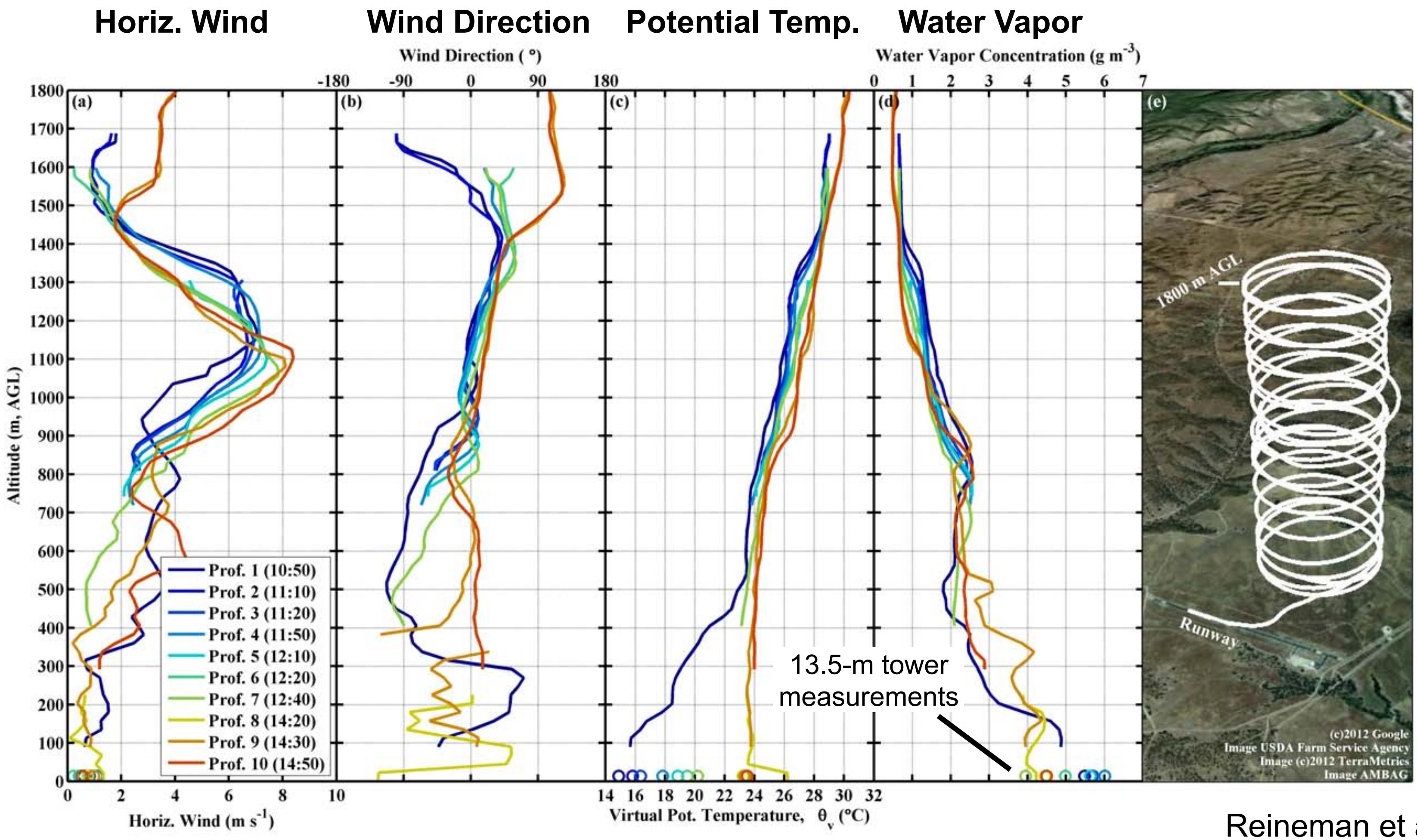
SIO Manta: Camp Roberts flight, Jan.2011



McMillan Airfield (35.7190◦N, 120.7703◦W) runway and ground instrumentation used during Manta UAV flight tests, 24 – 28 January 2012. Location of the ground control station (GCS) and photographs of the GPS ground station, Leosphere Windcube, and eddy covariance tower are shown. Note the contrast between the black runway and the lighter gravel and vegetation near the tower. A map inset marks the location of the airfield with a black arrow.

SIO Manta: sample atmospheric profiles of wind, temperature, H_2O vapor

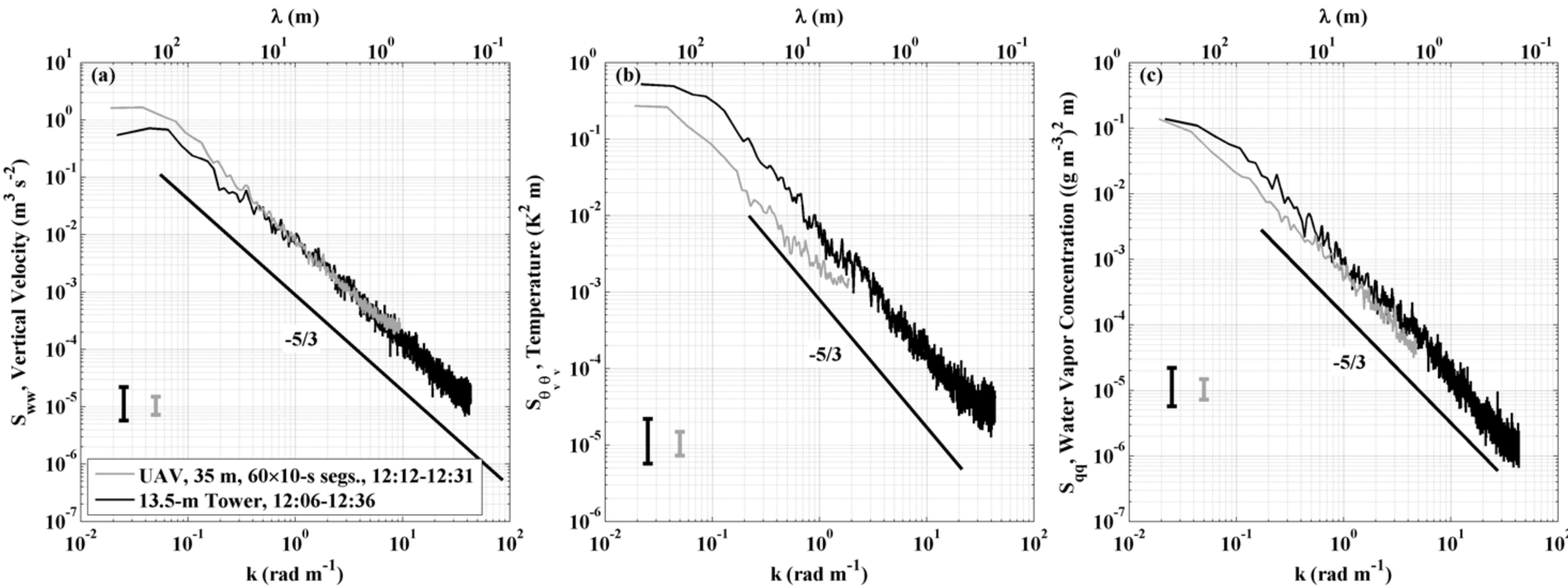
- Camp Roberts, CA; 27 Jan 2011
- Sample helical profiles in lower 1800 m (5900 ft)
- Observed ageostrophic wind jet



Reineman et al. 2012

SIO Manta: Wind, temperature & water vapor spectra

UAV measurements comparison with the fixed Eddy Covariance tower



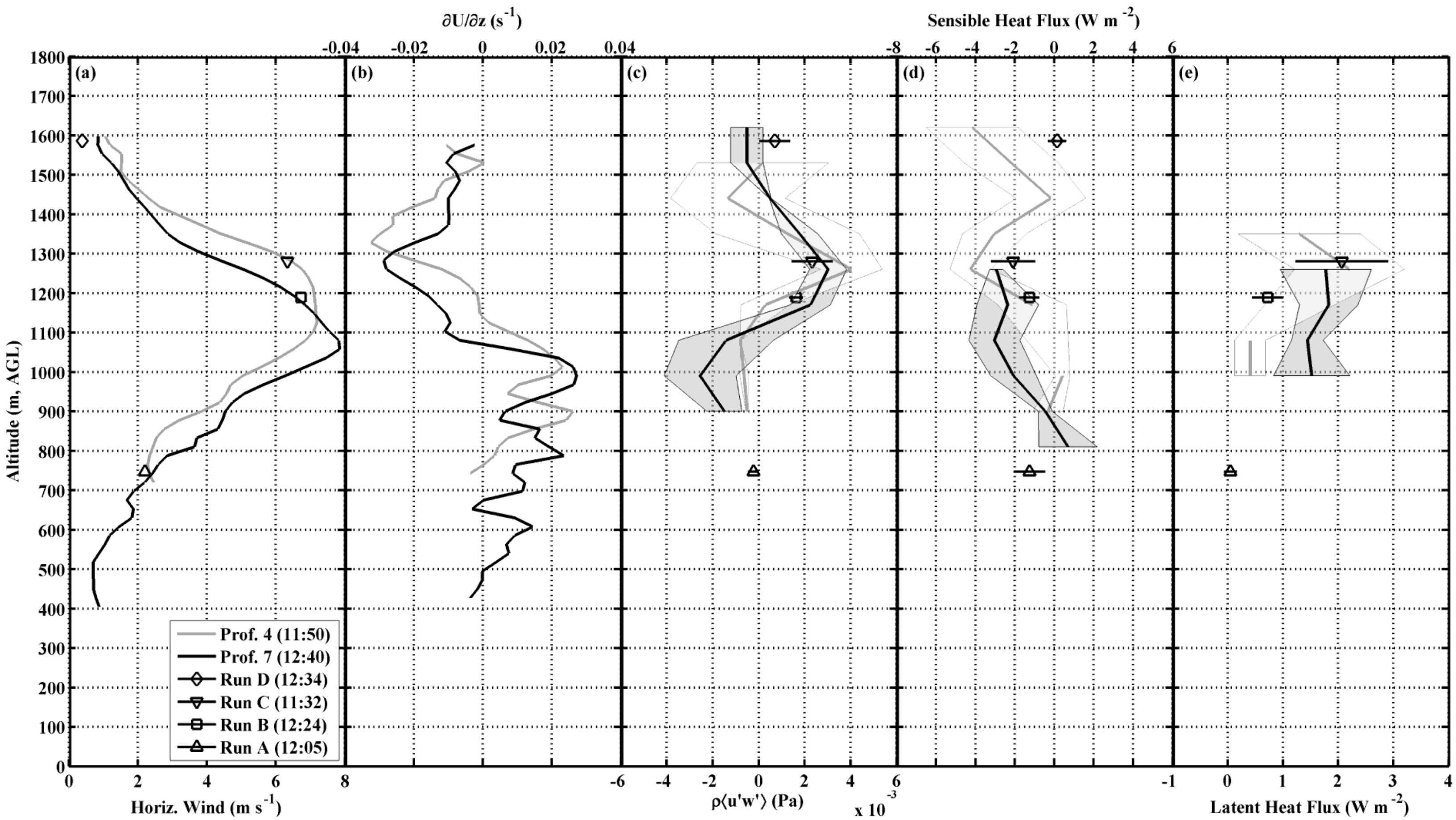
Spectra of (a) vertical wind, (b) virtual potential temperature, and (c) water concentration as measured by the fixed 13.5-m eddy covariance tower and the instrumented Manta UAV flying adjacent to the tower at 35 m AGL, on 28 Jan 2011. We assume Taylor's hypothesis to transform spectra into the wavenumber domain using, for the UAV, the mean airspeed during the passes (33.2 m s−1), and for the eddy covariance tower, the mean horizontal wind speed (1.5 m s−1).

We attribute the spectral offsets in temperature and water vapor to variability within the surface layer likely due to the surrounding man-made structures and inhomogeneous surfaces.

SIO Manta: sample atmospheric profiles of wind, temperature water vapor

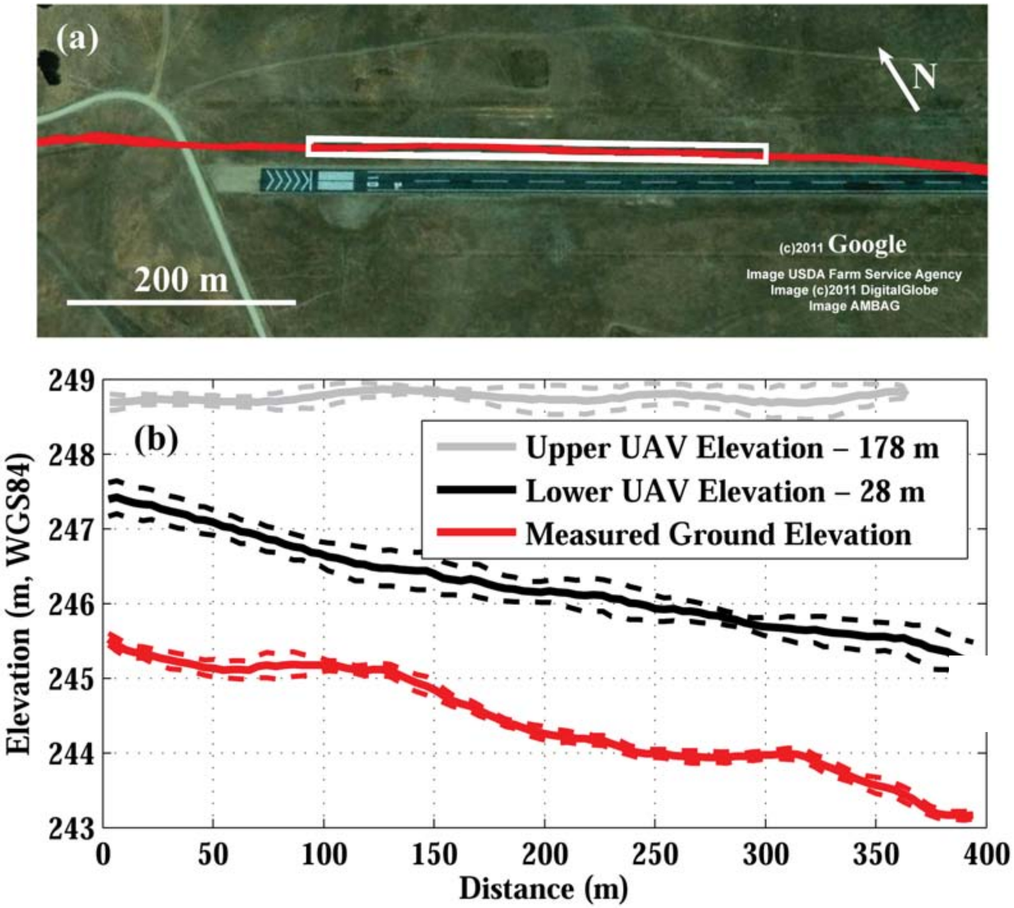
- Fluxes measured within vertical helical profiles
- 45-s segments used, averaged into 180-m vertical bins with 50% overlap
- Observed momentum flux out of the top and bottom of wind jet

Horiz. Wind   Vertical Shear   Momentum Flux   Sensible Heat Flux   Latent Heat Flux



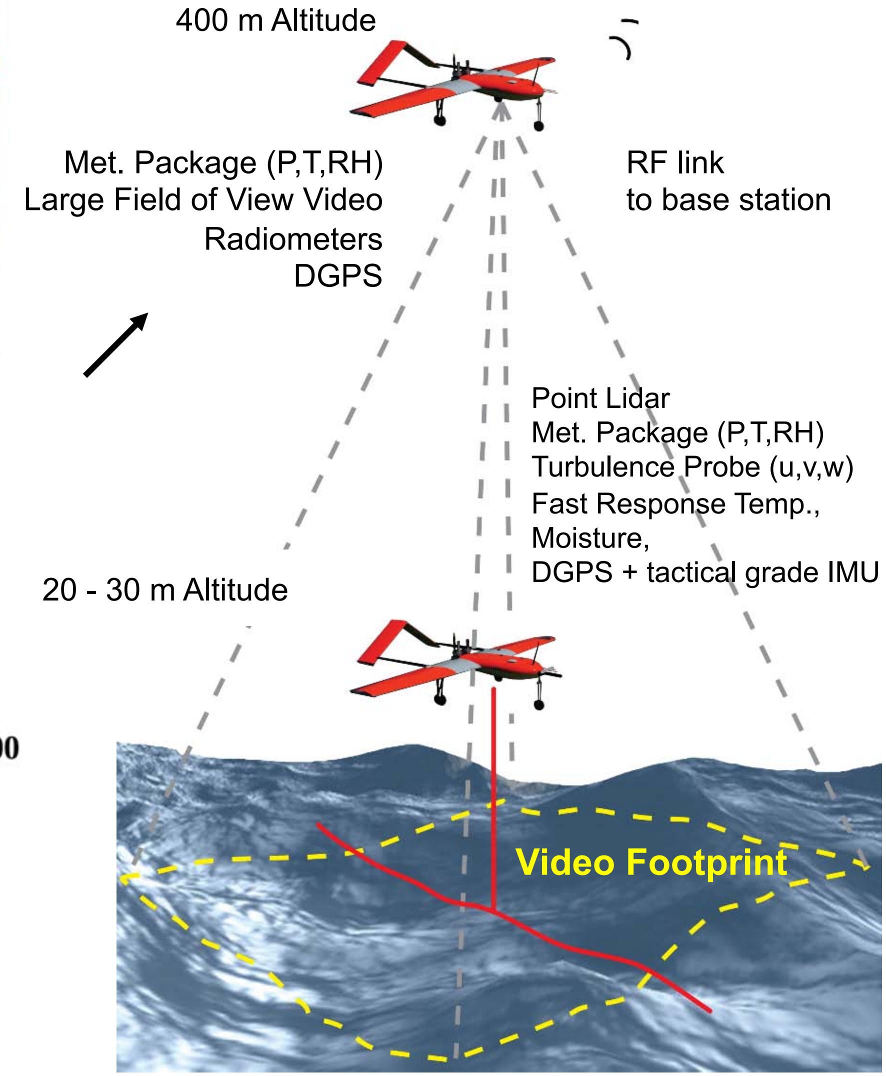
Reineman et al. 2012

SIO Manta: Low level stacked flight



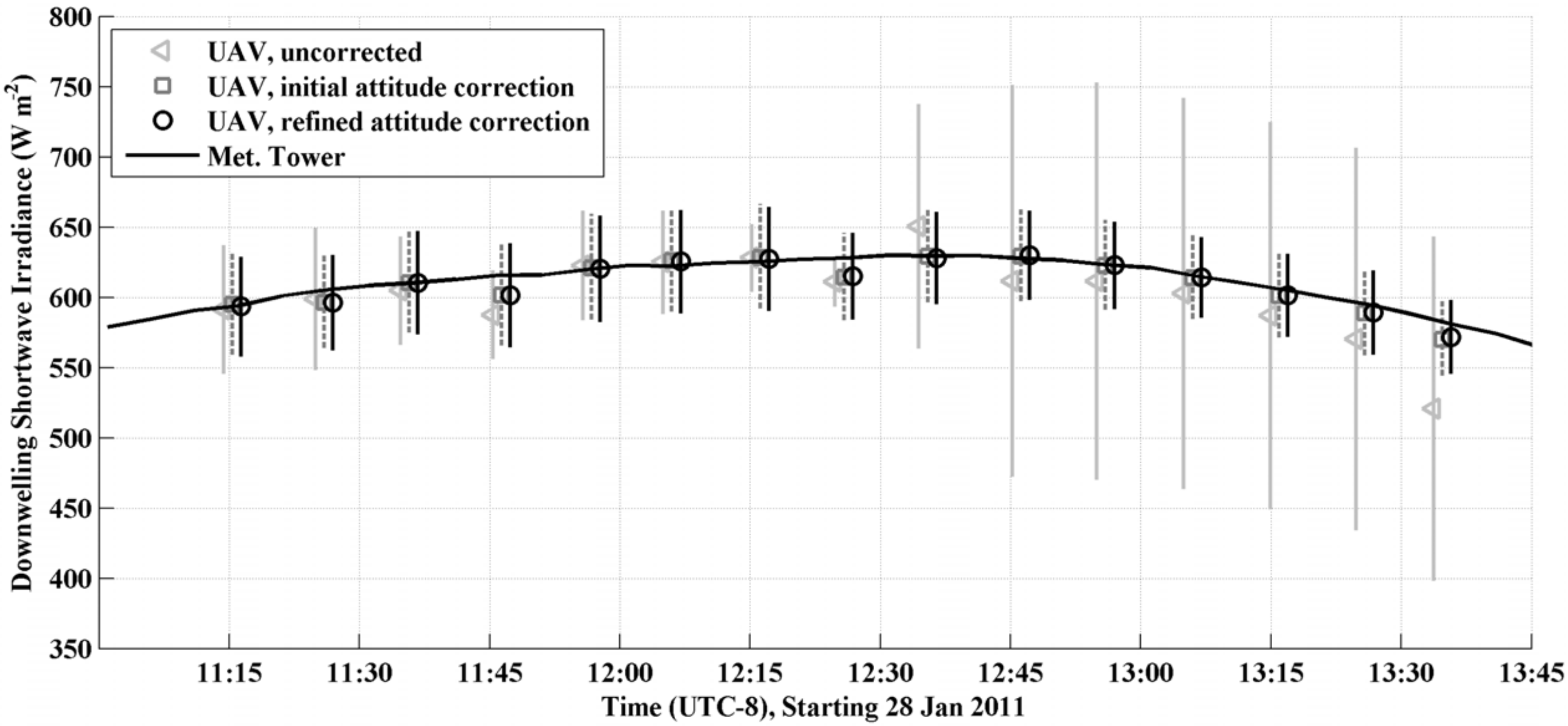
Repeat track lidar topography near the runway, with data overlaid on Google Earth imagery. Two Manta UAVs were in stacked formation: the upper Manta was programmed to maintain a constant GPS altitude for these segments, while the lower UAV was programmed to maintain constant height above ground using measurements from the lidar.

Over this region, the lower UAV maintained an altitude over ground of 29.8 m ±0.9 m.



Reineman et al. 2012

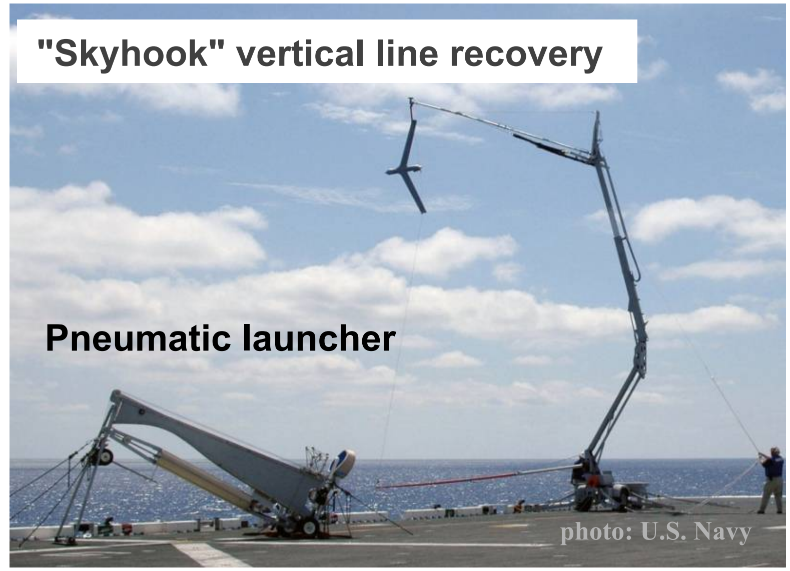
SIO Manta: Upwelling/Downwelling radiations

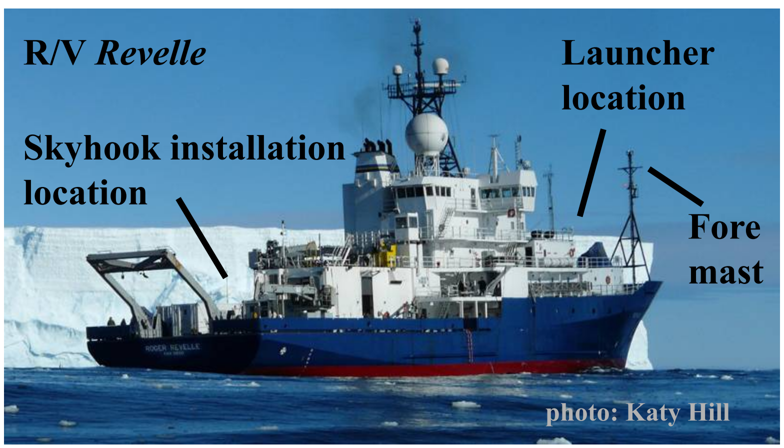


Time series of downwelling shortwave radiation, as measured with the Manta Radiometric payload and the CNR1 on the 13.5-m meteorological tower. Conditions were clear sky, and the sun reached a maximum elevation of 36.2◦ at 12:16 local time. Different symbols denote 10-min bin averages at different stages of the correction process (see section 4f), with vertical bars showing ±1σ from the mean. Steep turns, ascents, and descents are not considered. The first half of the data (11:15 – 12:30) is obtained while the UAV is following a racetrack pattern over the runway, the second (12:30 – 13:35) is from slow, repeated, constant-altitude orbits. During circular orbits, the roll is about 11◦, which accounts for the spread in the uncorrected radiation. UAV altitude was between 200 and 600 m over the course of these measurements.

SIO ScanEagle UAS for air-sea interaction research

- >12 hrs endurance, 2 – 3 kg payload
- **Capable of ship launch/recovery**
- Scheduled Cruise: October 2012 on R/V *Revelle*
- Equatorial mixing research (140W, 0N)





Additional shipboard instrumentation

A. Fore mast:
   - Eddy covariance station (wind, atmospheric temperature, humidity, short-/longwave, up-/downwelling radiation, momentum and heat fluxes)
   - Scanning lidar (surface wavefield measurements)

B. Wind doppler profiler (Leosphere WindCube; up to 450 m, 20 bins)

SIO Manta, ScanEagle platform comparison

	BAE Manta C1	Boeing-Insitu ScanEagle
Mission Endurance	5 hrs (for 6.8 kg payload)	(see Payload Capacity, below)
Mission Airspeed	21 – 39 m s^{-1} (40 – 75 kts)	25 m s^{-1} (48 kts)
Dash Airspeed	41 m s^{-1} (80 kts)	41 m s^{-1} (80 kts)
Stall Airspeed	20 m s^{-1} (36 kts)	20 m s^{-1} (36 kts)
Service Ceiling	5.3 km	5 km
Control Radio Range	37 km (20 nm) line-of-sight	100 km (54 nm) line-of-sight
Engine	4.0 kW (5.5 hp), 2-stroke/2-cylinder	1.4 kW (1.9 hp), 2-stroke/2-cylinder
Payload Capacity	6.8 kg (5-hr endurance)	2 kg (8-hr endurance), 6 kg fuel+payload
Fuel Capacity	8.1 L	(see Payload Capacity)
Wing Span	2.7 m	3.11 m
Fuselage Length	1.9 m	1.37 m
Tail Height	0.6 m	N/A
Navigation System	Cloud Cap Piccolo II GPS/INS	Boeing-Insitu
Launch method	runway rolling takeoff	portable pneumatic launcher
Recovery method	runway rolling landing	"Skyhook" wing capture with vertical cable

Ship-Based UAS Measurements of Air-Sea Interaction and Marine Atmospheric Boundary Layer Processes in the Equatorial Pacific

Originally planned December 2011 deployment as part of the DYNAMO project postponed (funding delays and identifying adequate flight support group).

Deployment of instrumented ScanEagle UAVs from the R/V *Revelle* during the Papeete to Nuku Hiva, Tahiti cruise (4 - 22 Oct., 2012; Jerome Smith - SIO , Chief Scientist) EquatorMix experiment (NSF PO funded)

ScanEagles will extend the capabilities of the research vessel by measuring air-sea fluxes, marine atmospheric boundary layer (MABL) variables, and surface signatures of ocean boundary layer (OBL) processes. Low level flight and stacked flight using two GCS.

A. Air-sea Fluxes and the Marine Atmospheric Boundary Layer

- Measure momentum, heat, and moisture fluxes, atmospheric soundings, and surface wave measurements
- Measure spatial decorrelation scales of the air-sea fluxes and related MABL variables relative to the research vessel.

B. Atmospheric Convection & Precipitation

- Measure horizontal entrainment velocities approaching the perimeter of convective cells
- Correlation of recently precipitated pools of cooler fresher water at the surface with the convective activity

C. The Diurnal Surface Layer

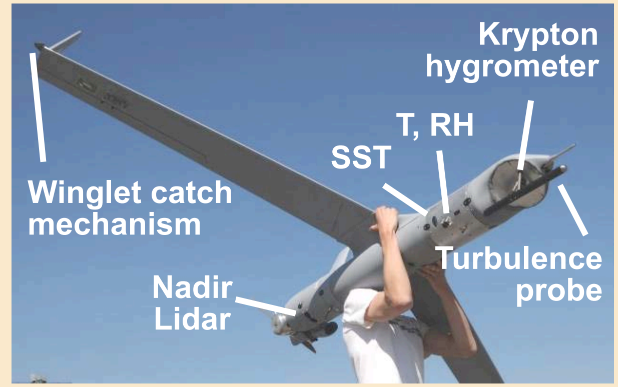
- Coordinated flights with fast CTD profiling the DSL (air-sea fluxes, waves, met.)

D. Surface Wave Processes and Mixing

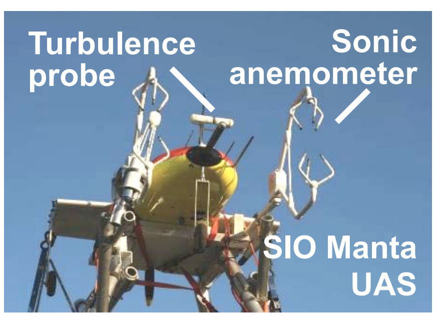
SIO ScanEagle UAS for air-sea interaction research

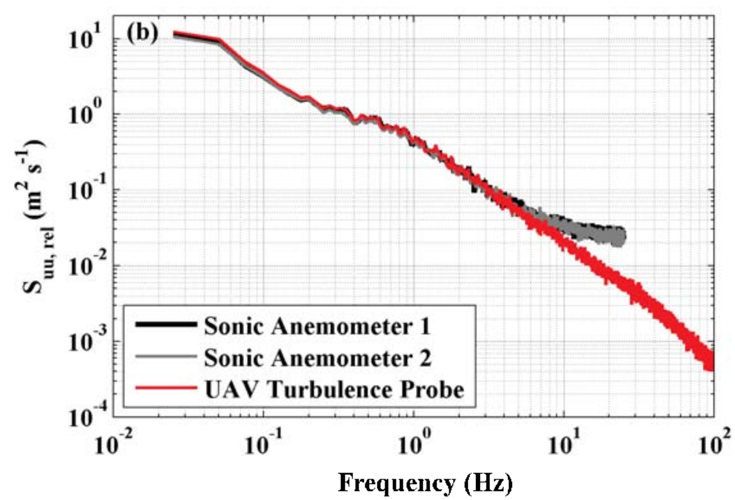
"Flux" payload

Instrumentation	Measurement
9-port turbulence/gust probe	Winds, momentum fluxes, other fluxes (vertical wind est. accuracy 2.6 cm/s)
Laser altimeter	Surface waves, a/c control
Humidity/temperature	H/T profiles and bulk fluxes
SST sensor	SST, frontal processes
Fast response optical temp. sensor	T, sensible heat flux
Krypton hygrometer	H_2O covariance fluxes
DAQ system	Data acquisition
DGPS	georeferencing, winds, a/c control
IMU – LN200	georeferencing, winds



- Relative vertical wind spectra, comparison with CSAT3 sonic anemometers
- Instruments mounted on pickup truck

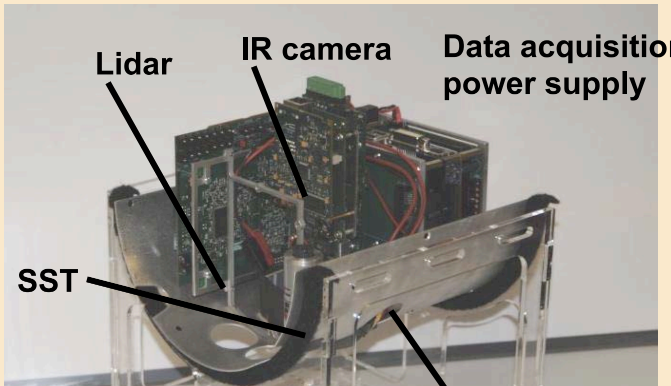




"Block D" ScanEagle

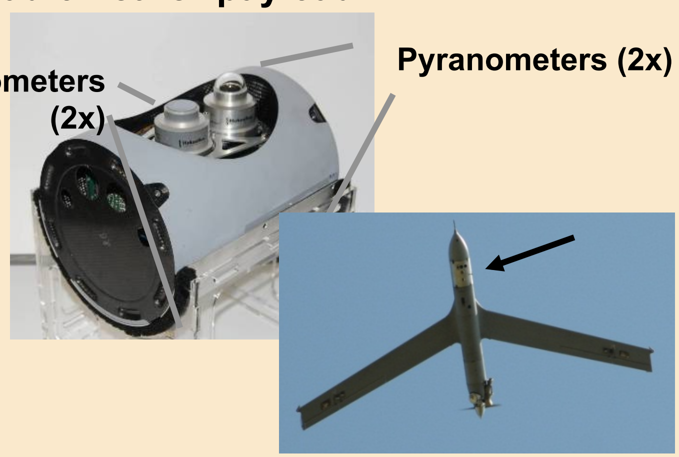
SIO ScanEagle UAS for air-sea interaction research

“Imaging" payload



Instrumentation	Measurement
Laser Altimeter	Surface waves, a/c control
Digital Video Camera	Ocean surface processes, wave kinematics and breaking
SST sensor	SST,frontal processes
Humidity/Temperature	H/T profiles and bulk fluxes
FLIR A325 LWIR Camera	SST, fronts, ocean surface processes
DAQ system	Data acquisition
DGPS	georeferencing, winds, a/c control

“Radiometric" payload

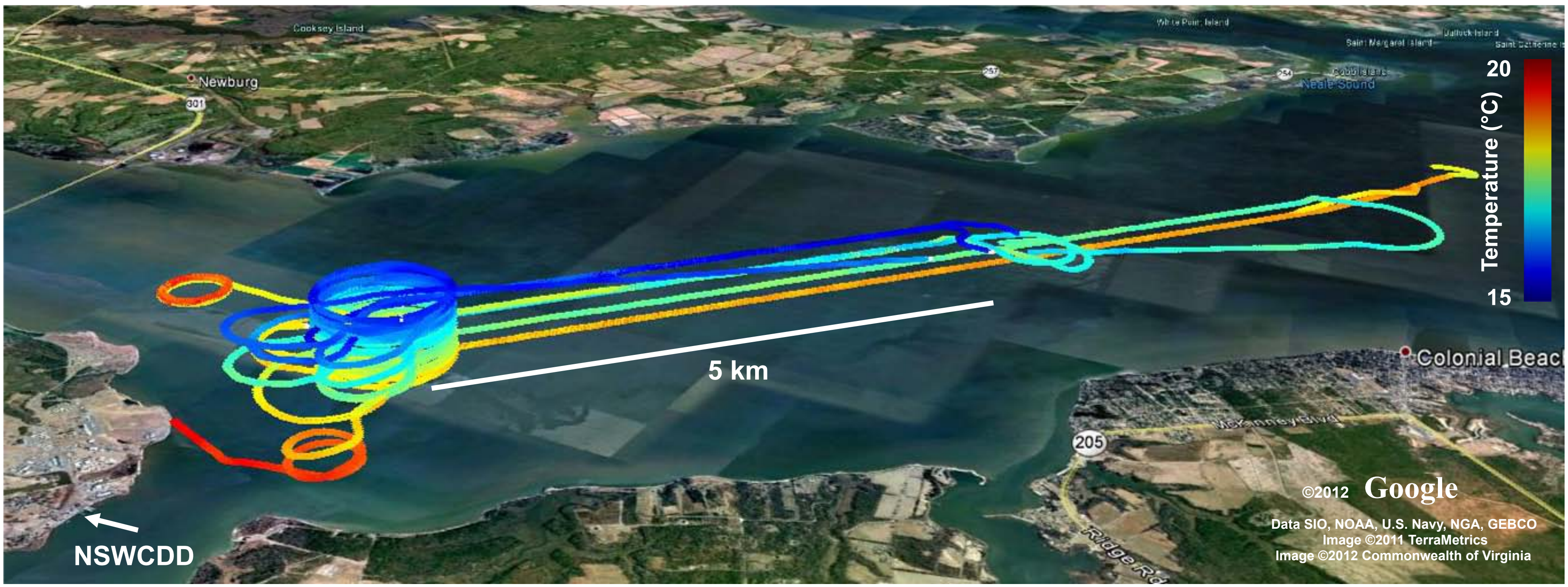


Instrumentation	Measurement
Humidity/Temperature	H/T profiles and bulk fluxes
Radiometers	SST, radiation budget
SST sensor	SST
Digital Video Camera	Ocean surface processes, wave kinematics and breaking
DAQ system	Data acquisition
DGPS	georeferencing, winds, a/c control

“Block C & CD” ScanEagles

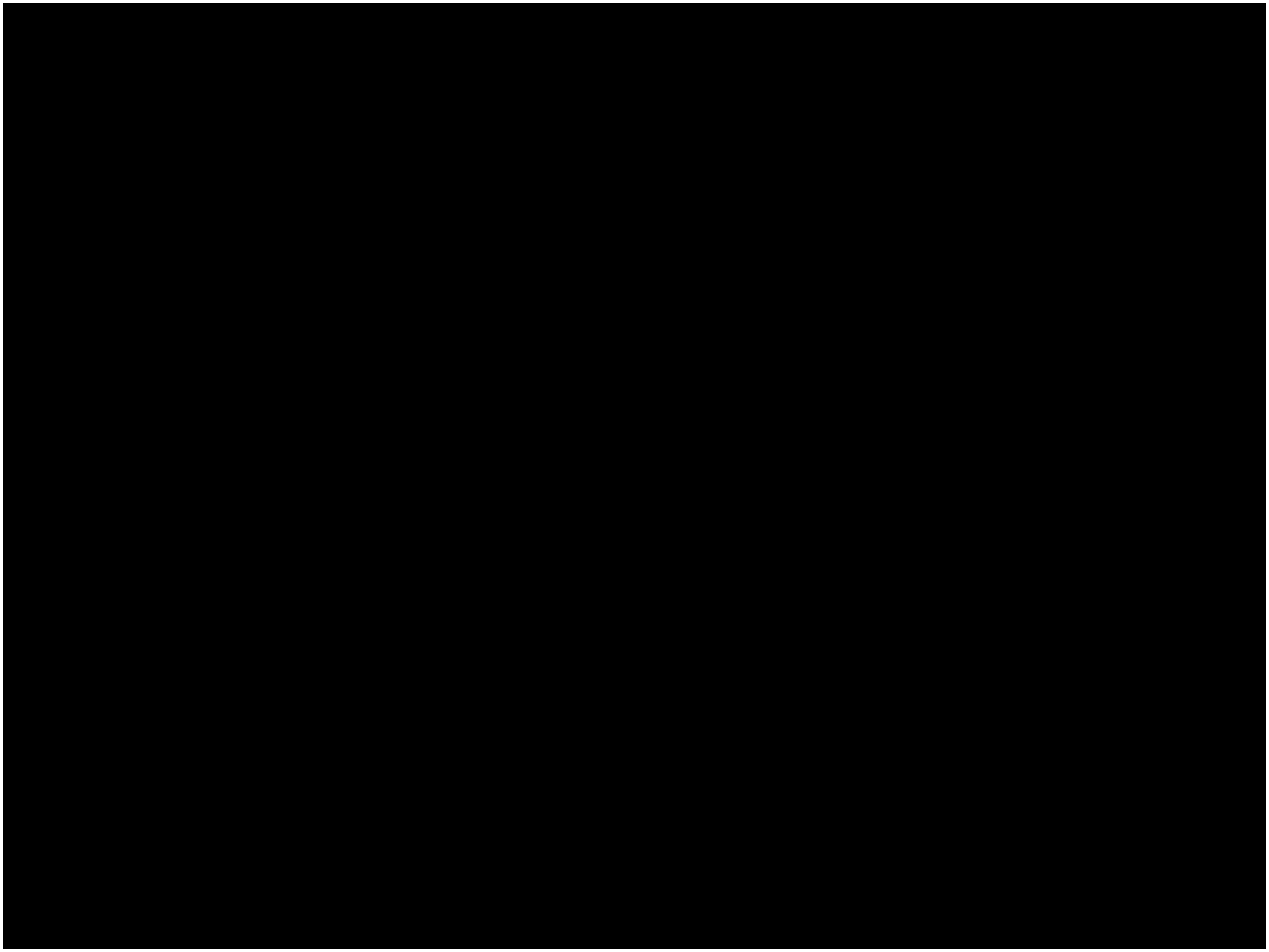
SIO ScanEagle UAS flight tests - Dahlgren, VA

- Naval Surface Warfare Center Dahlgren Division, 12-16 April 2012 1220 - 1420 EDT
- Below: flight paths from flight test of FLUX payload, with color corresponding to atmospheric temperature
- 3x 10-km straight-and-level passes, 6x 5-km, 4x helical soundings



SIO ScanEagle UAS flight tests - Dahlgren, VA

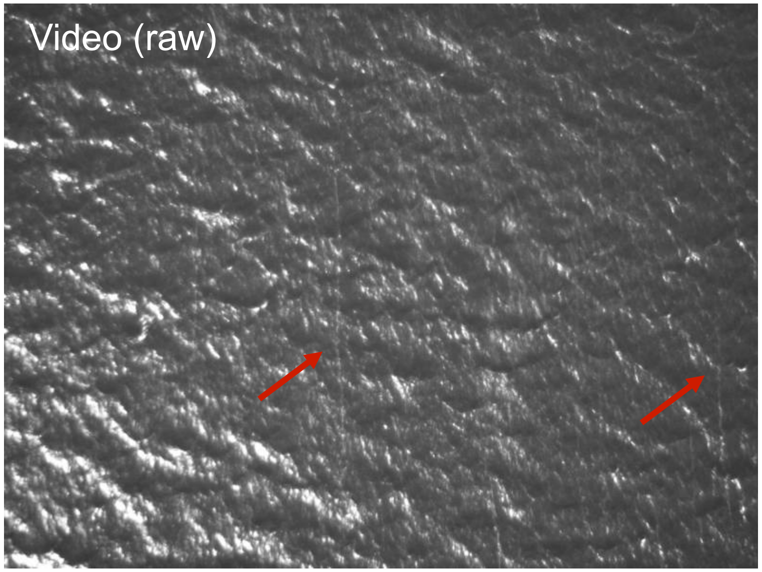
- Naval Surface Warfare Center Dahlgren Division, 12-16 April 2012

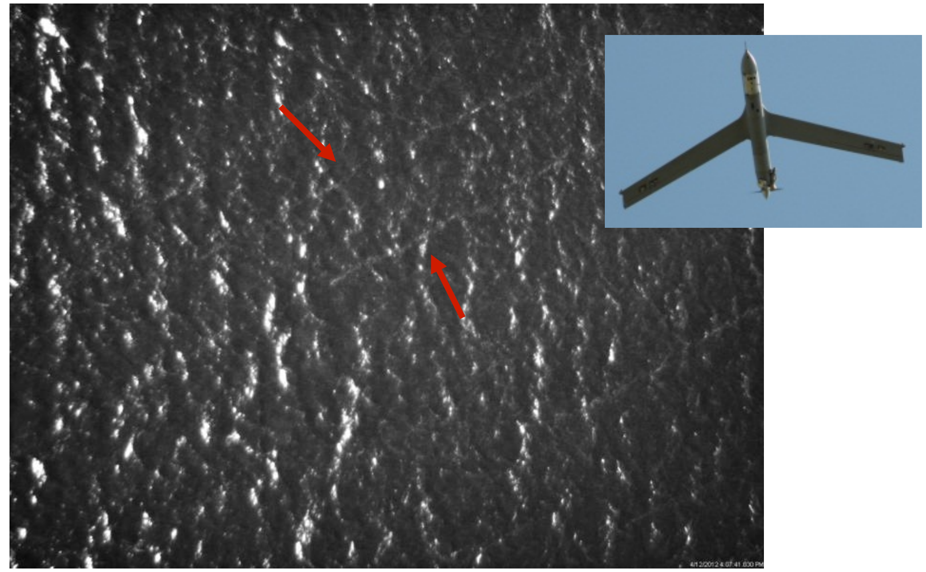


NSWCDD Flight ops POC: Lorenz Eber

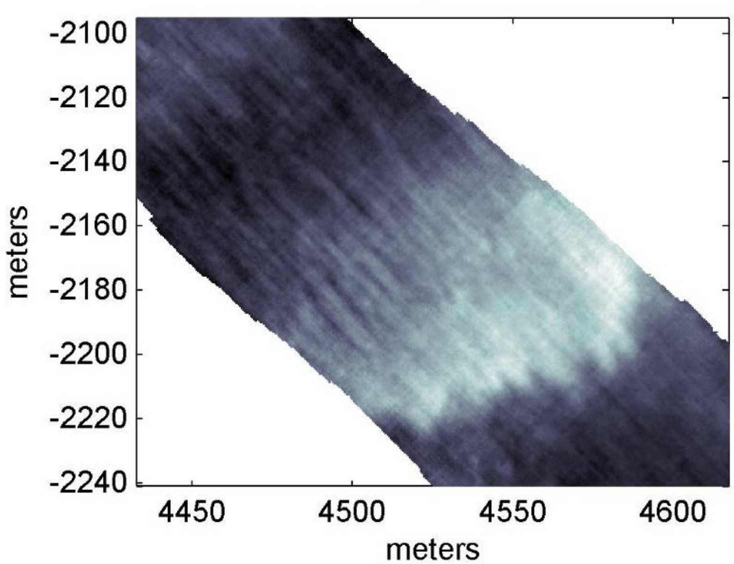
SIO ScanEagle video/infrared measurement of the Potomac river

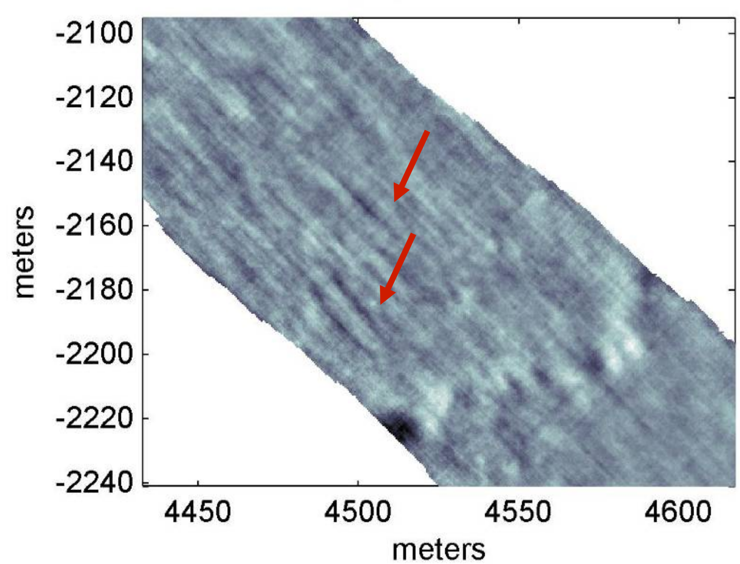
Example of video & infrared imagery – Langmuir Cells



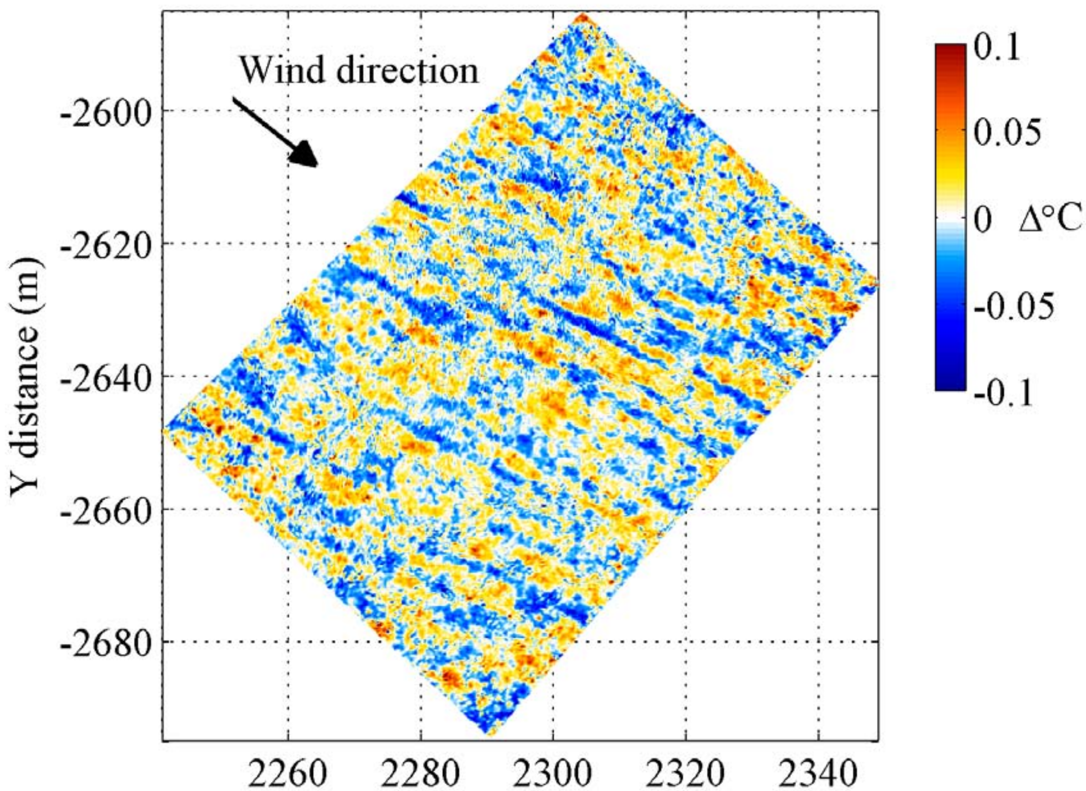


Infrared (Earth-referenced)





SIO ScanEagle infrared measurement of the Potomac river

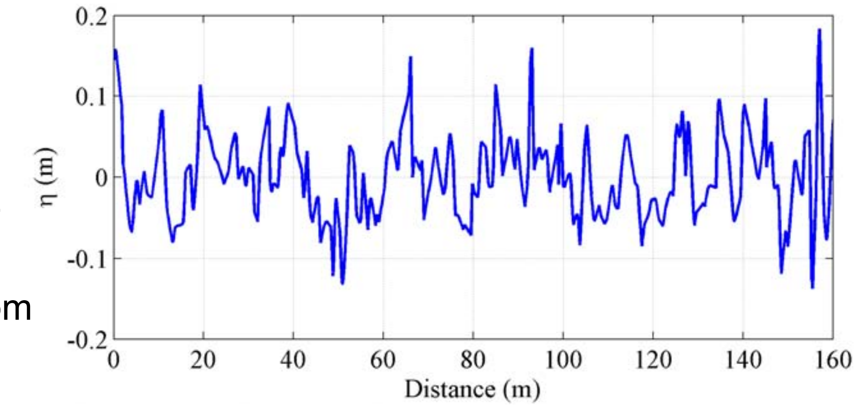


Sample georeferenced infrared image obtained with the ScanEagle Imaging payload during flights over the Potomac River on 12 April 2012 from an altitude of 193 m AGL. Note the along-wind structures with a persistent 4 – 6 m spacing, indicative of Langmuir-type circulations. Water depth in the vicinity of the image location is 2.5 – 3.0 m. Wind speed (15.9 m s^{-1} ±2.5 m s^{-1}, 1σ) and direction (313◦ ±14◦) are calculated at the UAV altitude with the ScanEagle autopilot system based on heading, airspeed, and aircraft track.

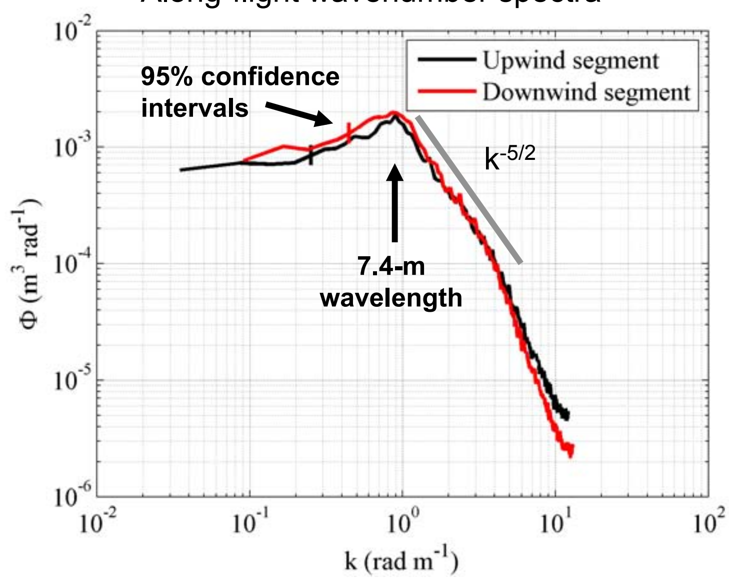
Nadir lidar surface measurements

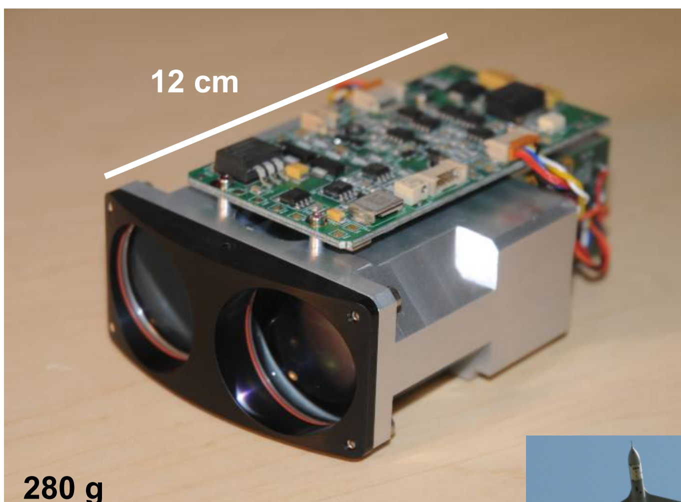
- Light Detection and Ranging (lidar) for measurements of surface topography
- Modified MDL ILM-500-R
- Near-IR (not surface penetrating) – Class IM
- Range: 500 m hard target, >300 m over water, 44 Hz sampling rate (averaged from 1kHz laser ping rate)
- Accuracy approx. 9 cm rms, after georeferencing (from similar UAV lidar experiments with repeated passes over a runway – Camp Roberts, Jan 2011)

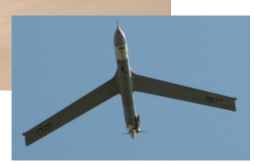
Sample sea surface elevation
32 m AGL UAV altitude



Along-flight wavenumber spectra

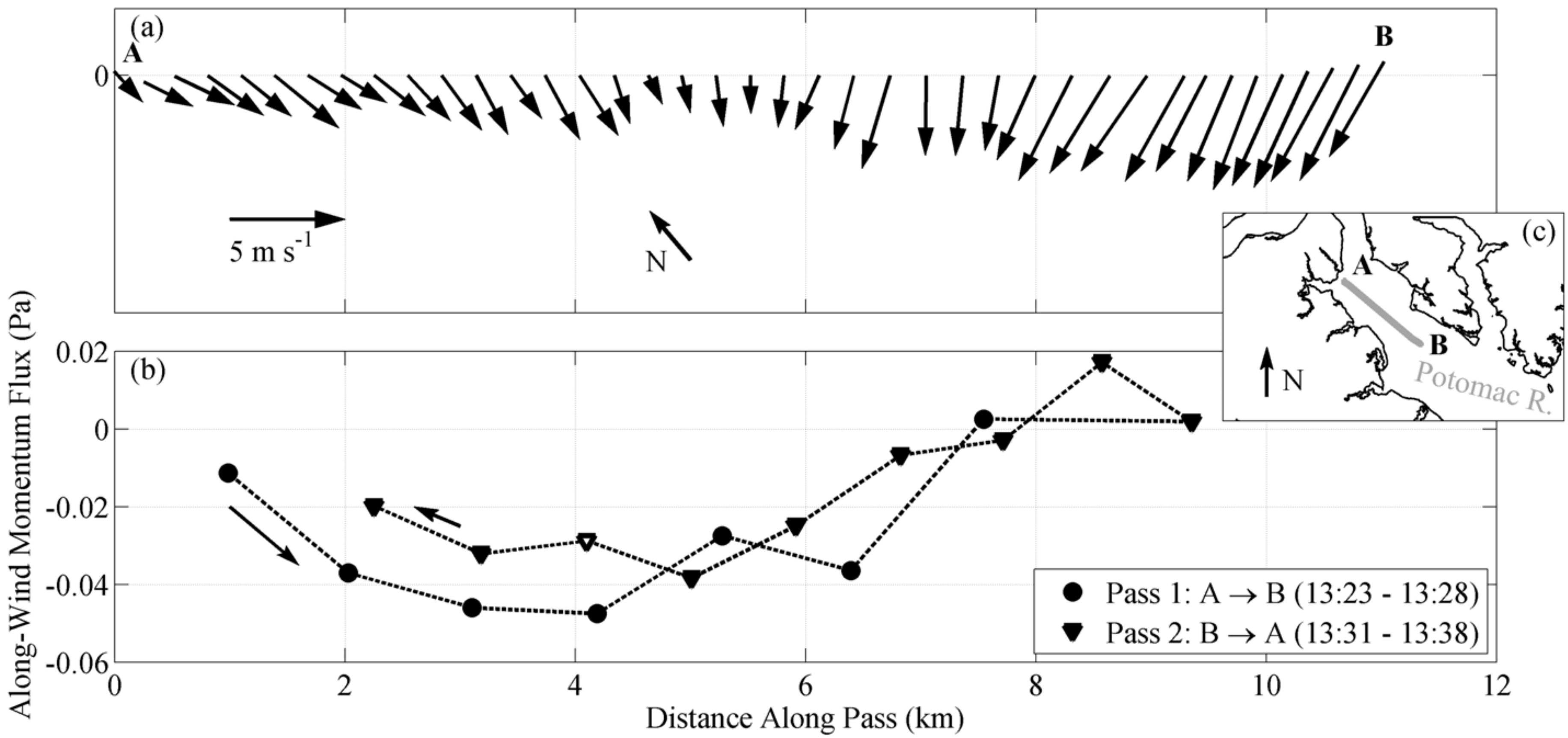






4500 m used in each spectra
100-m Hanning windows
spectra are Doppler-shifted to account for speed of UAV

Low-altitude wind and flux measurements (31m above MSL)

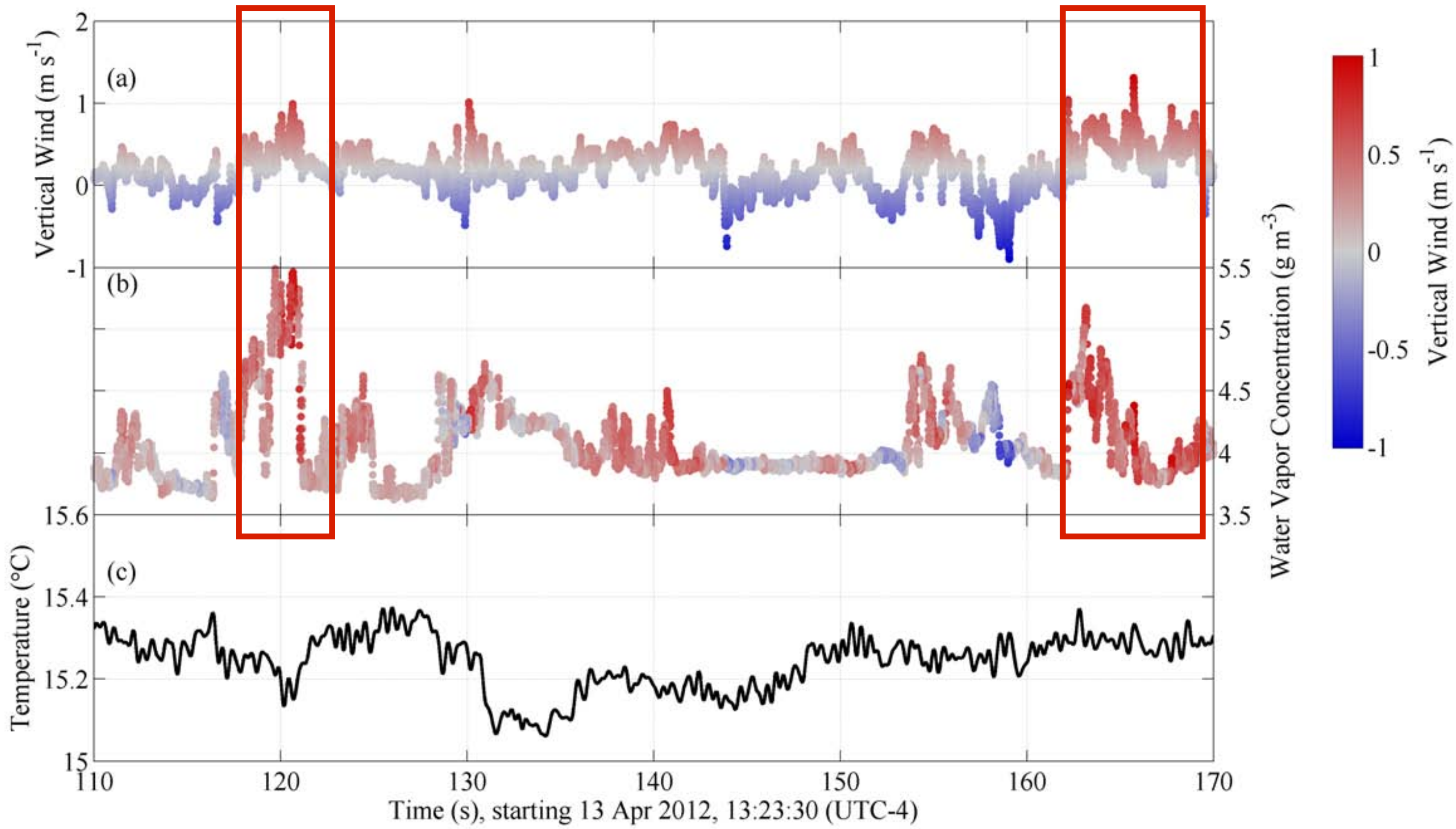


(a) Low-altitude (31 m) flight track with measured horizontal wind vectors (pointing downwind) at 10-s intervals. (b) Along-wind vertical momentum flux for the two passes. A trend of more positive momentum flux is observed towards the southeastern (down-river) region in both pass directions, associated with an increase is wind speed and a shift in wind direction. Local start times (UTC-4) are given. (c) Map inset, showing the location of the 9-km segments as a thick gray line.

SIO ScanEagle UAS flight tests – FLUX payload

- Naval Surface Warfare Center Dahlgren Division, 12-16 April 2012
- Sample time sereis from low-altitude (31 m, 100 ft) pass over Potomac River
- Positive correlation between vertical wind and water vapor
- Implies positive latent heat flux (quantified in following slide)

Time series, 31 m AGL (100 ft)



SIO ScanEagle UAS flight tests, flux measurements

- Naval Surface Warfare Center Dahlgren Division, 12-16 April 2012
- **First low-altitude over-water flux measurements from a UAV**

Along-wind momentum flux: $\tau_x = \rho\langle u'w'\rangle,$

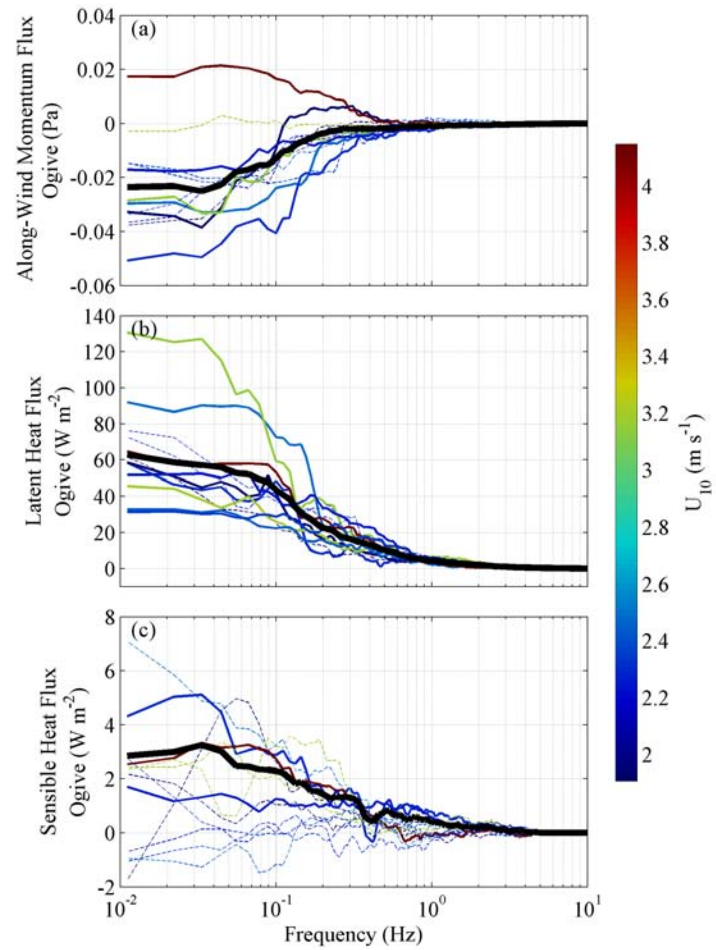
Across-wind momentum flux: $\tau_y = \rho\langle v'w'\rangle,$

Latent heat flux: $Q_L = L_v\langle q'w'\rangle,$

Sensible heat flux: $Q_S = \rho C_p\langle \theta_v'w'\rangle,$

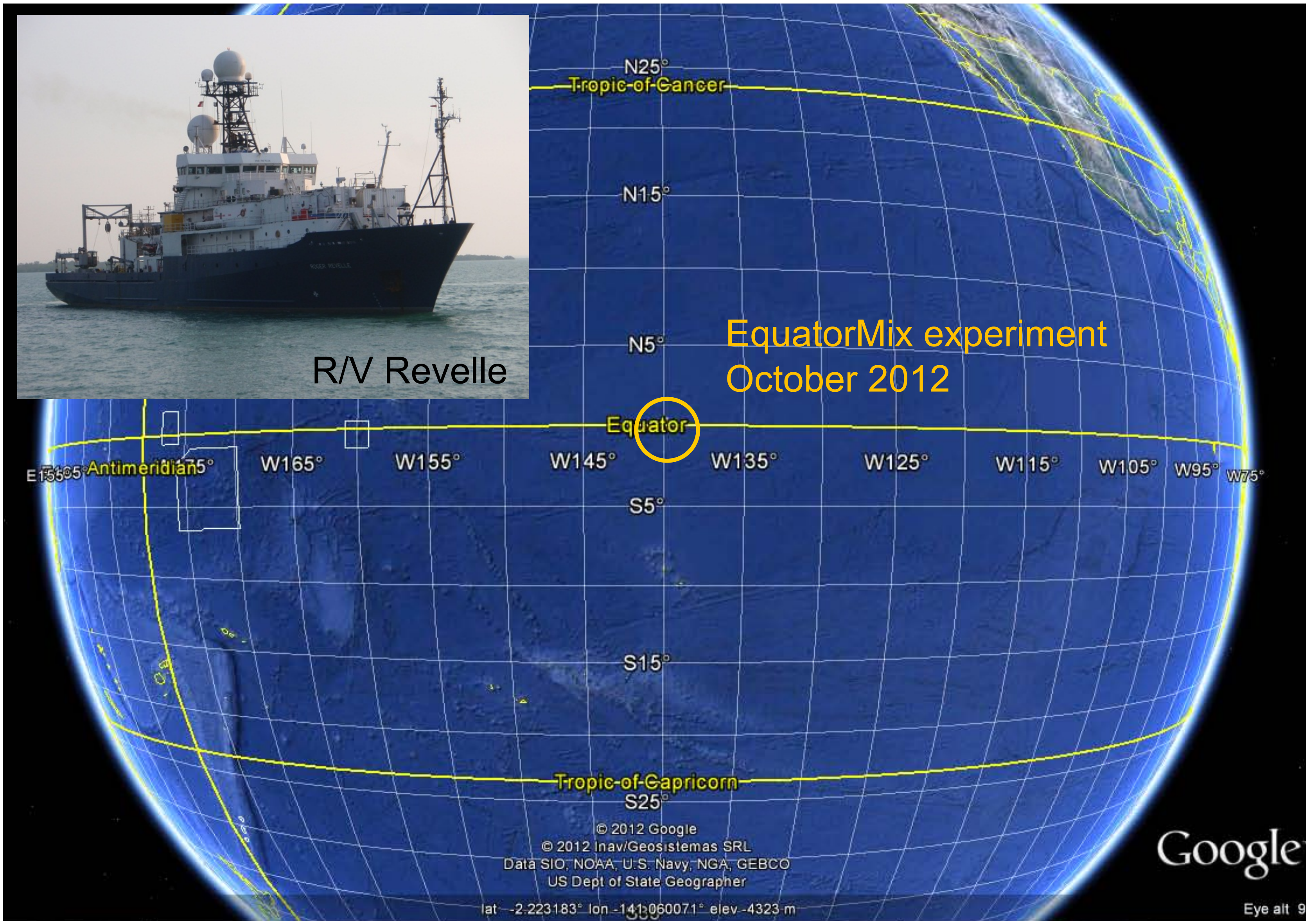
u', v', w'	turbulent along, across, and vertical wind
θ_v'	turbulent virtual potential temperature
q'	turbulent water vapor concentration
ρ	air density
C_p	specific heat of air
L_v	latent heat of vaporization
< >	ensemble average

Integrated cospectra "ogives" for flux measurements



- 90-s segments (2.5-km @ 28 m/s)
- Dotted ogives have been rejected

Questions?



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SIO Manta, ScanEagle payload instrumentation

Payload key:

MF: Manta Flux
MR: Manta Radiometric

SF: ScanEagle **Flux**
SR: ScanEagle **Radiometric**
SI: ScanEagle **Imaging**

Payload(s)	Instrument	Weight (kg)	Measurement/function
MF, SF	Turbulence probe	0.15	Relative wind, momentum and scalar fluxes
MF, SF	Campbell Sci. krypton hygrometer	0.14	Water vapor, latent heat flux
MF, SF/I	Measurement Specialities nadir lidar	varies$^{\dashv}$	Topography, surface waves (MF only: low-alt. flight)
MF	Honeywell IMU (HG1700 AG58)	0.73	Georeferencing winds and lidar
SF	Northrop Grumman IMU (LN200)	0.75	Georeferencing winds and lidar
MF, SF	NovAtel SPAN circuitry	0.13	GPS/IMU synchronization
MF, SF	Opsens Fiber optic temp. sensor	0.12	Temperature, sensible heat flux
MR, SR	Pyranometers/pyrgeometers (2x ea.)	varies$^{\vdash}$	Short-/long-wave, up-/downwelling radiation, SST
MR, SR/I	Prosilica camera	0.19	Ocean surface processes, wave kinematics and breaking
SI	FLIR LWIR camera	0.46	Ocean surface temperature structure
SF/R/I	Everest Sea-Therm	0.03	SST
all	NovAtel OEMV-3 RTK-DGPS	0.08	Position, aircraft control
all	Vaisala humidity, temperature sensor	0.20	RH/T profiles, bulk fluxes
all	DAQ, electronics	varies$^{\perp}$	Acquisition, processing, power regulation, SSDs

$^{\dashv}$ILM-1500-R (0.82 kg) for Manta payloads, ILM-500-R (0.28 kg) for ScanEagle payloads.

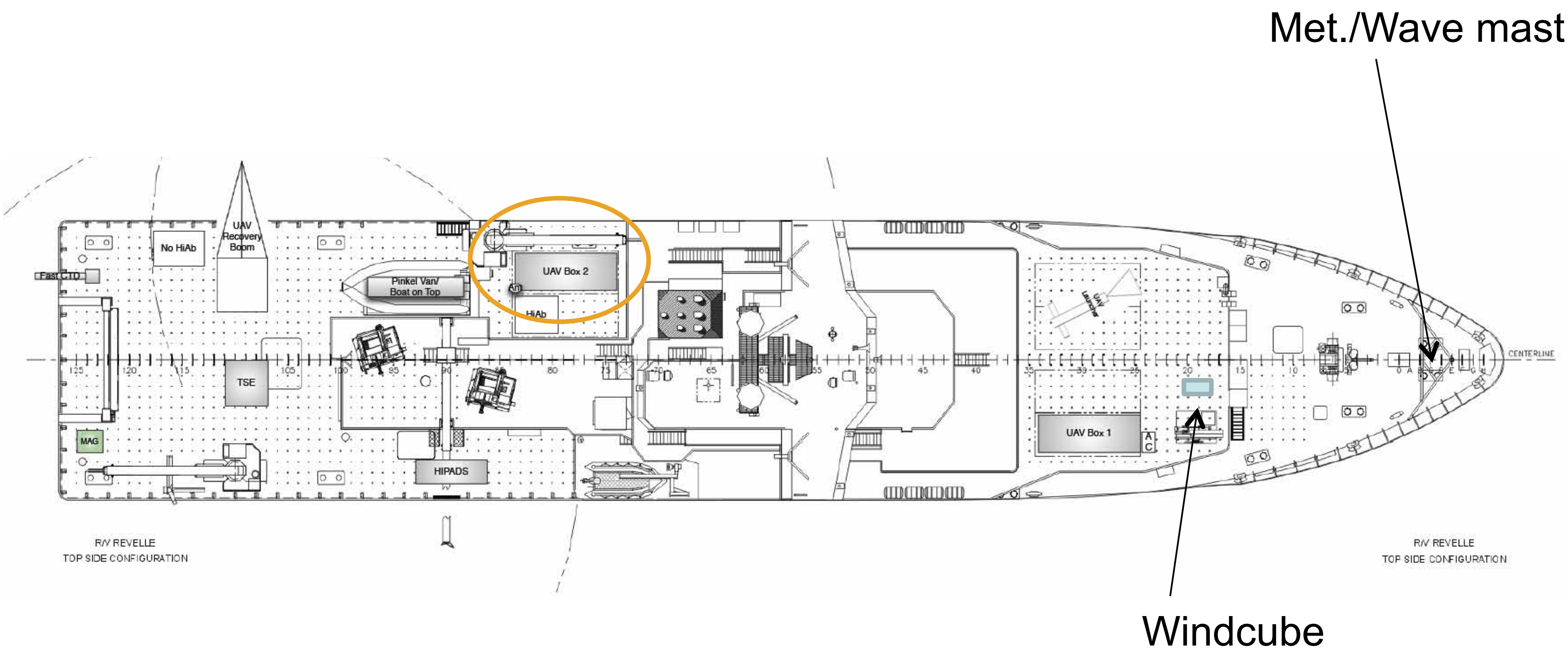
$^{\vdash}$Kipp and Zonen CMP3 and CGR3 (0.27 kg ea.) for Manta payloads, Hukseflux SR03 and IR02 (0.18 kg ea. after custom modifications) for ScanEagle payloads.

$^{\perp}$1.74 kg for Manta payloads, 0.73 kg for ScanEagle payloads.

SIO Manta, ScanEagle platform comparison

	BAE Manta C1	Boeing-Insitu ScanEagle
Mission Endurance	5 hrs (for 6.8 kg payload)	(see Payload Capacity, below)
Mission Airspeed	21 – 39 m s^{-1} (40 – 75 kts)	25 m s^{-1} (48 kts)
Dash Airspeed	41 m s^{-1} (80 kts)	41 m s^{-1} (80 kts)
Stall Airspeed	20 m s^{-1} (36 kts)	20 m s^{-1} (36 kts)
Service Ceiling	5.3 km	5 km
Control Radio Range	37 km (20 nm) line-of-sight	100 km (54 nm) line-of-sight
Engine	4.0 kW (5.5 hp), 2-stroke/2-cylinder	1.4 kW (1.9 hp), 2-stroke/2-cylinder
Payload Capacity	6.8 kg (5-hr endurance)	2 kg (8-hr endurance), 6 kg fuel+payload
Fuel Capacity	8.1 L	(see Payload Capacity)
Wing Span	2.7 m	3.11 m
Fuselage Length	1.9 m	1.37 m
Tail Height	0.6 m	N/A
Navigation System	Cloud Cap Piccolo II GPS/INS	Boeing-Insitu
Launch method	runway rolling takeoff	portable pneumatic launcher
Recovery method	runway rolling landing	"Skyhook" wing capture with vertical cable

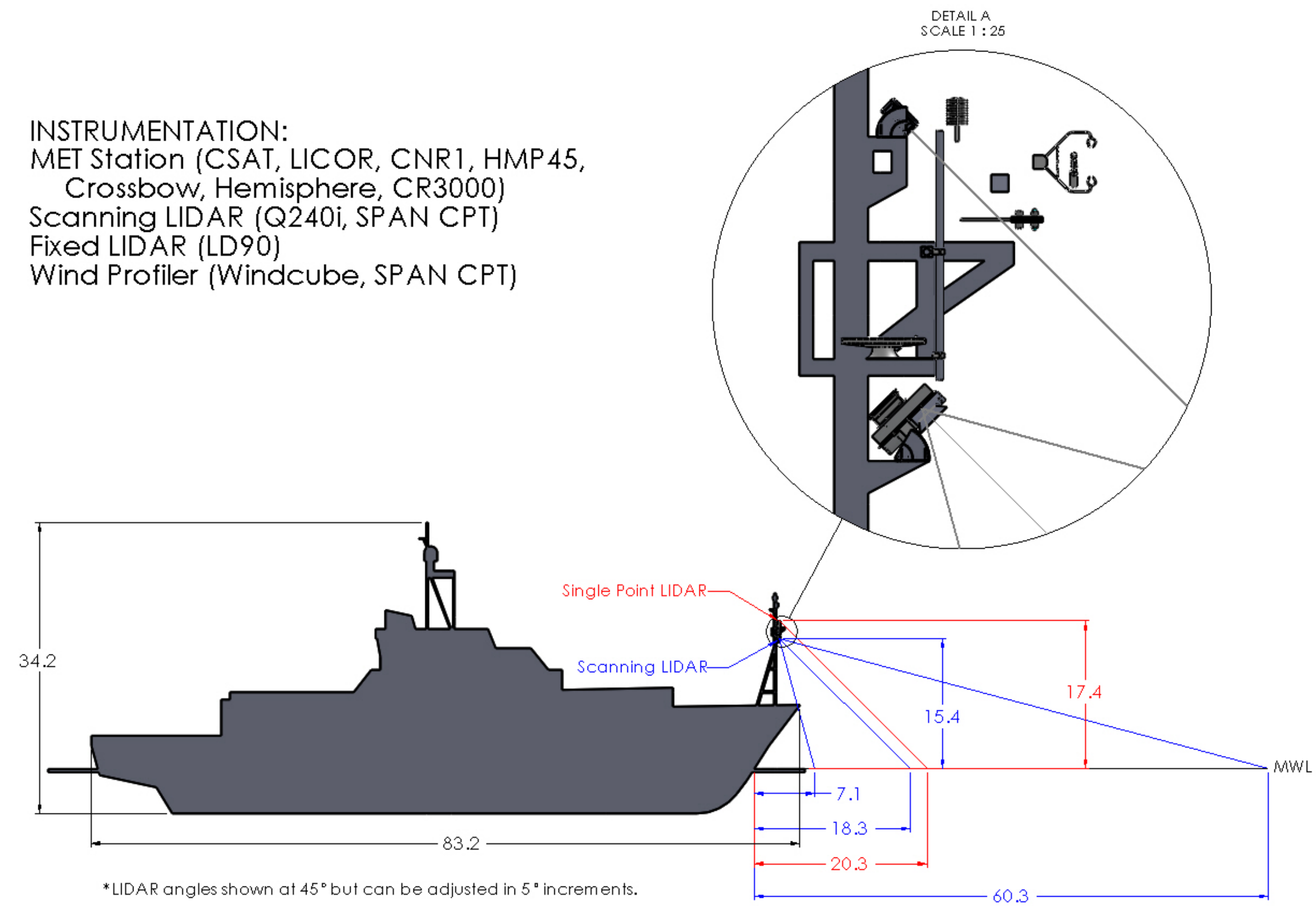
Ship Layout


Met./Wave mast
Windcube
UAV Recovery Boom
No HiAb
Fast CTD
Pinkel Van/ Boat on Top
UAV Box 2
HiAb
TSE
MAG
HIPADS
UAV Box 1
CENTERLINE
R/V REVELLE
TOP SIDE CONFIGURATION
R/V REVELLE
TOP SIDE CONFIGURATION

Ship Layout

Ship Layout

INSTRUMENTATION:
MET Station (CSAT, LICOR, CNR1, HMP45, Crossbow, Hemisphere, CR3000)
Scanning LIDAR (Q240i, SPAN CPT)
Fixed LIDAR (LD90)
Wind Profiler (Windcube, SPAN CPT)



*LIDAR angles shown at 45° but can be adjusted in 5° increments.