Probing the Surface Layer over the Gulf Stream with the Controlled Towed Vehicle (CTV): Unique High-Resolution Turbulence Measurements

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Outline

Motivation for the Controlled Towed Vehicle (CTV) development

Brief description of main CTV instrumentation and systems

CTV improved height-keeping and Attitude performance

Research goals of ongoing CASPER project

CTV air-sea interaction observations over the Gulf Stream during CASPER-East

Summary and Conclusions

Controlled Towed Vehicle (CTV) Motivation & Goals

1. Measure air-sea fluxes of momentum (stress), sensible heat, water vapor (latent heat) and trace gases (CO_2) **near the ocean surface even in high winds and seas.**

2. Profile the boundary layer for determination of mean and turbulent variations, e.g., wind profile, flux divergences for model verification.

3. Manned aircraft are suitable platforms due to their mobility (large spatial coverage), ability to sample cross-wind and capability to fly in high winds. However, they are limited to > 33 m (some much higher). It is desirable to extend their reach nearer the surface **without compromising safety.**

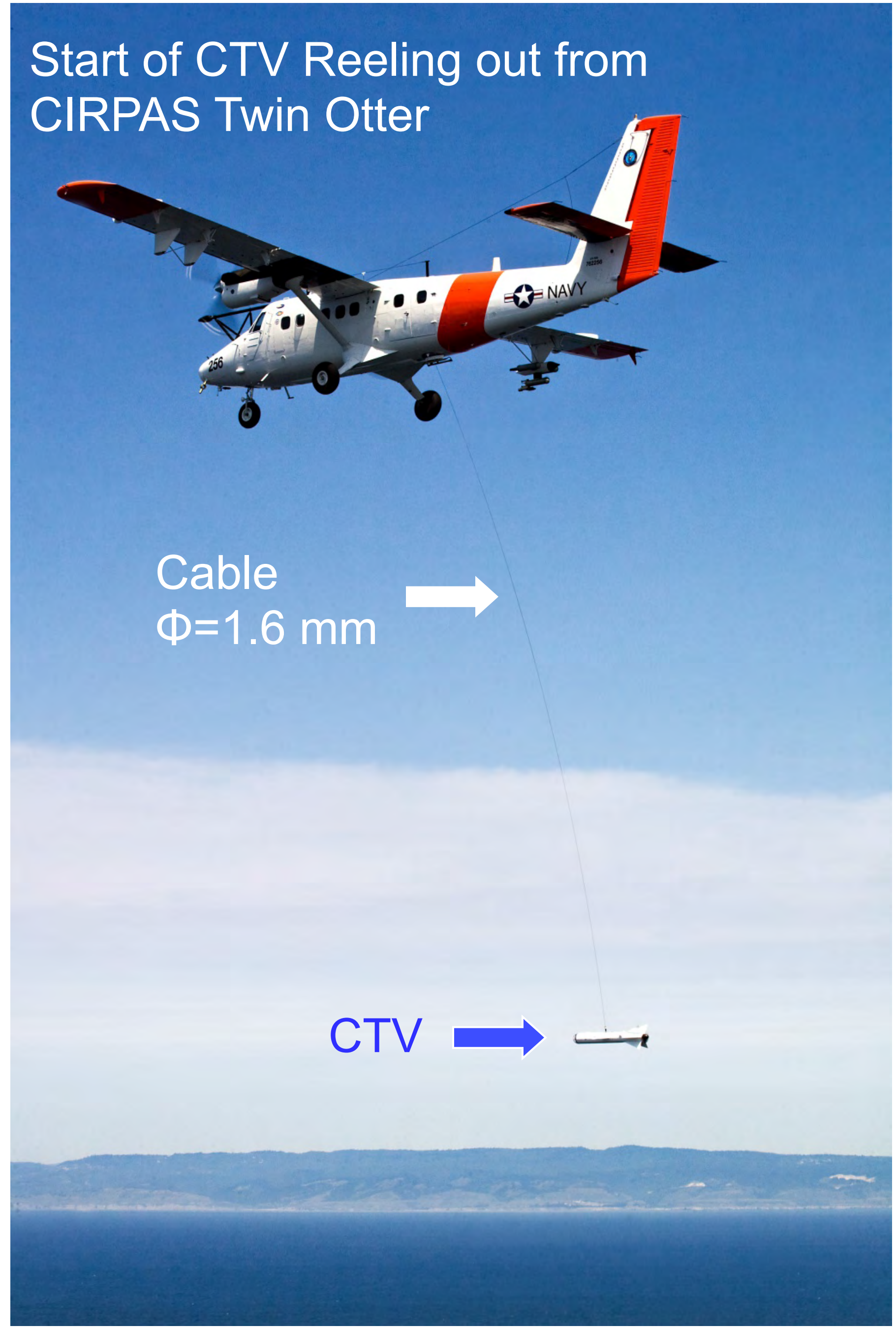
4. Towed target drones with active height-keeping control are proven technology and are readily adaptable for scientific measurements and can "fly" **as low as 10 meters** long enough for eddy correlation fluxes measurements.

5. No need to rely on Monin-Obukhov similarity theory which assumes constant flux surface layer, steady state and no heterogeneities.

Choice of platform in Inhospitable Ocean Environment

1. Buoy – few, fixed-point, **motion**
2. Ship – slow, **motion, flow distortions**
3. Aircraft – mobile, low altitude limit
4. Unmanned Aerial Systems – small payload, underpowered, restrictions

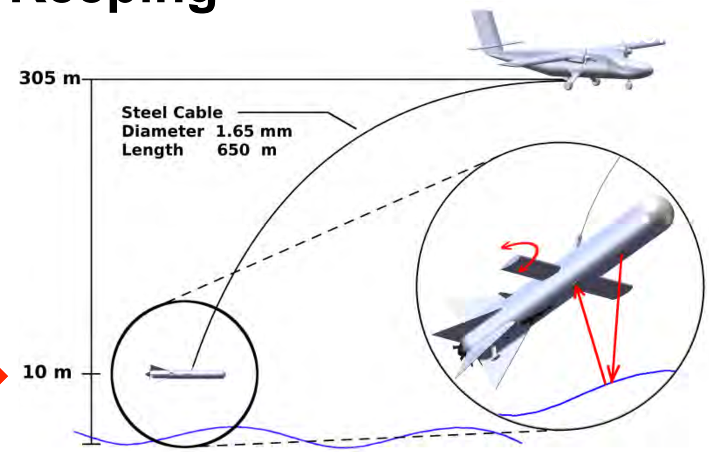
5. Controlled Towed Vehicle (CTV): Modified existing "sea-skimming" towed target drone technology to develop a sampling platform capable of **active height-keeping as low as 10 m ASL** while tow aircraft flies safely above.



Controlled Towed Vehicle (CTV)

Height Keeping

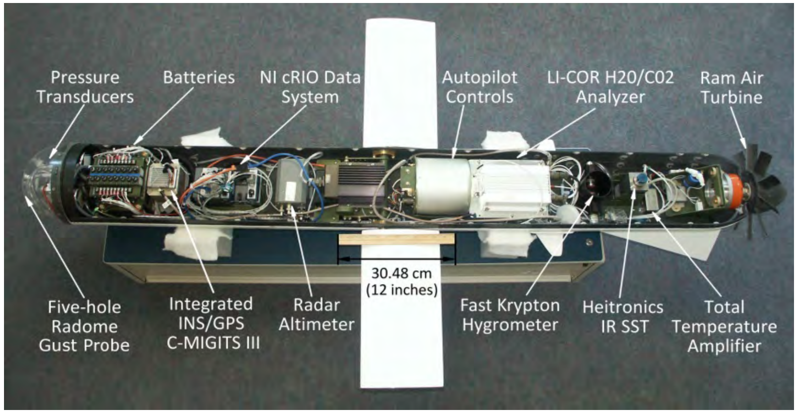
No need for MOST

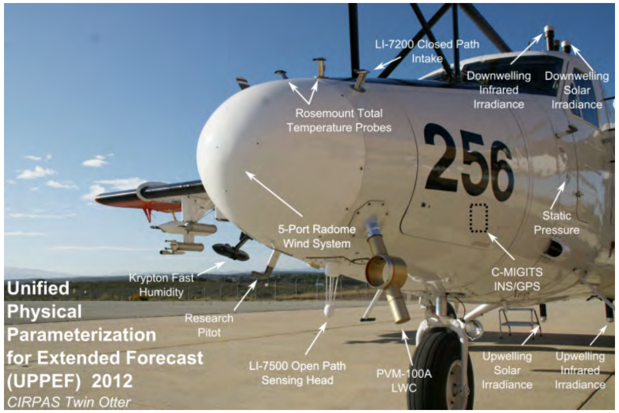


On flux leg at 10 m

- Mean & fluctuating u,v,w (**motion corrected**)
- Mean & fluctuating T, q, p (redundant sensors)
- Sea surface and "sky" IR temperatures
- Platform motion sensing INS/GPS units
- High bandwidth ~40 Hz for eddy covariance fluxes

Instrumentation (~identical to Twin Otter's)





D=0.23 m; L=2.2m; Payload=45 kg; Power=250 W Self-generated

Improved CTV Control System

Piccolo SL Autopilot

(Cloud Cap Technology)

100 waypoints saved in autopilot

3 axis gyroscopes. 300 deg/sec

3 axis acceleration. 6g

Transponders, Secondary Comms Radios, Iridium SatComm, TASE Gimbals, Servo PTZ gimbals, Magnetometers, Laser Altimeters, Payload Passthrough, RTK GPS

Vin: 4.5 – 28 volts

Power: 4 W (typical including 900 MHz radio)

Size: 130 x 59 x 19 mm (5.1 x 2.34 x 0.76 inches)

Weight: 110 grams (3.9 oz) with 900 MHz radio

Operating Temperature: -40C to +80C (calibrated Range, no case)

Miniature Radar Altimeter Autopilot (Roke Manor Research, LTD)

MRA Type 2 – system specification

Altitude	
Nominal Range	0.2 to 100m
Resolution	
Default	0.02m

Physical	
Length	140 mm
Width	75 mm
Height	46 mm
Weight	400g
Integrated antenna dimensions	
Length	12.6 mm
Width	8.6 mm

04May2015 Height-Keeping Performance

Table 4: Simple statistics of radar height, z (MRA 2), true heading, ψ, pitch angle, θ, and roll angle, φ, from the RF03 04May2015 CTV flight with new control height-keeping (Piccolo/ UCI MRA2 altimeter). Runs are ordered from low to high altitudes.

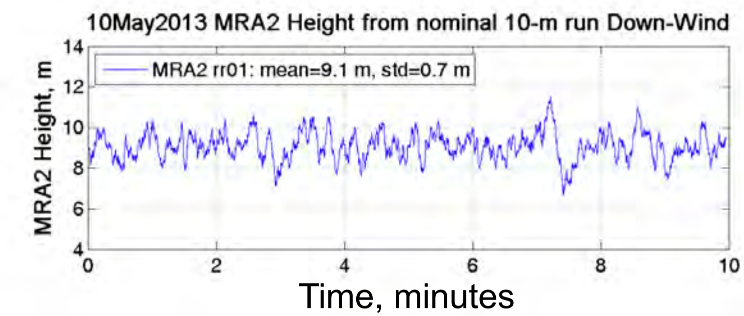
Run	Mean (z) m	Min (z) m	Max(z) m	Span(z) m	σ(z) m	σ(ψ) °	σ(θ) °	σ(φ) °
r03	9.0	6.3	10.9	4.6	0.8	0.8	0.5	0.6
r04	9.1	6.5	11.3	4.8	0.7	0.9	0.5	0.6
r07	9.1	6.3	12.4	6.2	1.2	1.0	0.6	0.7
r08	9.2	6.4	12.1	5.6	0.9	1.0	0.5	0.6
r09	11.1	8.7	13.7	4.9	1.0	0.8	0.5	0.5
r05	13.7	10.6	16.3	5.7	0.9	1.6	0.6	0.6
r10	15.2	12.0	18.1	6.0	0.9	3.4	0.7	0.7
r06	18.3	16.2	21.1	4.9	0.8	1.1	0.5	0.5
r01	30.4	25.7	33.7	8.0	1.1	1.5	0.7	0.5
r02	30.4	27.5	32.9	5.4	0.9	2.0	0.5	0.6
r11	30.4	26.3	34.0	7.7	1.2	1.3	0.7	0.6

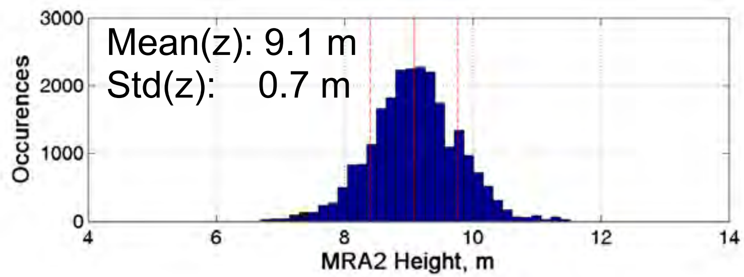
Heading

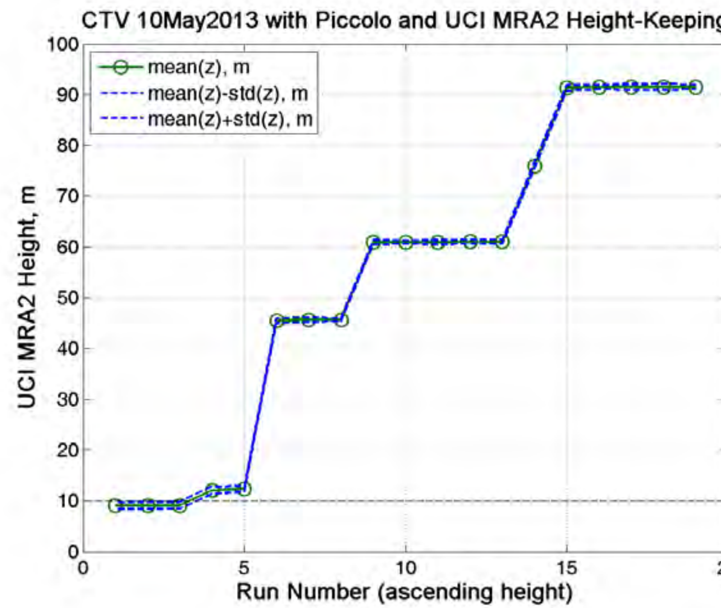
Pitch

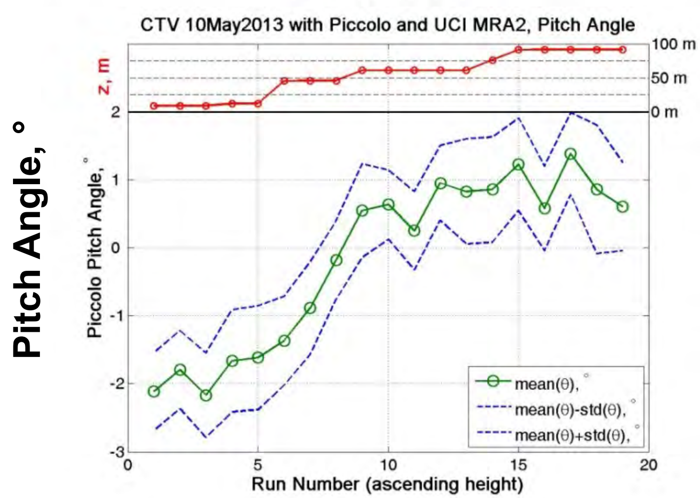
Roll

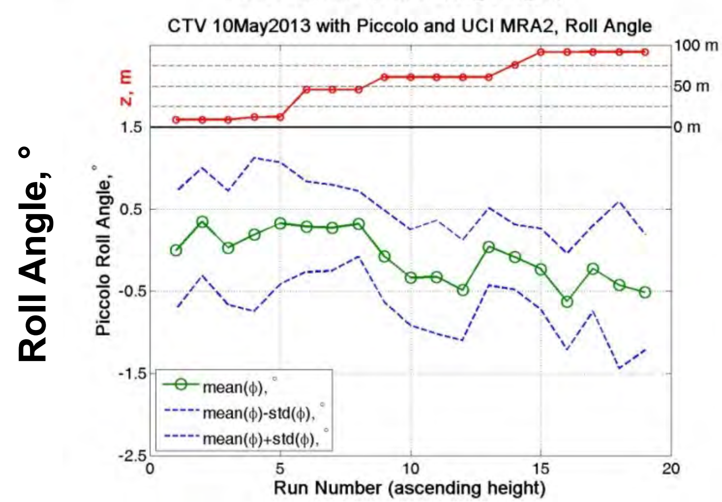
Height-Keeping, Pitching and Rolling Performance





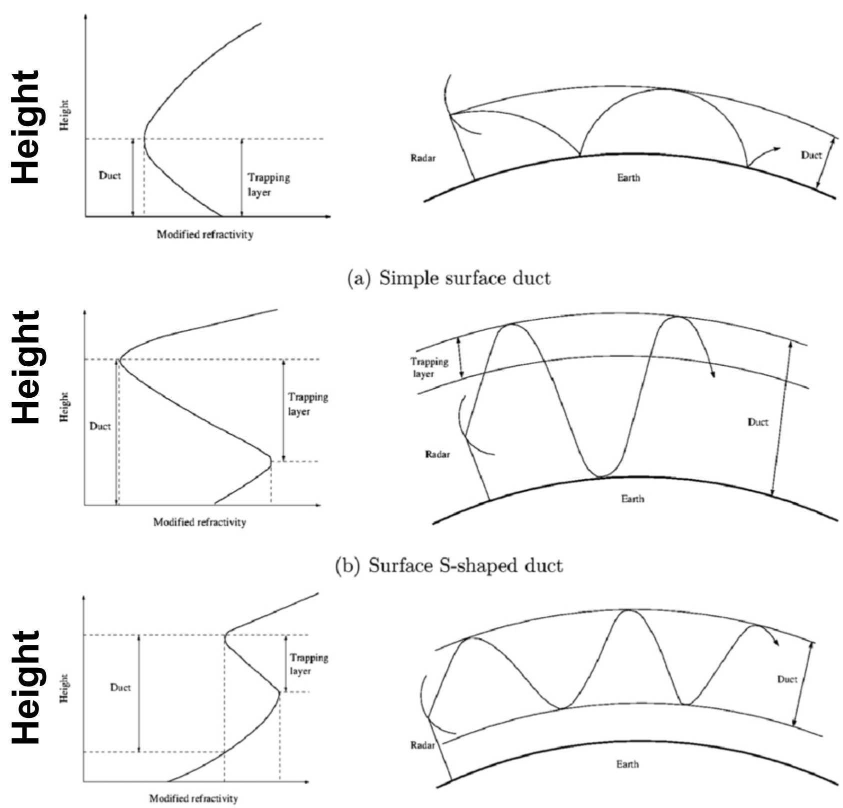






CASPER ONR MURI Project

Coupled **A**ir-**S**ea **P**rocesses and **E**M ducting **R**esearch (CASPER) ONR **MURI** project objective: **improve our understanding of air-sea interaction processes that cause *non-standard* electromagnetic (EM) propagation in coastal Marine Atmospheric Boundary Layers (MABL) with the ultimate goal to help improve EM propagation models.**



(a) Simple surface duct

(b) Surface S-shaped duct

(c) Elevated duct

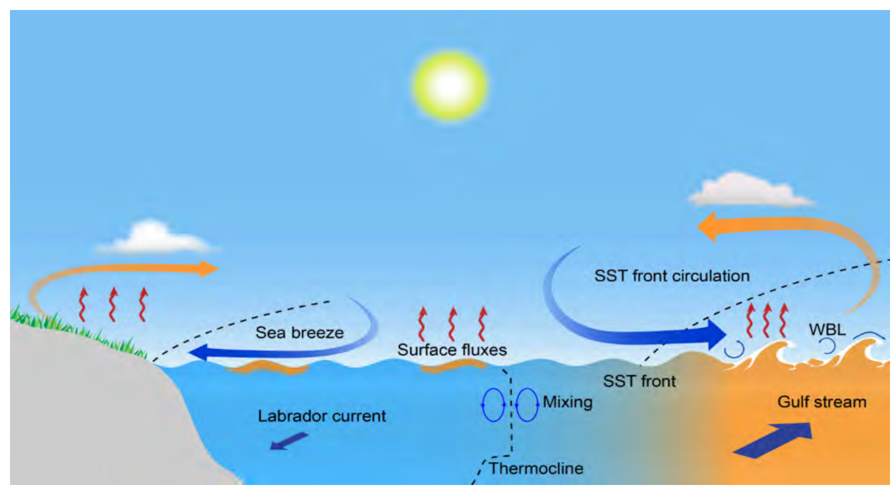
Zeng et al. (2014)

$$N = (n-1) \times 10^6$$

$$N = \frac{77.6}{T}\left(p + 4810\,\frac{e}{T}\right)$$

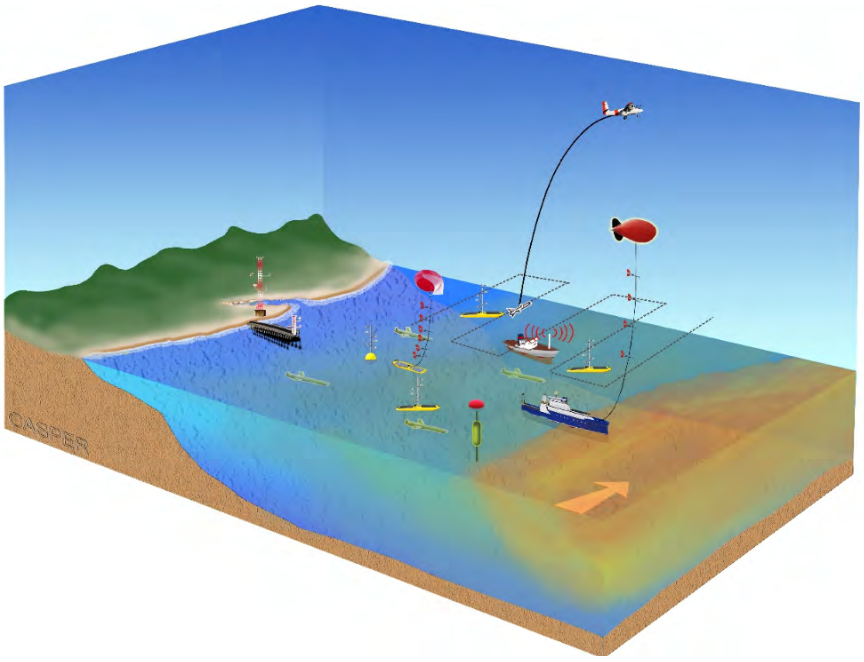
$$M = N + \frac{z}{R} \times 10^6 \qquad \text{(Modified Refractivity)}$$

n: index of refraction of the air
e: water vapor pressure, hPa.
T: air temperature, K
p: air pressure, hPa
z: height above the sea, m
R: mean radius of the earth, m



CASPER-East Field Experiment

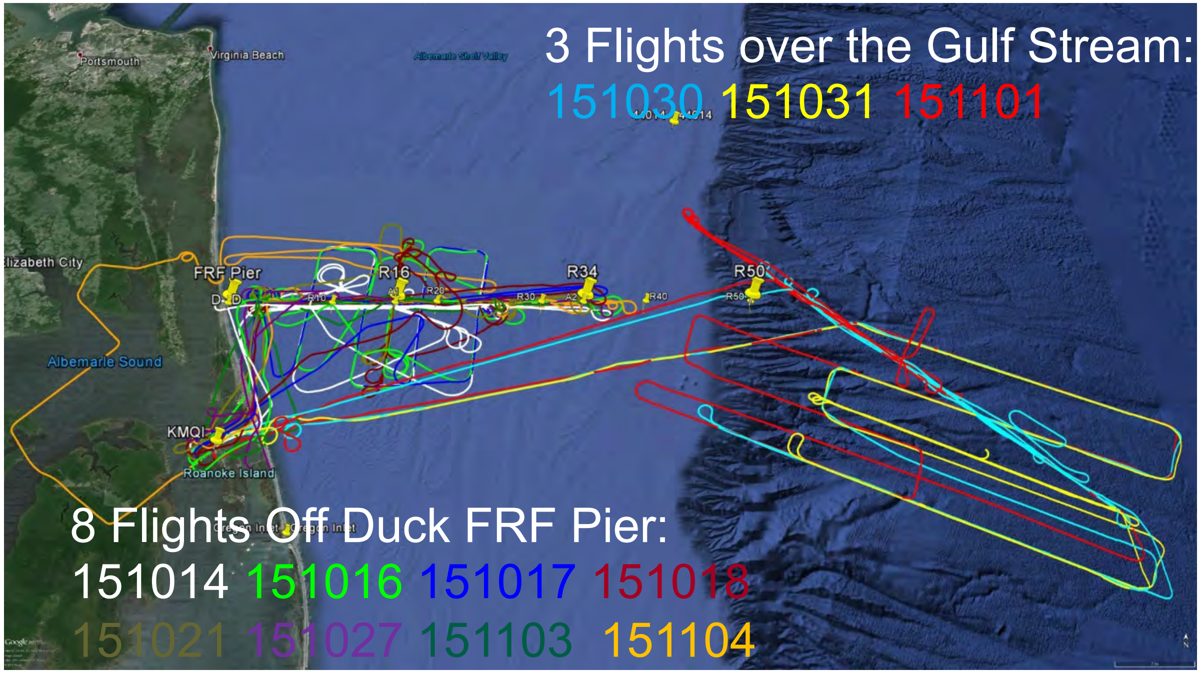
Our specific CASPER objective:
Characterize the EM propagation environment with high-resolution turbulence measurements in the MASL concurrently with EM propagation loss and oceanographic measurements

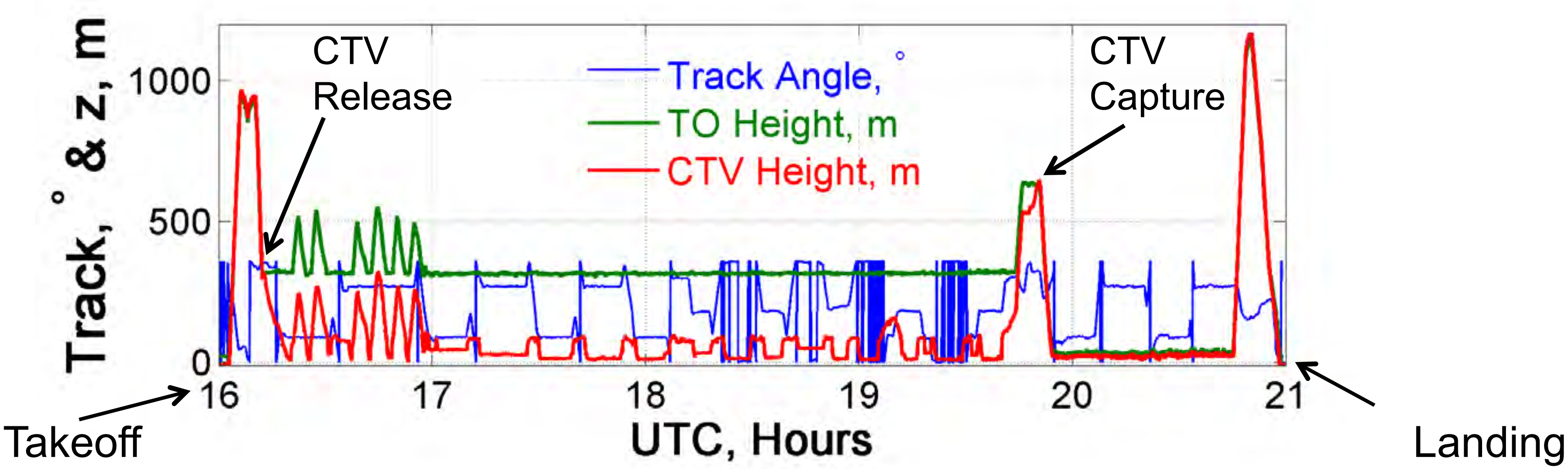


Method:
Use of Twin Otter and CTV aircraft flying the following modules:

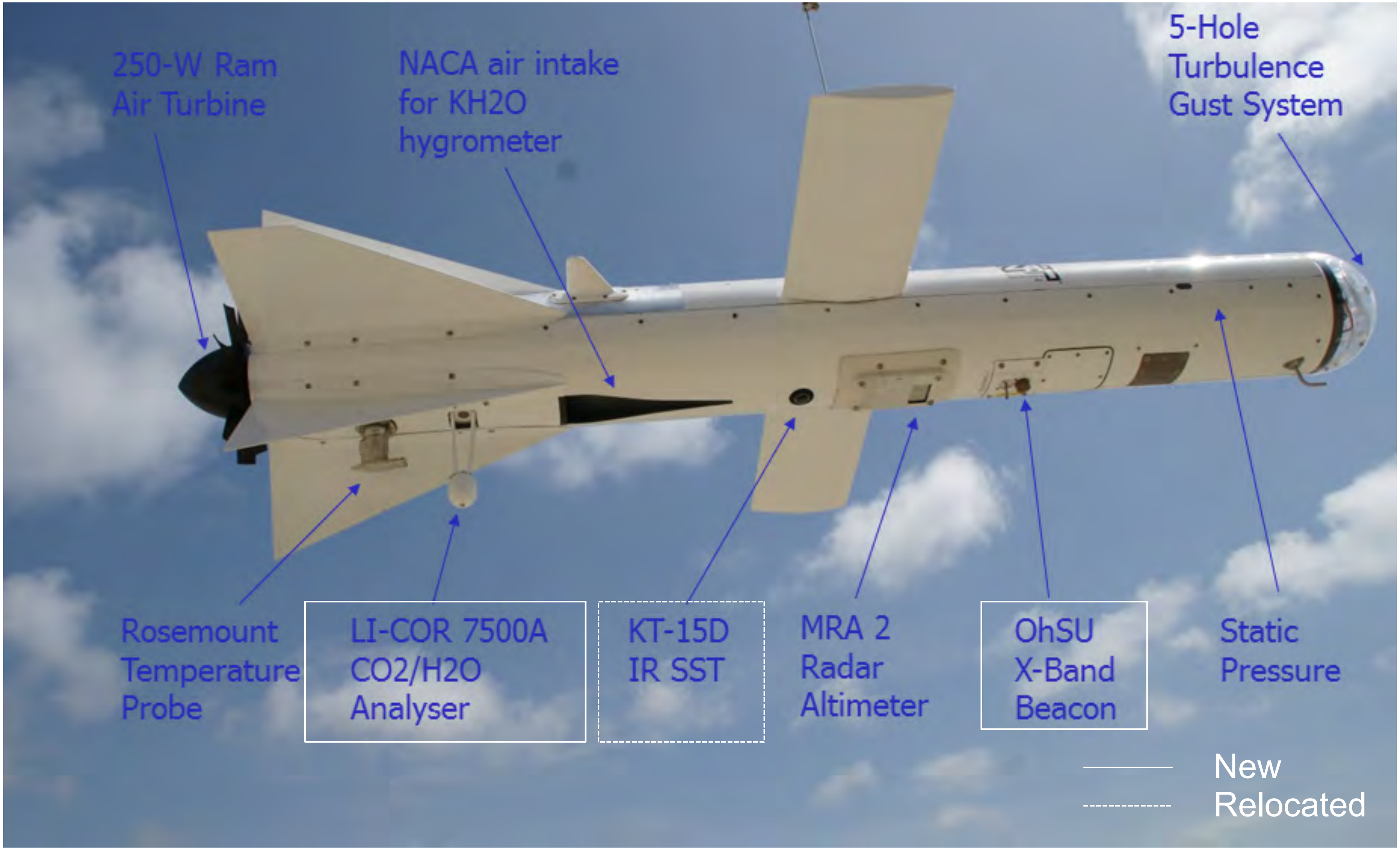
1. Flux Mapping patterns to characterize horizontal heterogeneities and surface forcing
2. Vertical sawtooth pattern to characterize surface MABL structure and vertical gradients
3. Deep soundings to characterize elevated ED structure and refractivity vertical gradients
4. Long flux stacks to characterize flux divergence and obtain more robust statistics on the scales affecting the refractivity variability

Twin Otter and CTV CASPER-East Flights

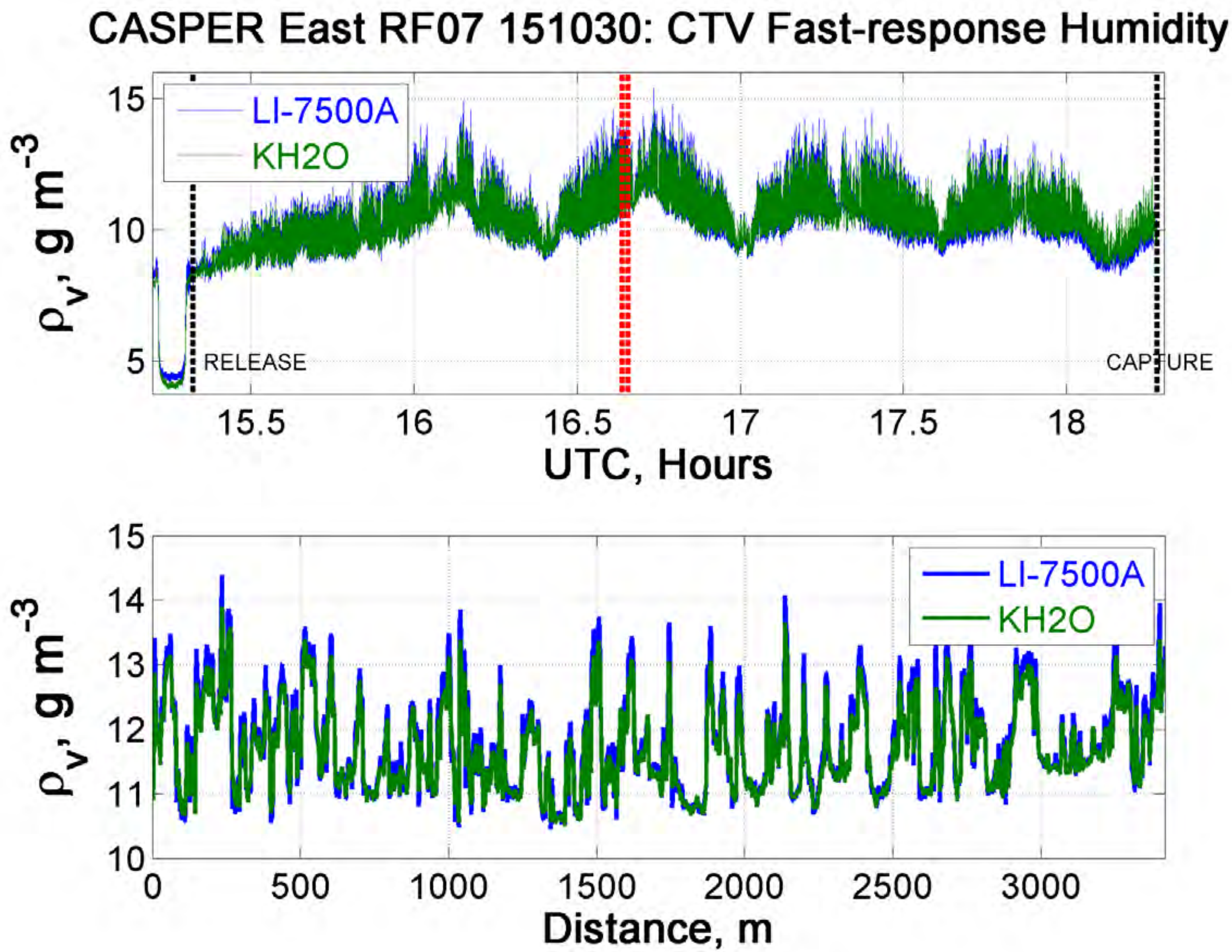




CTV Modifications for CASPER

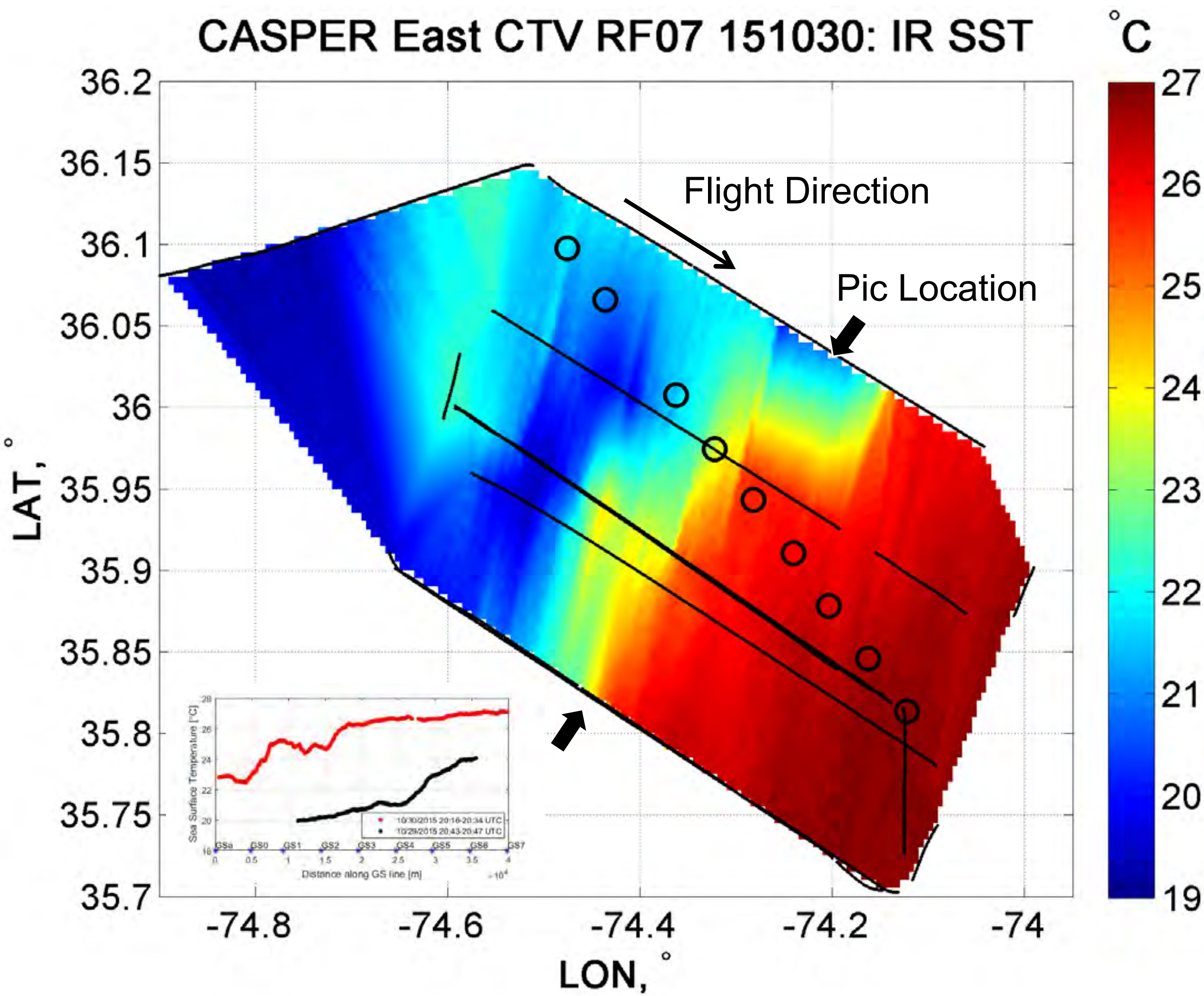


CTV Fast-response Humidity

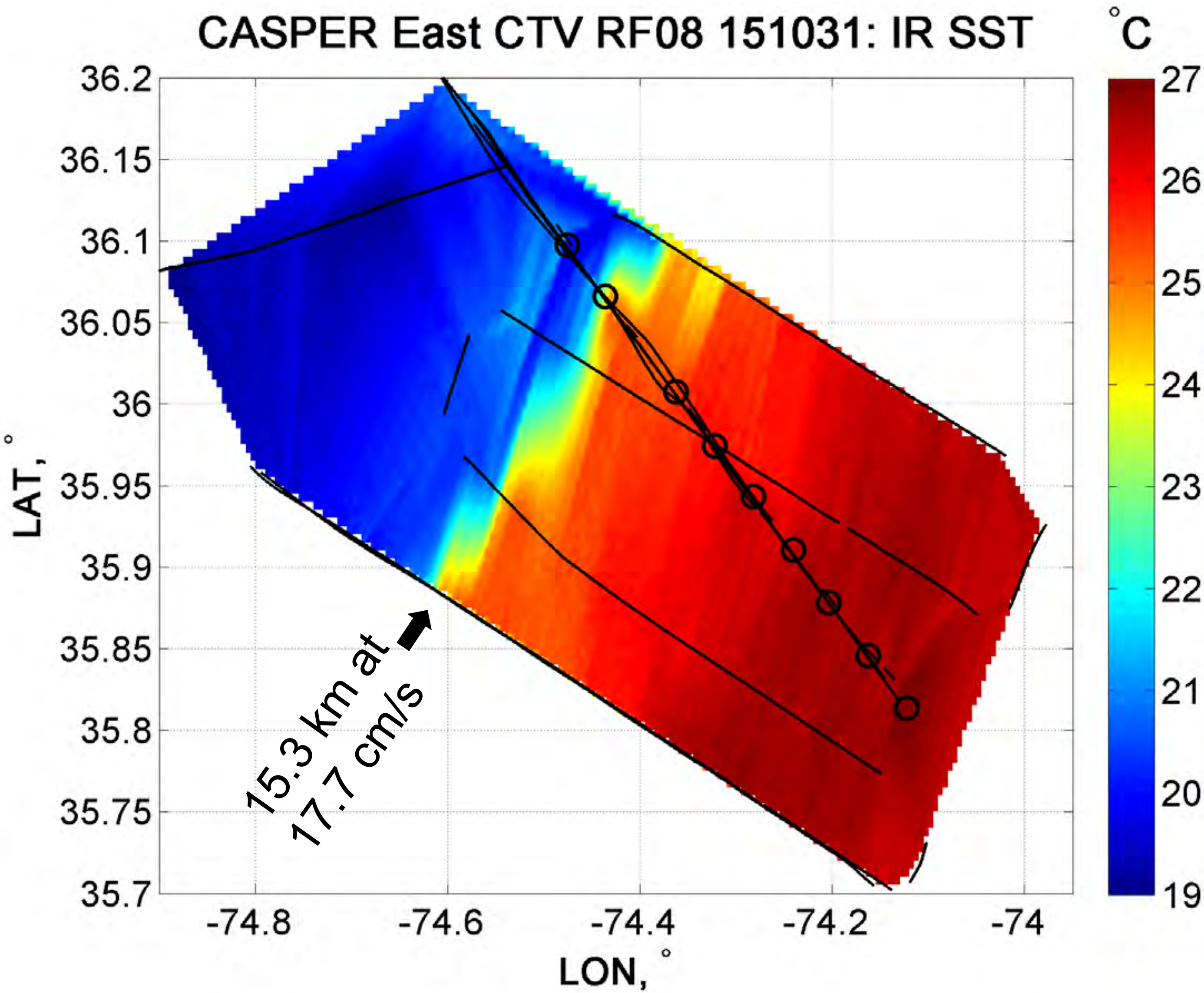


Gulf Stream Wave-Current Interaction

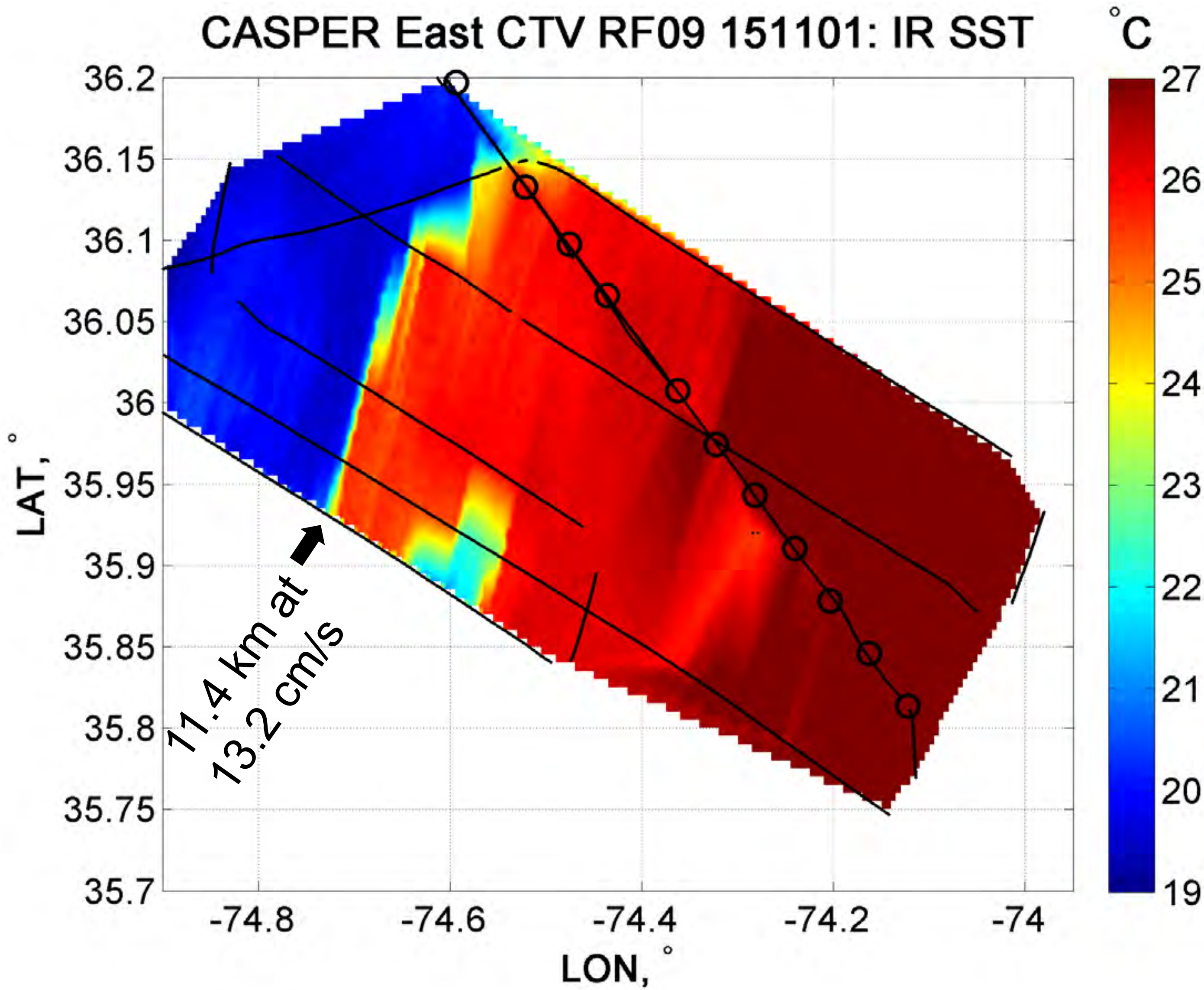
Gulf Stream SST Variability



Gulf Stream SST Variability



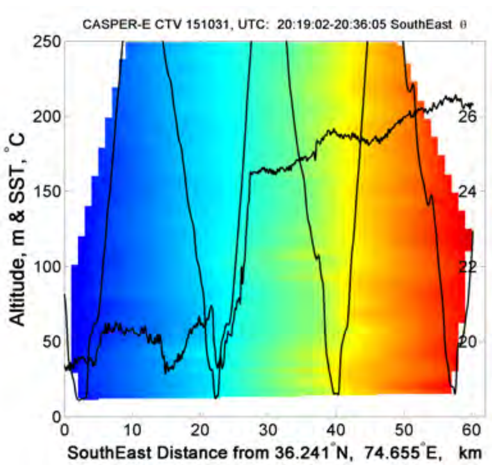
Gulf Stream SST Variability



Vertical Structure over the Gulf Stream

CTV Southeast porpoises on Oct 31, 2015 UTC: 20:19:02-20:36:05 (17 min)

θ



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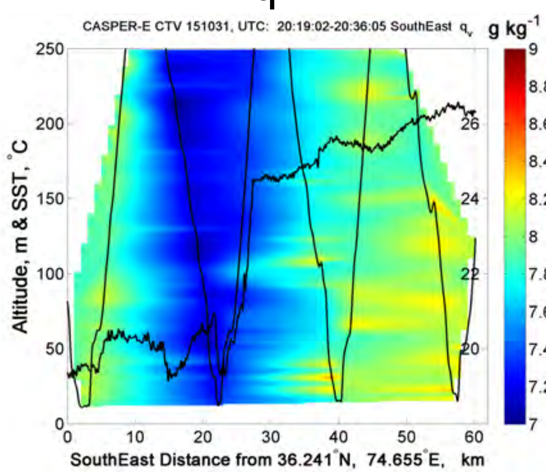
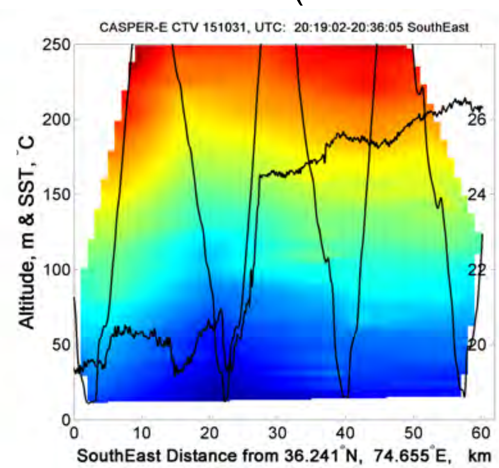


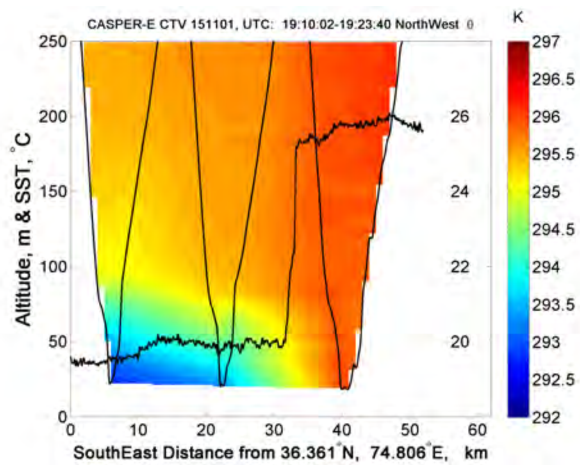
M (Modified Refractivity)



Vertical Structure over the Gulf Stream

CTV Northwest porpoises on Nov 01, 2015 UTC: 19:10:02-19:23:40 (13.5 min)

θ



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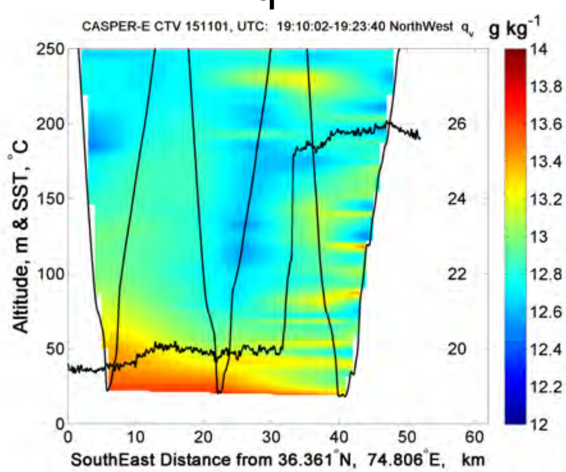
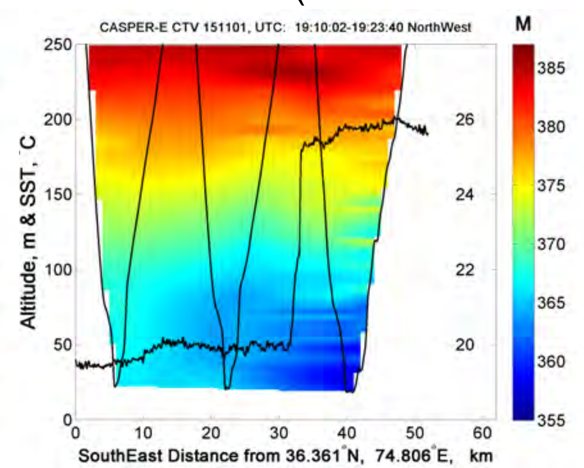


M (Modified Refractivity)



This is as close as one can get to a “snapshot ”of the MASL with in situ sampling. Ship are too slow to cover the distance (deviation from quasi-steady state assumption) with radiosondes (and even dropsondes from aircraft are not practical for just covering the lower part of the MABL) in addition to lower-quality instrumentation inherent to expendables.

Reynolds' Fluxes and Coefficients

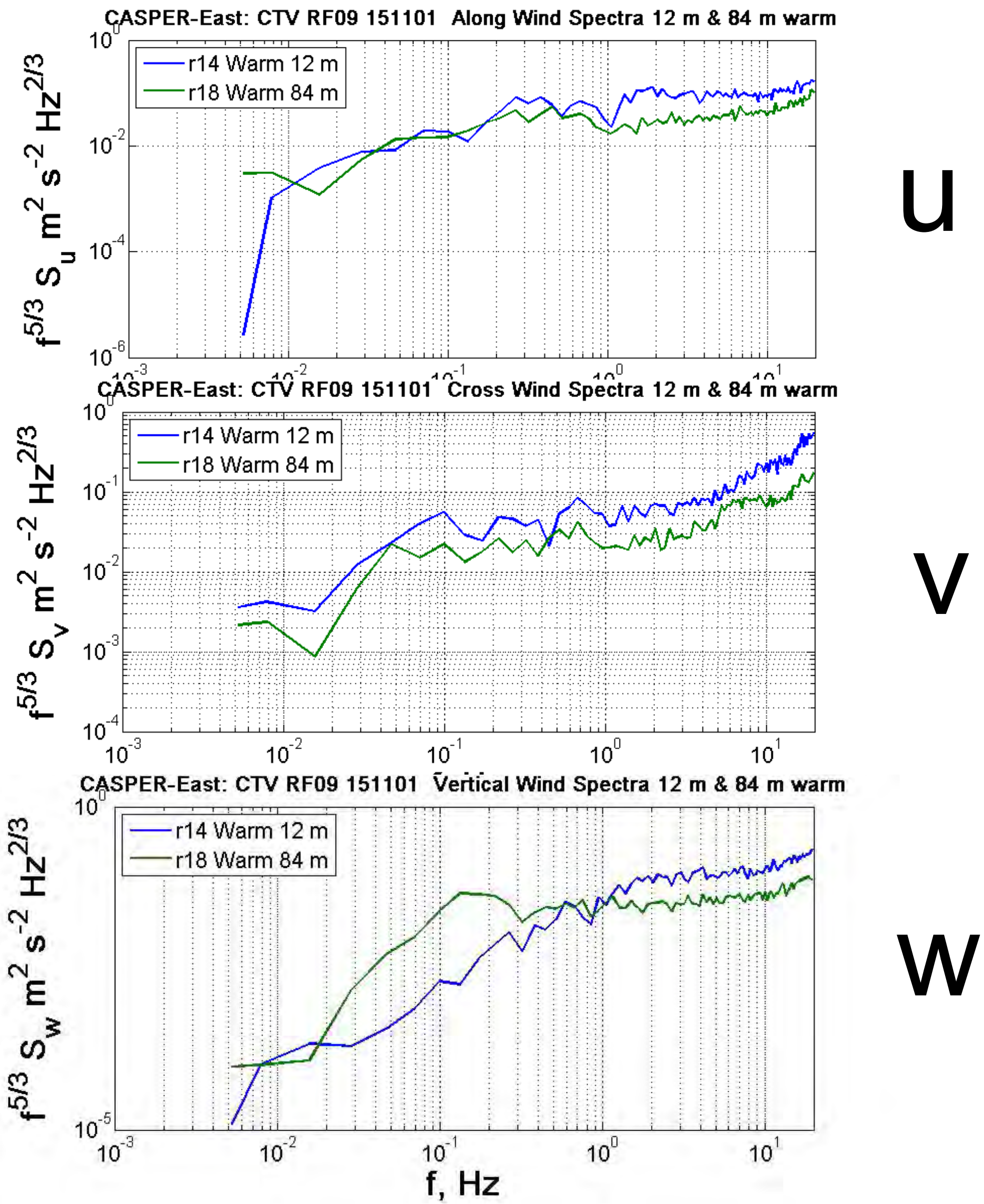
$$\boldsymbol{\tau} = -\rho(\overline{uw}\boldsymbol{i} + \overline{vw}\boldsymbol{j}) = \rho C_{d10} U_{10}^2$$

$$H_s = \rho C_p \overline{w\theta} = \rho C_p C_H U_{10} (\Theta_s - \Theta_{10})$$

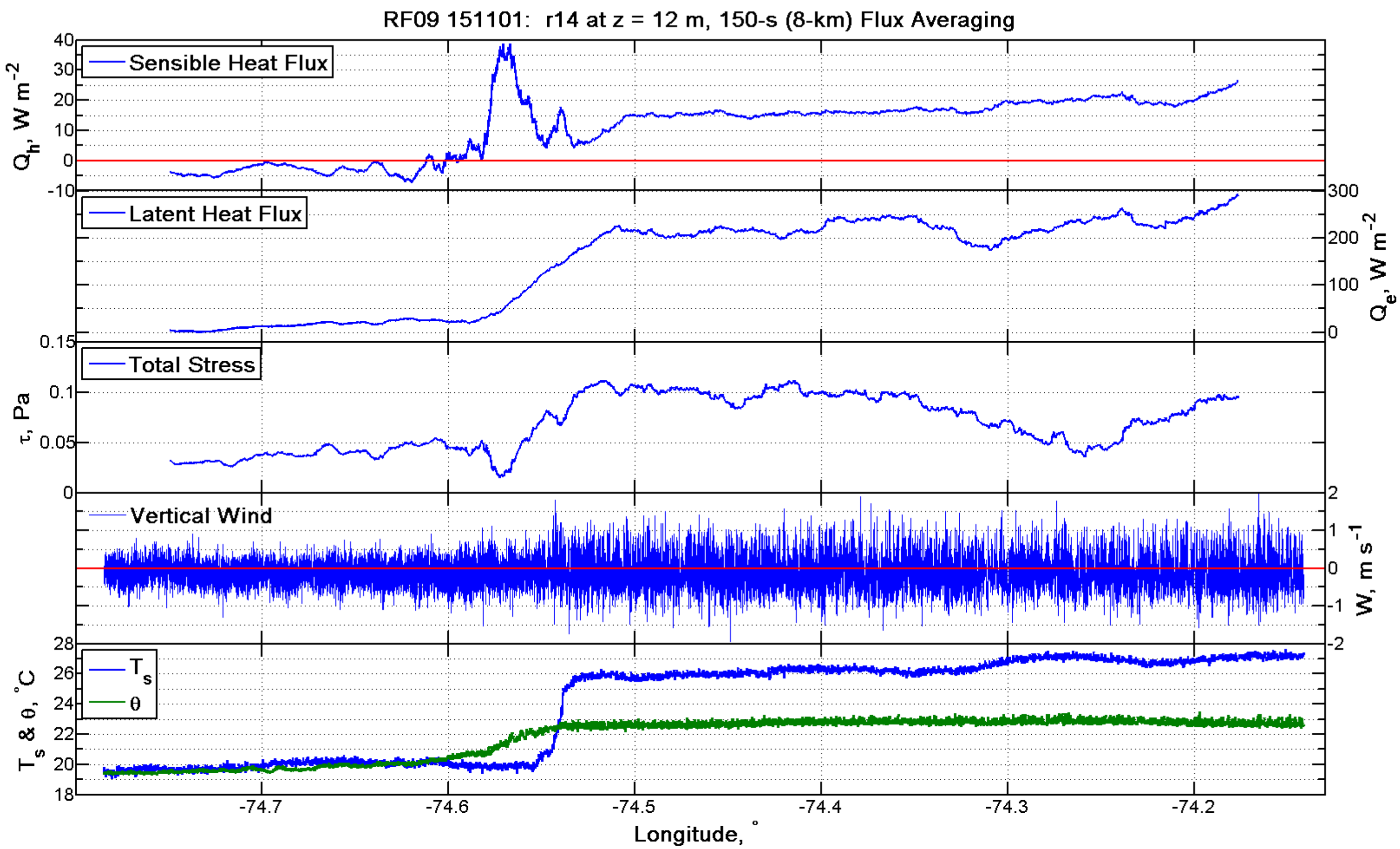
$$E = \overline{w\rho_v} = C_E U_{10} (\rho_{vs} - \rho_{v10})$$

$$H_l = h_{fg} E$$

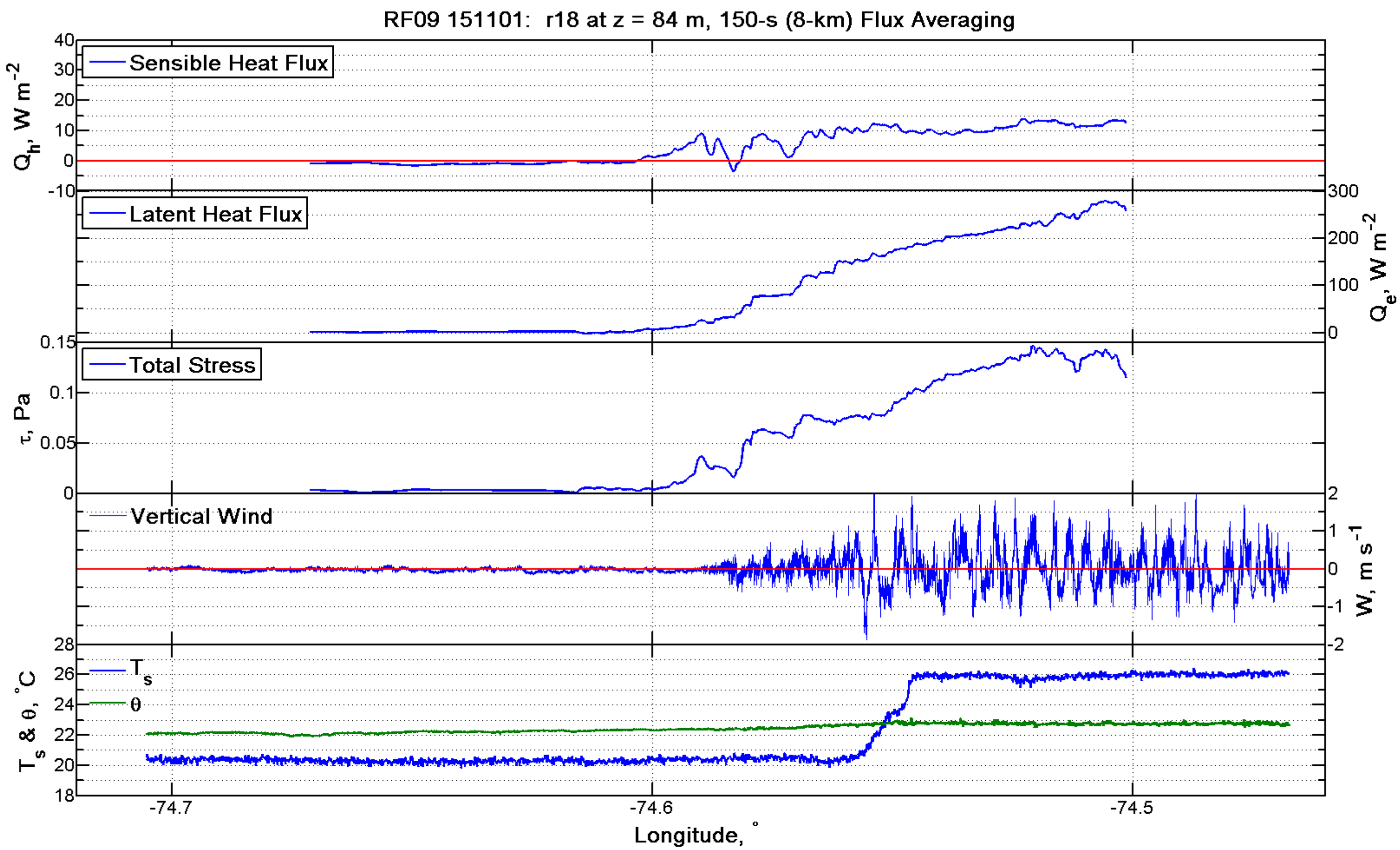
Corresponding Wind Spectra × $f^{5/3}$



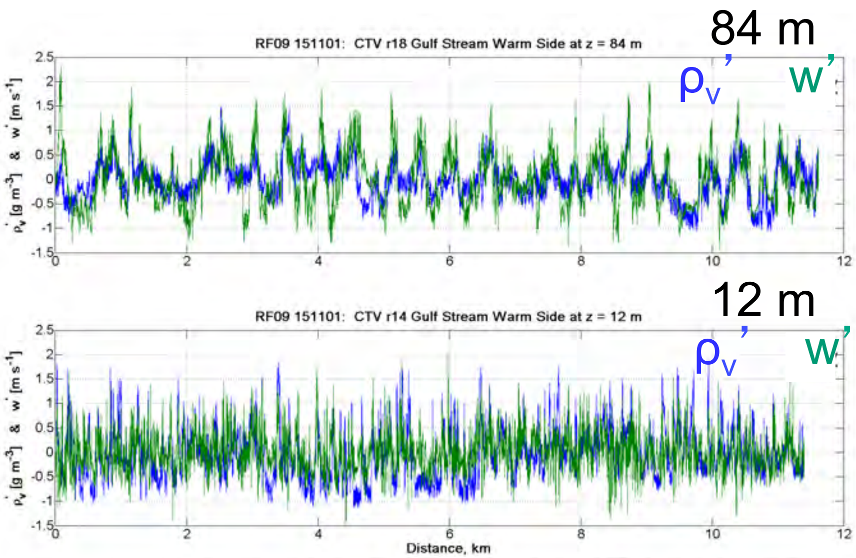
Fluxes Across Gulf Stream Boundary at 12 m

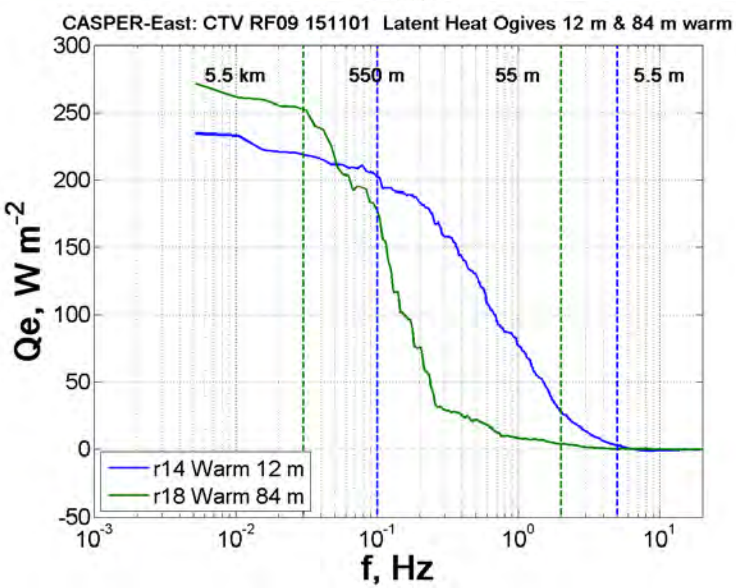


Fluxes Across Gulf Stream Boundary at 84 m



Details GS Latent Heat Flux at 12 m and 84 m





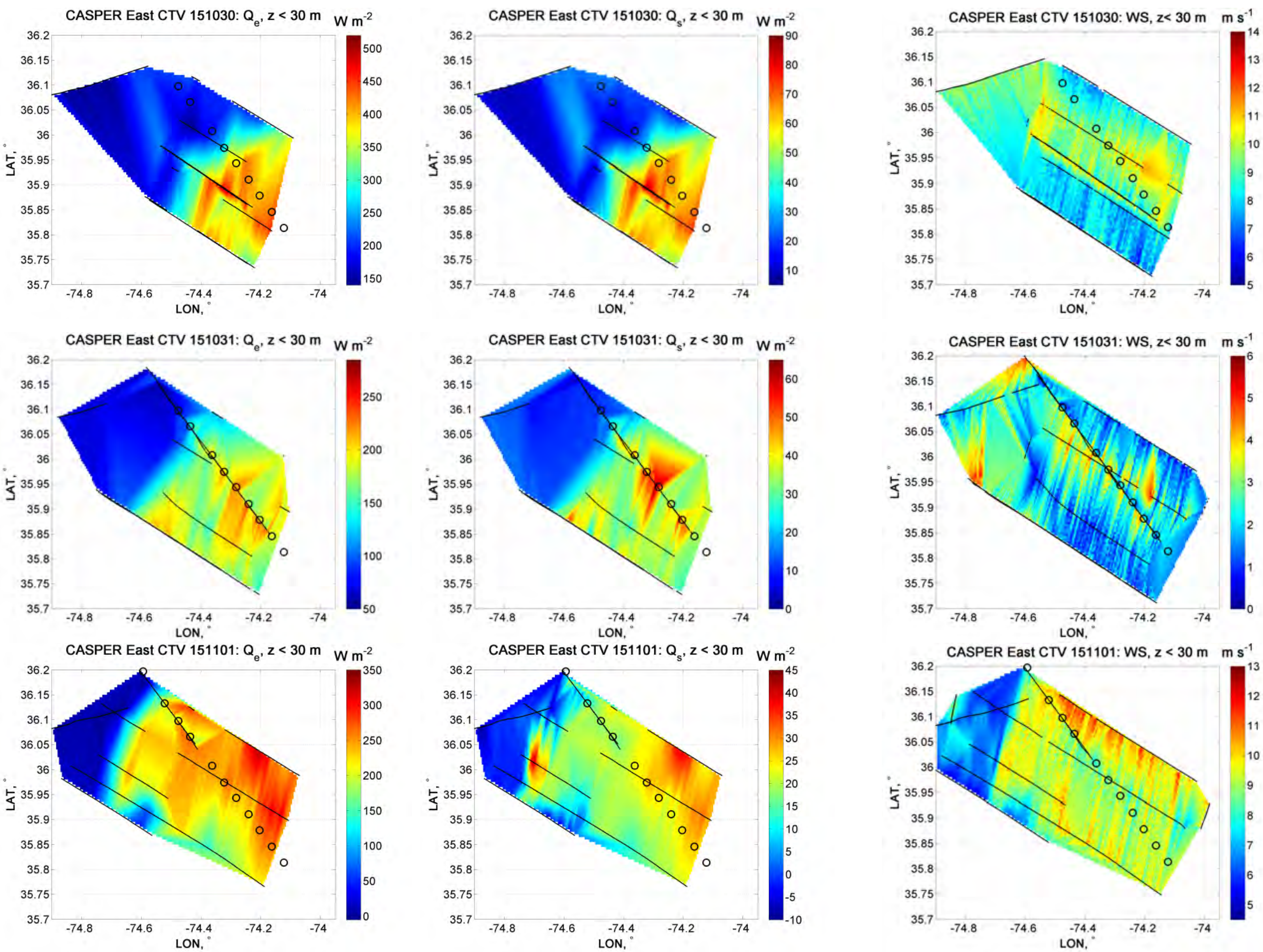
Time series show positive correlation of w' and ρ_v' over the GS but the scale of the flux carrying eddies are much larger at 84 m above the surface compared to 12 m

Ogives of latent heat flux reveal that the sizes of the eddies that carry most of the flux are comprised between:
~11 m and ~550 m at 12 m ASL
~25 m and ~1830 m at 84 m ASL

Question: What are the effects of these different scales fluctuations on EM propagation other than scintillation?

CTV Latent & Sensible Heat Fluxes and Wind Speed over GS

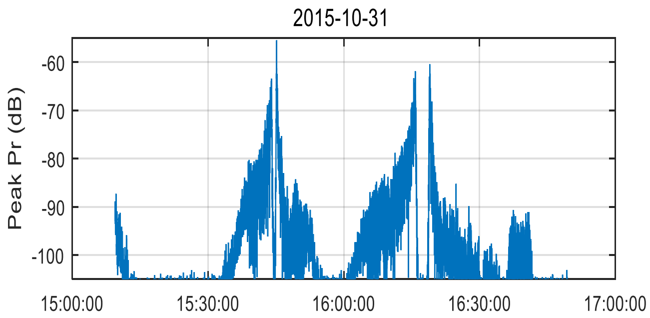
	Qe	Qs	WS	WD
Oct 30				8 °
Oct 31				Var
Nov 01				205°



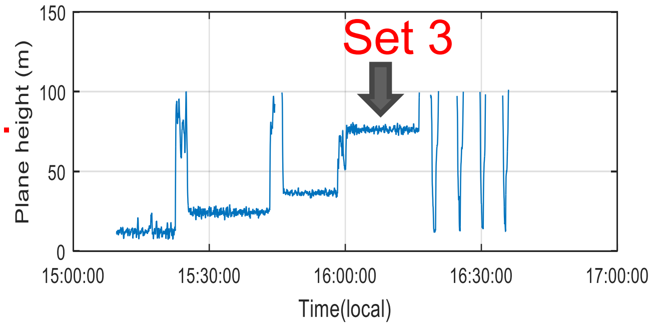
X-Band Received Signal 2015-10-31: Level Flight Set 3

Courtesey of Bob Burkholder, OhSU

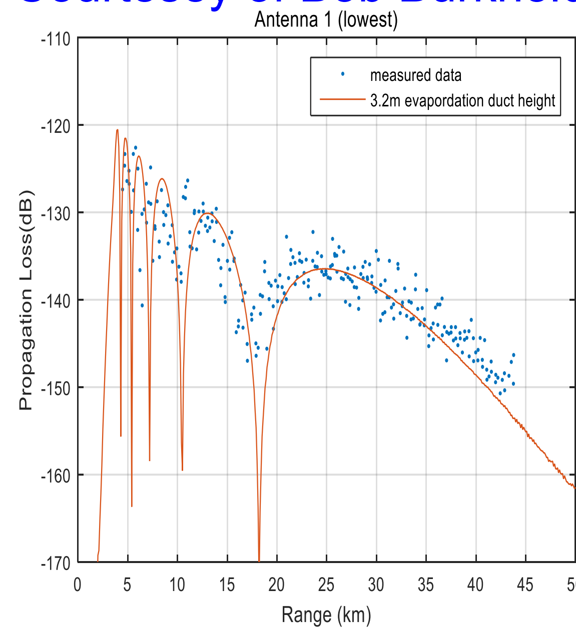
Received power vs. time

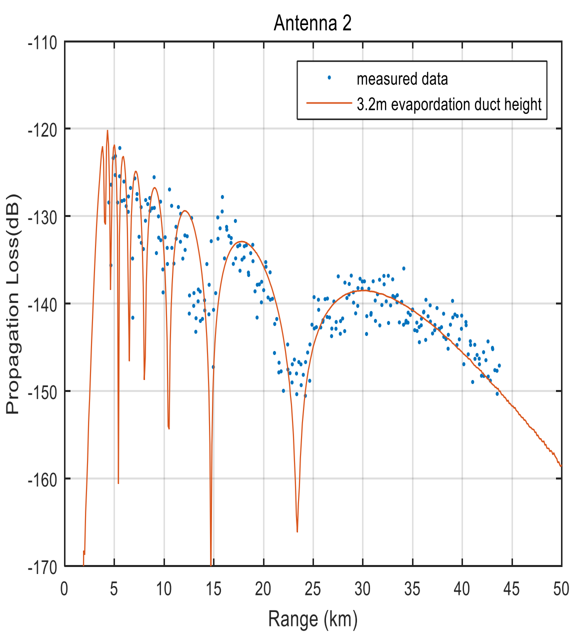


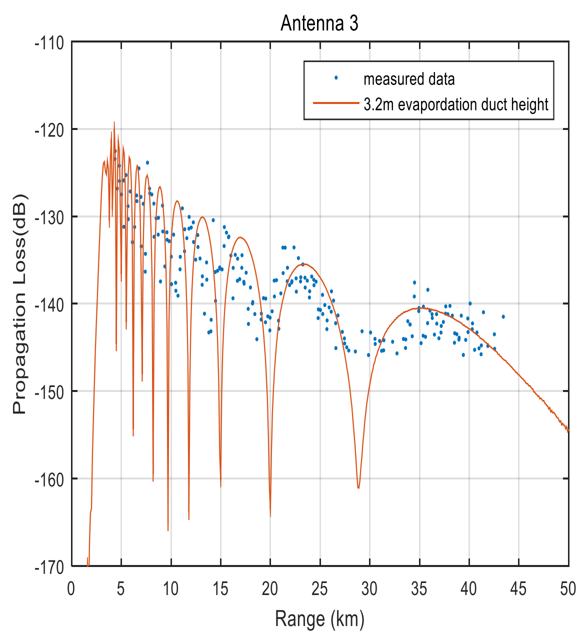
CTV height vs. time

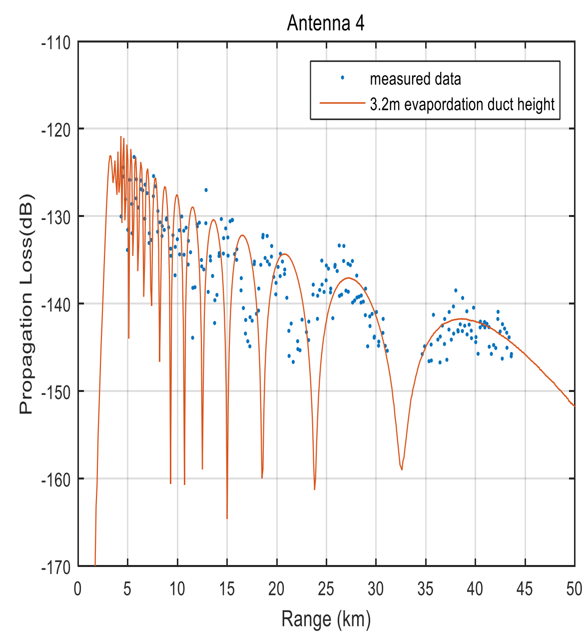


Received power vs. range









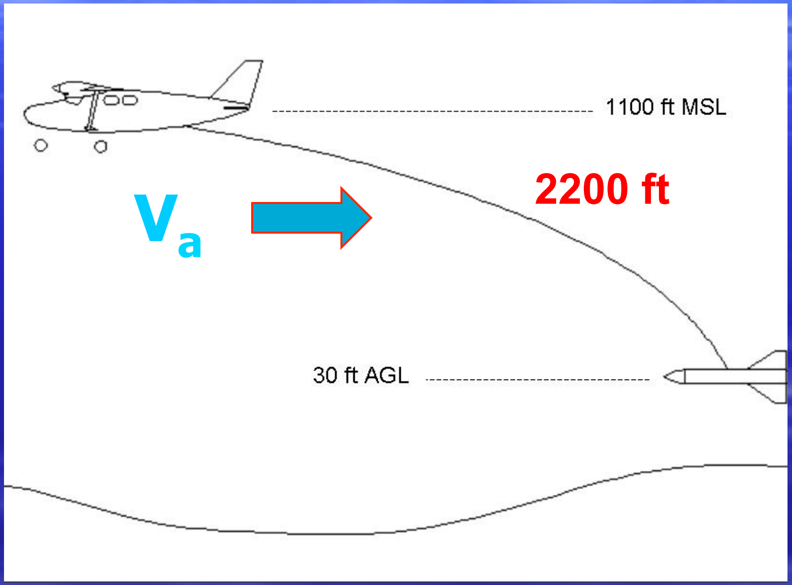
Summary & Conclusions

- A high-quality data set was obtained from CTV during CASPER-East field experiment.
- A three-consecutive-day survey over the Gulf Stream with the CTV successfully captured the spatial and temporal variability of the SST field and its impact on air-sea interaction.
- Observations from CTV runs across the GS boundary showed vigorous enhancement in turbulence intensity and fluxes over the warmer water even well above the surface layer.
- Improved CTV height-keeping system with Roke Miniature Radar Altimeter and the Piccolo SL autopilot **performed very well ~10-m.**
- Successfully repackaged and Integrated a new LI-COR LI-7500A CO2/H2O gas analyzer
- CTV Data system is flawless after installing a miniature PC in the CTV as the host computer to communicate with and operate the realtime CTV cRIO controller and thus avoiding malfunction in the event of data wireless link loss like in severe ducting.
- The CTV is essentially a non-intrusive comprehensive turbulence probe suitable for measurements of stable BLs, OLEs, and EM propagation in surface ducts. **Ship-based measurements are prone to flow distortions, heat island effects and wave induced motion and do not sample cross-wind while UASs do not fly as low, have limited payload and operate in low/moderate winds only.**

Extra Slides

How Safe is the CTV?

1. Cable "natural" lift: when enough cable is reeled out its resultant lift force balances the weight of the CTV and prevents it from going further down. **The active control system has to be engaged** to pitch down the wings forcing the CTV further down to the commanded height. **If malfunction, wings auto-set to neutral→ CTV CLIMBS.**



2. Weak link on the CTV end of the cable breaks when cable tension is too high

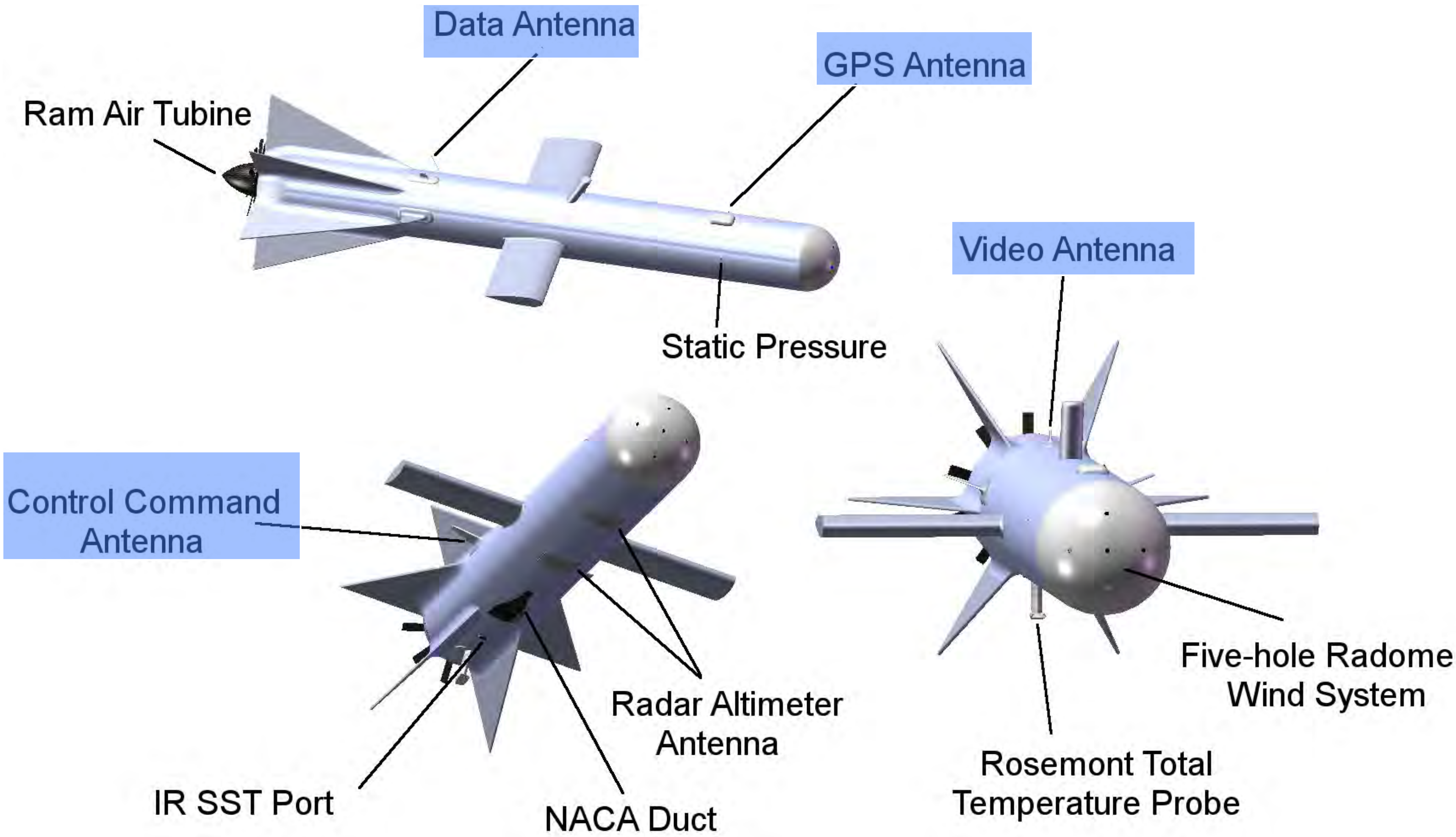
3. Automatic cable cutter switches on flight deck and at CTV control station

4. Manual cable cutter nearby winch system

5. Video from CTV nose camera and from downward-looking aircraft camera

6. Twin Otter radar detects ships, obstacles…

Instruments and Systems



Eddy Correlation Flux Ogive

Averaging and Co-Spectra

The time-series average is

$$\overline{uw} = \frac{1}{N}\sum_{i=1}^{N}(u_i \cdot w_i) = cov(u, w), \qquad (1)$$

which is also equal to the integral of the co-spectrum of u, w

$$\overline{uw} = \int_0^\infty Co_{uw}(f)df. \qquad (2)$$

The cumulative co-spectrum from high to low frequencies, the 'Ogive,' is used to identify convergence:

$$\mathcal{O}(f) = \int_{f_{max}}^{f} Co_{uw}df. \qquad (3)$$

$$\overline{uw} = \mathcal{O} \Rightarrow const. \qquad (4)$$

Eddy Correlation Flux Ogive