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
1. Measure air-sea fluxes of momentum (stress), sensible heat, water vapor (latent heat) and trace gases (CO2) 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 In hospitable 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

**Instrumentation (~identical to Twin Otter’s)**

- 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

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

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**Miniature Radar Altimeter Autopilot**
*(Roke Manor Research, LTD)*

**MRA Type 2 – system specification**

<table>
<thead>
<tr>
<th><strong>Altitude</strong></th>
<th>0.2 to 100m</th>
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<tbody>
<tr>
<td><strong>Resolution</strong></td>
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<tr>
<td><strong>Default</strong></td>
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<table>
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<th><strong>Physical</strong></th>
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<tbody>
<tr>
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<tr>
<td><strong>Width</strong></td>
<td>75 mm</td>
</tr>
<tr>
<td><strong>Height</strong></td>
<td>46 mm</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>400g</td>
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</table>

**Integrated antenna dimensions**

<table>
<thead>
<tr>
<th>Length</th>
<th>12.6 mm</th>
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</thead>
<tbody>
<tr>
<td>Width</td>
<td>8.6 mm</td>
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</table>
04May2015 Height-Keeping Performance

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

<table>
<thead>
<tr>
<th>Run</th>
<th>Mean (z) ( m )</th>
<th>Min (z) ( m )</th>
<th>Max(z) ( m )</th>
<th>Span(z) ( m )</th>
<th>( \sigma(z) ) ( m )</th>
<th>( \sigma(\psi) ) ( \circ )</th>
<th>( \sigma(\theta) ) ( \circ )</th>
<th>( \sigma(\phi) ) ( \circ )</th>
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<tr>
<td>r03</td>
<td>9.0</td>
<td>6.3</td>
<td>10.9</td>
<td>4.6</td>
<td>0.8</td>
<td>0.8</td>
<td>0.5</td>
<td>0.6</td>
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<tr>
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<td>6.5</td>
<td>11.3</td>
<td>4.8</td>
<td>0.7</td>
<td>0.9</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>r07</td>
<td>9.1</td>
<td>6.3</td>
<td>12.4</td>
<td>6.2</td>
<td>1.2</td>
<td>1.0</td>
<td>0.6</td>
<td>0.7</td>
</tr>
<tr>
<td>r08</td>
<td>9.2</td>
<td>6.4</td>
<td>12.1</td>
<td>5.6</td>
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<td>1.0</td>
<td>0.5</td>
<td>0.6</td>
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<td>16.2</td>
<td>21.1</td>
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<td>1.1</td>
<td>0.5</td>
<td>0.5</td>
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<td>1.1</td>
<td>1.5</td>
<td>0.7</td>
<td>0.5</td>
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<tr>
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<td>7.7</td>
<td>1.2</td>
<td>1.3</td>
<td>0.7</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Heading | Pitch | Roll
Height-Keeping, Pitching and Rolling Performance

Mean(z): 9.1 m
Std(z): 0.7 m
Coupled Air-Sea Processes and EM ducting Research (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.

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

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

\[ M = N + \frac{z}{R} \times 10^6 \] (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
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

3 Flights over the Gulf Stream:
151030, 151031, 151101

8 Flights Off Duck FRF Pier:
151014, 151016, 151017, 151018, 151021, 151027, 151103, 151104

Graph showing track, z, m over UTC, Hours with markers for Takeoff and Landing.
CTV Modifications for CASPER

- 250-W Ram Air Turbine
- NACA air intake for KH2O hygrometer
- 5-Hole Turbulence Gust System
- Rosemount Temperature Probe
- LI-COR 7500A CO2/H2O Analyser
- KT-15D IR SST
- MRA 2 Radar Altimeter
- OhSU X-Band Beacon
- Static Pressure

New
Relocated
CTV Fast-response Humidity

CASPER East RF07 151030: CTV Fast-response Humidity

UTC, Hours

Distance, m

LI-7500A
KH2O

RELEASE
CAPTURE

ρ_v, g m^-3

LI-7500A
KH2O

ρ_v, g m^-3

15
10
5
0
500
1000
1500
2000
2500
3000
Gulf Stream Wave-Current Interaction
Gulf Stream SST Variability

CASPER East CTV RF07 151030: IR SST

Flight Direction

Pic Location

LAT, °

LON, °

°C

°C
Gulf Stream SST Variability

CASPER East CTV RF08 151031: IR SST

LAT, °

15.3 km at 17.7 cm/s

LON, °
Gulf Stream SST Variability

CASPER East CTV RF09 151101: IR SST

LAT, °

LON, °

11.4 km at 13.2 cm/s

°C
Vertical Structure over the Gulf Stream

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

\[ \tau = -\rho (\bar{u} \bar{w} i + \bar{w} \bar{w} j) = \rho C_{d10} U_{10}^2 \]

\[ H_s = \rho C_p \bar{w} \theta = \rho C_p C_H U_{10} (\Theta_s - \Theta_{10}) \]

\[ E = \bar{w} \rho_v = C_E U_{10} (\rho_{vs} - \rho_{v10}) \]

\[ H_l = h_{fg} E \]
Corresponding Wind Spectra $\times f^{5/3}$
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 \( \rho_v' \) 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

Oct 30

Qe

Qs

WS

WD

Oct 31

Qe

Qs

WS

WD

Nov 01

Qe

Qs

WS

WD

8° Var

205°
X-Band Received Signal 2015-10-31: Level Flight Set 3

Received power vs. time

CTV height vs. time

Courtesey of Bob Burkholder, OhSU

Antenna 1 (lowest)

Antenna 2

Antenna 3

Antenna 4
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…
Eddy Correlation Flux Ogive

Averaging and Co-Spectra

The time-series average is

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

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

\[ \overline{uw} = \int_0^\infty C_{uw}(f) df. \]  

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

\[ \mathcal{O}(f) = \int_{f_{max}}^{f} C_{uw} df. \]  

\[ \overline{uw} = \mathcal{O} \Rightarrow \text{const.} \]
Eddy Correlation Flux Ogive

Wind Stress Co-Spectrum and Ogive: Aircraft Data @ 33 m Height and 100 ms\(^{-1}\)

2 km
2500 meters
20 m