Measurements of Air-Sea Fluxes with a Controlled Towed Vehicle (CTV)

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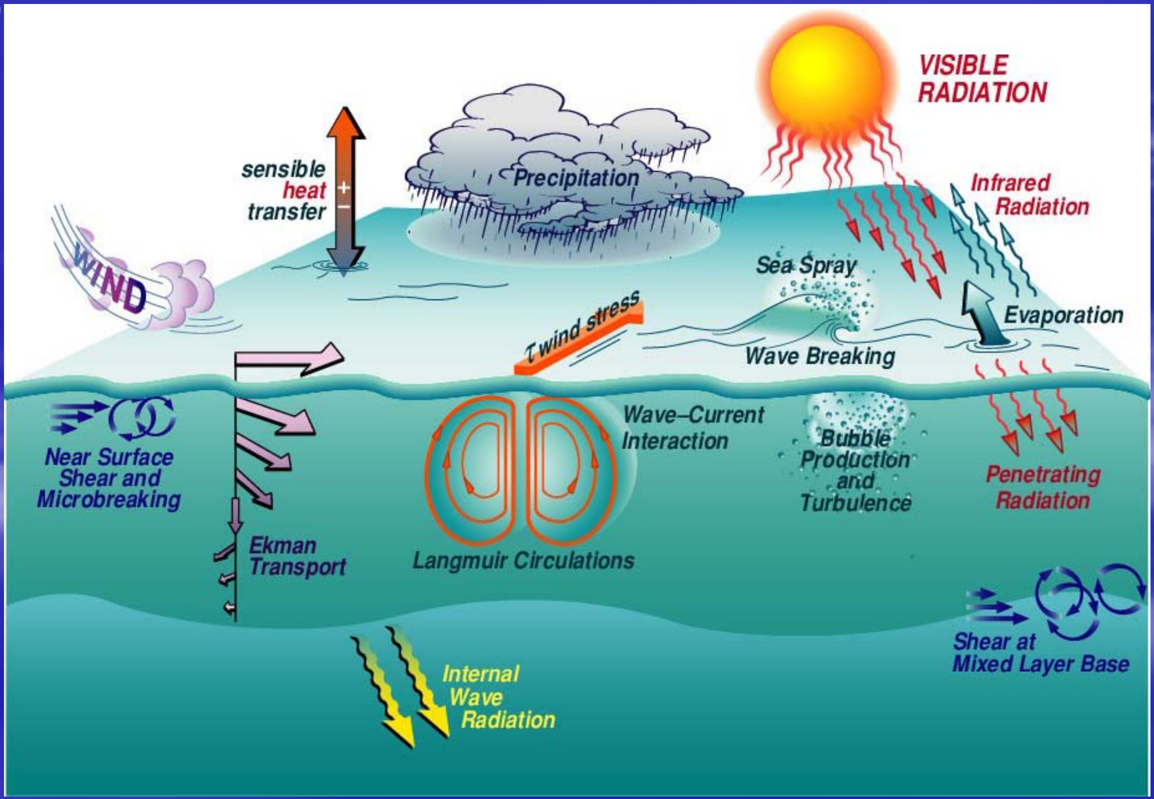
Office of Naval Research

Why Air-Sea Fluxes and Associated Measurements are Needed:

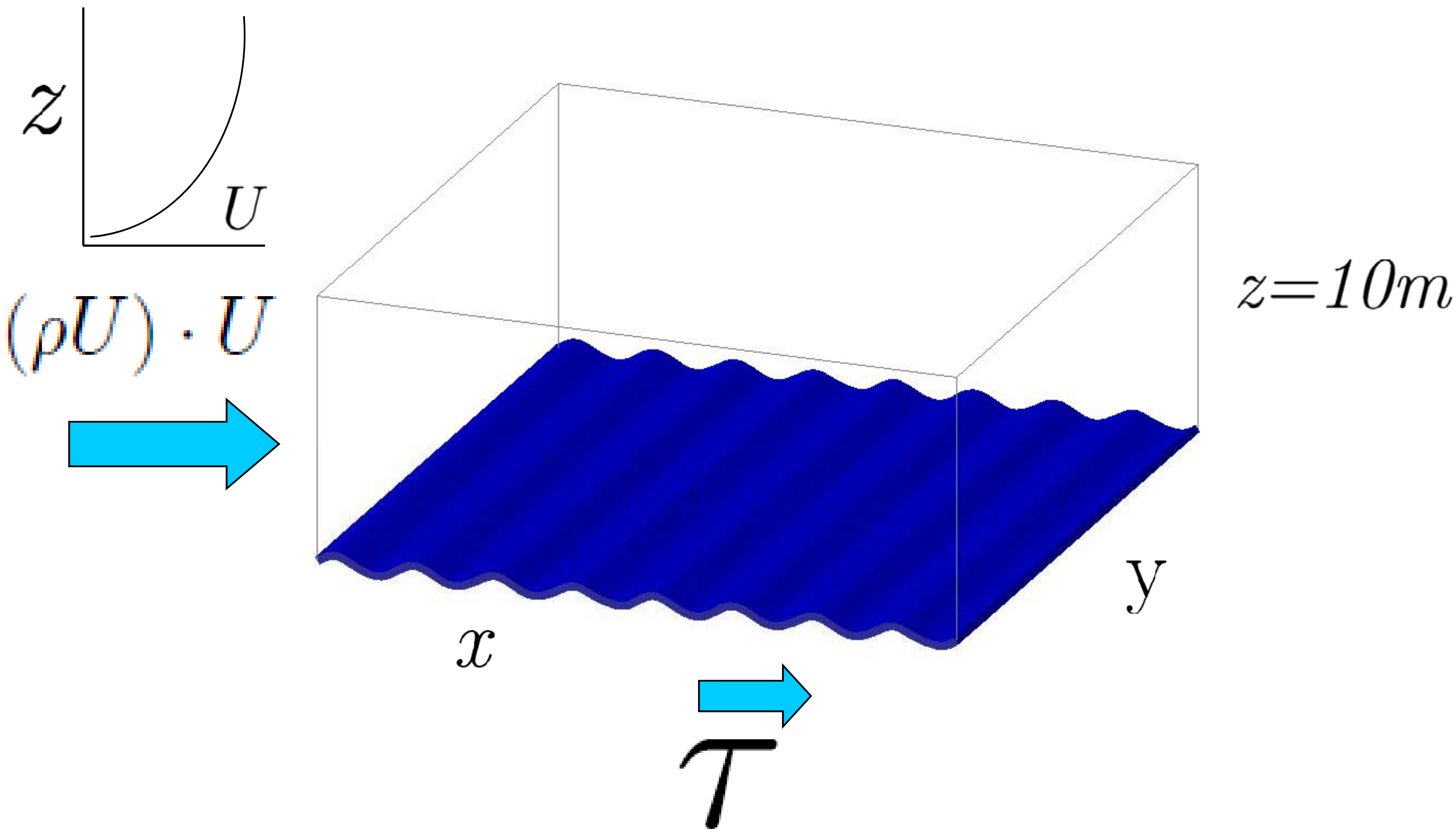
1. Model Parameterizations, Climate, Weather and Ocean
2. High Wind Speeds: Hurricanes
3. Process Studies, e.g. VOCALS
4. Ocean Wave Physics and Forecasts
5. Oil Spills (Wind Stress)
6. GFD (Geo Fluid Dynamics)
7. Wind/Wave Energy

Big 3 Fluxes:
Stress, Sensible Heat,
Latent Heat.

And CO_2, etc.



Surface Wind Stress = Loss of Horizontal Momentum of Mean Wind



Scalar Fluxes: Sensible Heat & Evaporation (Latent Heat)

Osborne Reynolds, $\sim$ *1880*

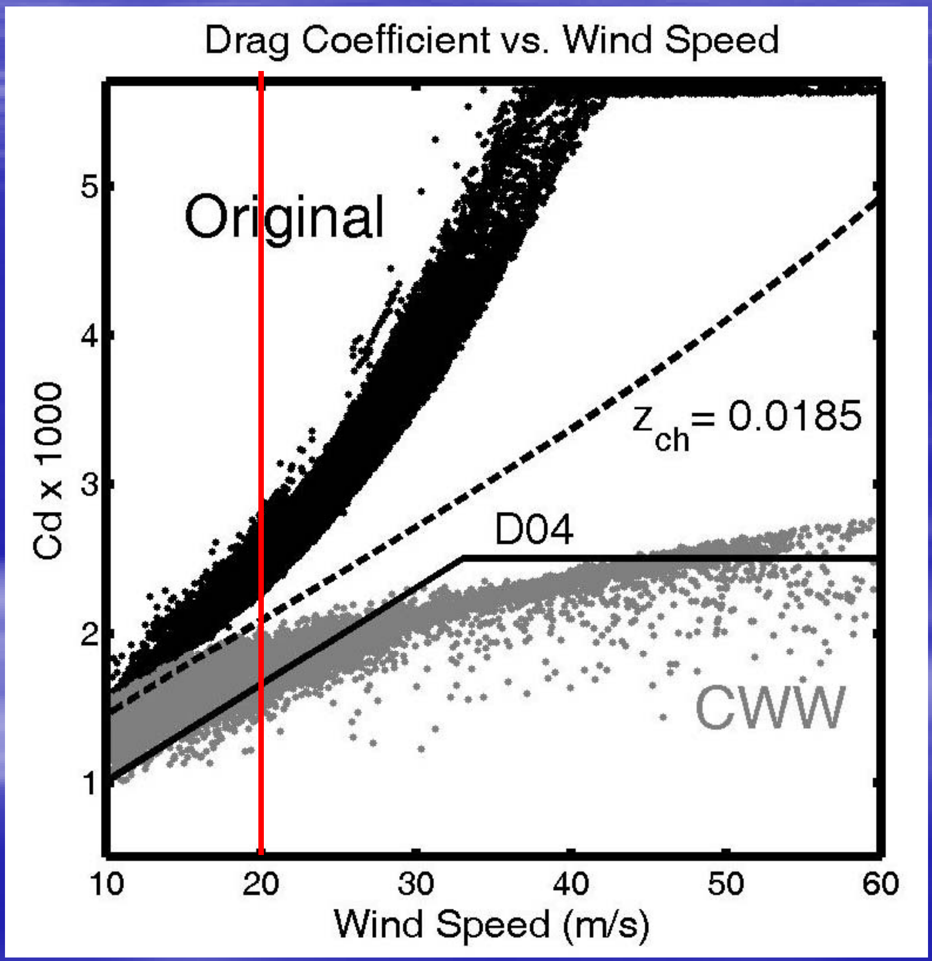
Reynolds' Analogy Between Momentum, Heat and Mass Transfer:

$$C_{d10} = C_H = C_E$$

$$C_{d10} = Stanton\# = Dalton\#$$

High Wind Conditions

Various Model Results – c/o Tetsu Hara URI



Above ~20 m/sec, mostly models or inference.

Waves

Summary

- Air-sea flux parameterizations require in-situ turbulence and mean measurements at 10m above the sea.
- Data at high winds are lacking: buoys and ships inadequate; aircraft >33m.
- Wind stress in hurricanes is needed to improve “intensity” forecasts.
- Stress Divergence. Extrapolate means to 10m.
- CTV can operate at ~10m while tow aircraft is safely above.

Flux Platforms for Fair to Moderate Weather

Buoy: 10m
Ship: 14m
Aircraft: >33m

Controlled Towed Vehicle (CTV) Goals

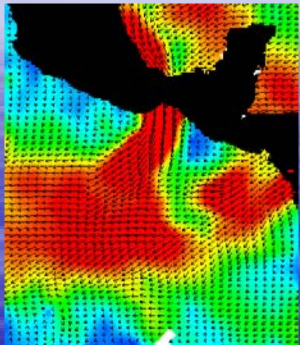
1. Measure surface fluxes of momentum (stress), sensible heat, water vapor (latent heat) and trace gases (CO_2) **near the ocean surface** in all conditions, especially high to hurricane strength winds. (Canonical measurement height is 10 meters.)

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

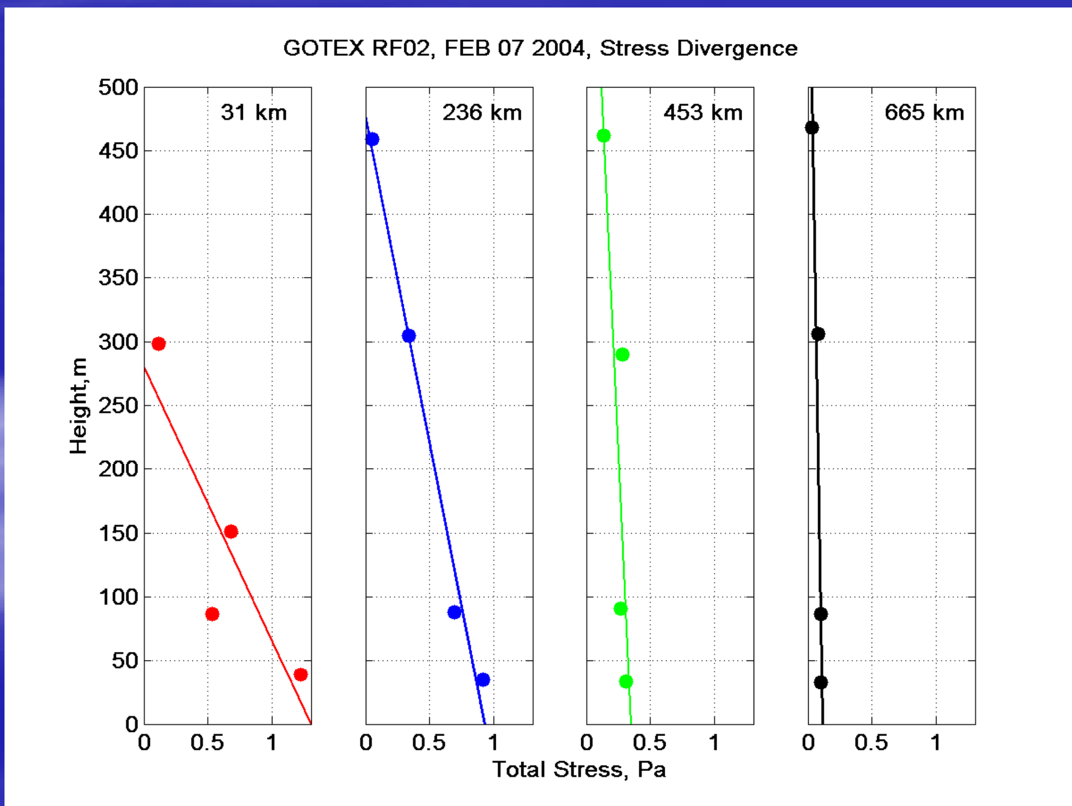
3. Aircraft are suitable platforms due to their mobility (large spatial coverage) and ability to fly in high winds, but are limited to > 33 m (some much higher). It is desirable to extend their reach nearer the surface without compromising safety.

4. Radar-height controlled target drones are proven technology and are readily adaptable for scientific measurements and can "fly" **as low as 10 meters**.

Motivation



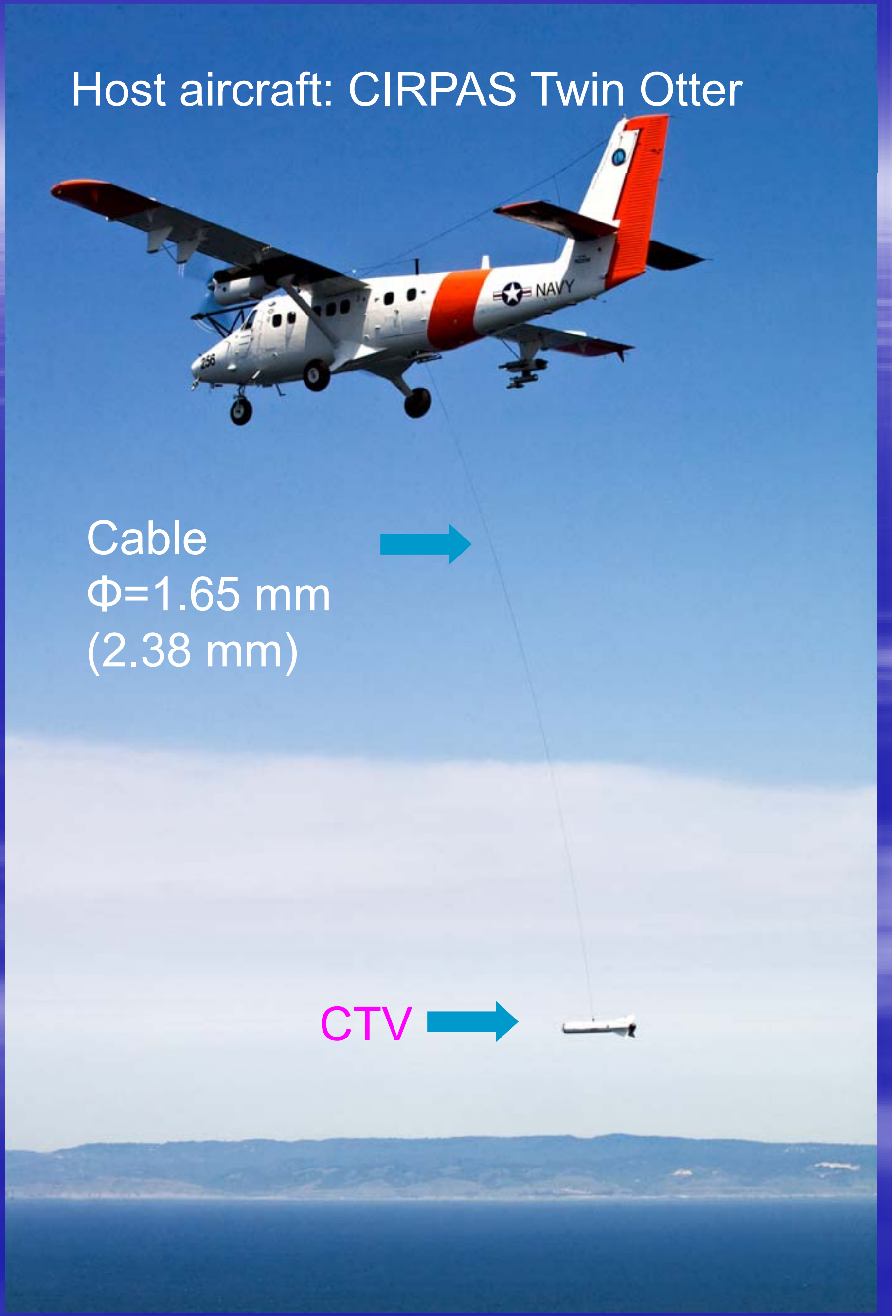
Stress Divergence in developing BL gap outflow in the Gulf of Tehuantepec, Mexico Feb 7, 2004 (GOTEX, NCAR C130)



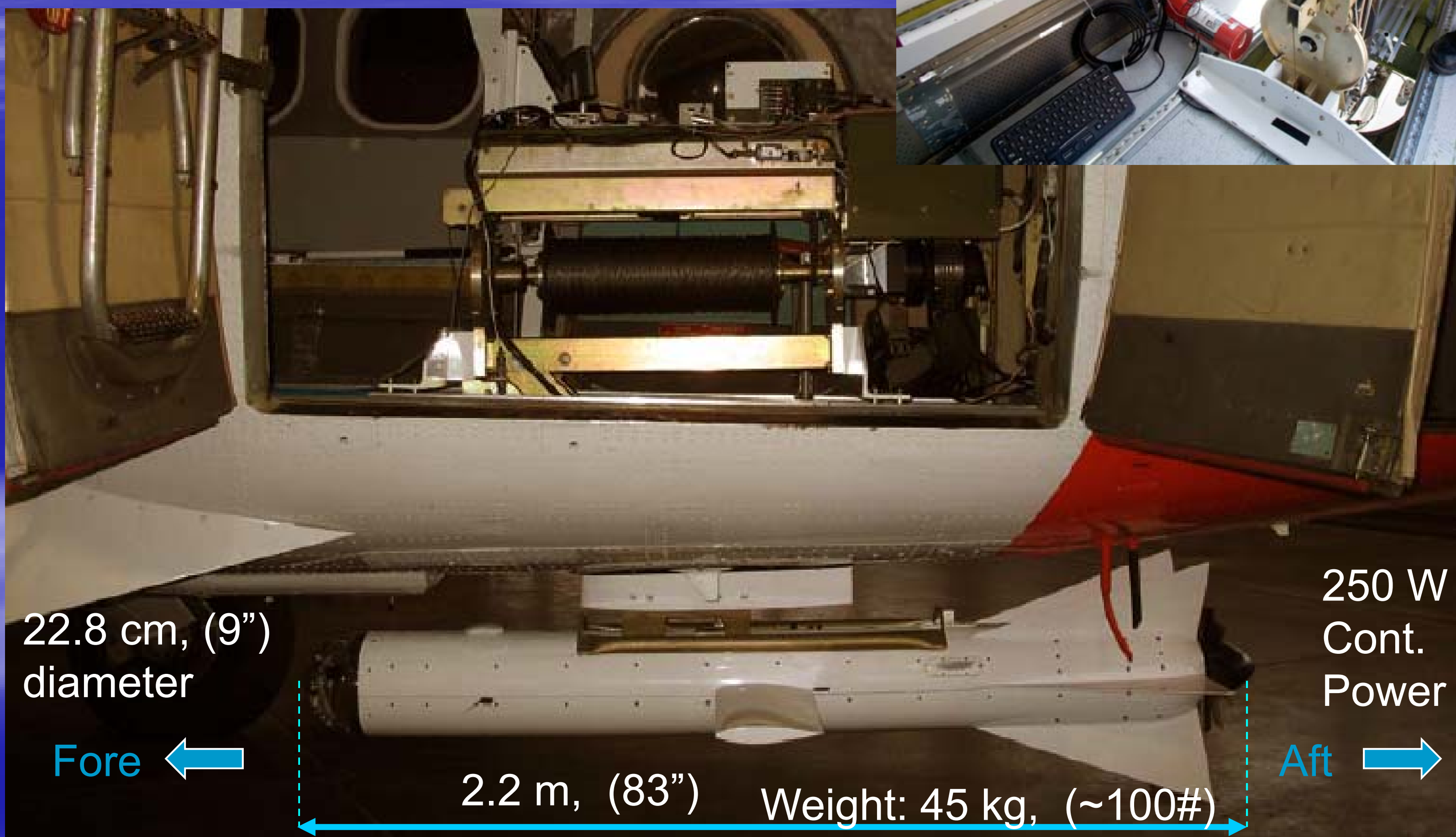
- Lowest flight level for most research aircraft is ~30 m, thus data need to be extrapolated to the 10-m reference height
- Monin-Obukhov similarity theory applies to the constant-fluxes surface layer and profiles functions used were obtained from overland data (Kansas Experiment 1968)
- 30 m may be above surface layer in some BL flows such as developing gap outflow close to shore or very stable BL as in CBLAST-Low
- Simultaneous measurements from two levels

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 (UASs, ex-UAVs) – small payload, underpowered)
5. Modify existing towed target drone technology for controlled height over the sea while tow aircraft is safely above.



CTV on CIRPAS Twin Otter

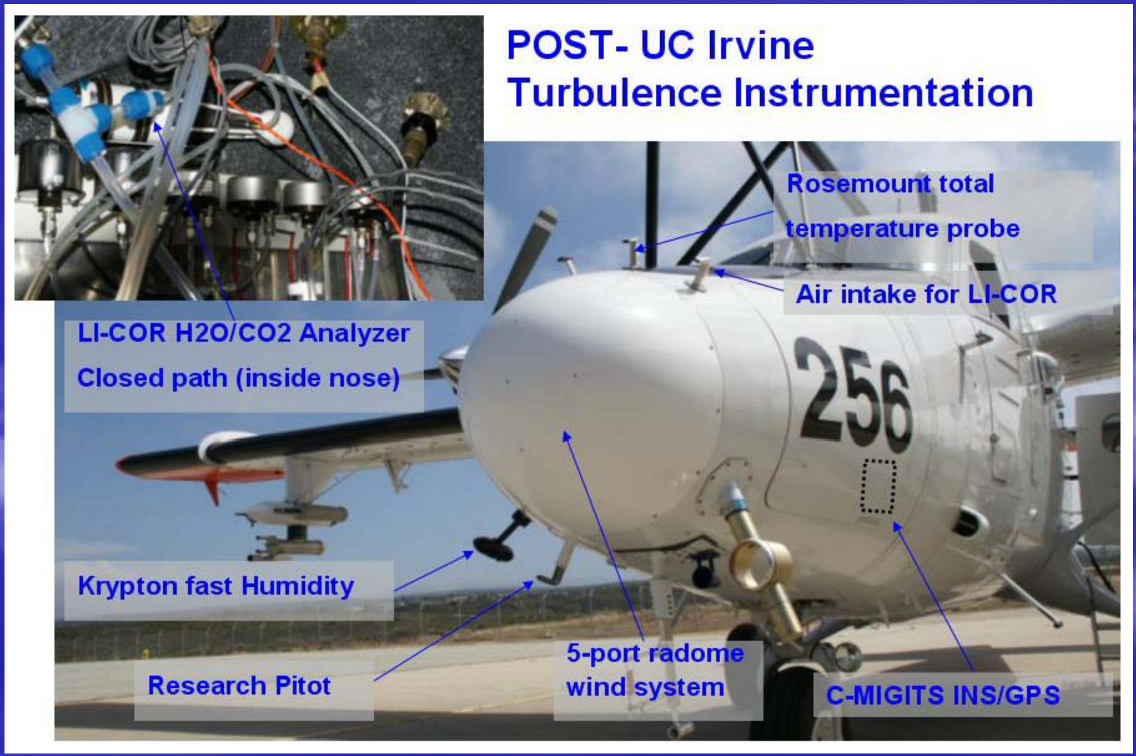


Requirements

1. Mean and fluctuating 3-component winds, U,V,W, motion corrected
2. Mean and fluctuating temperature and humidity
3. Sea surface temperature (IR)
4. Platform motion, altitude, navigation, GPS time.
5. BW: DC to ~50Hz for co-variances and inertial sub-ranges

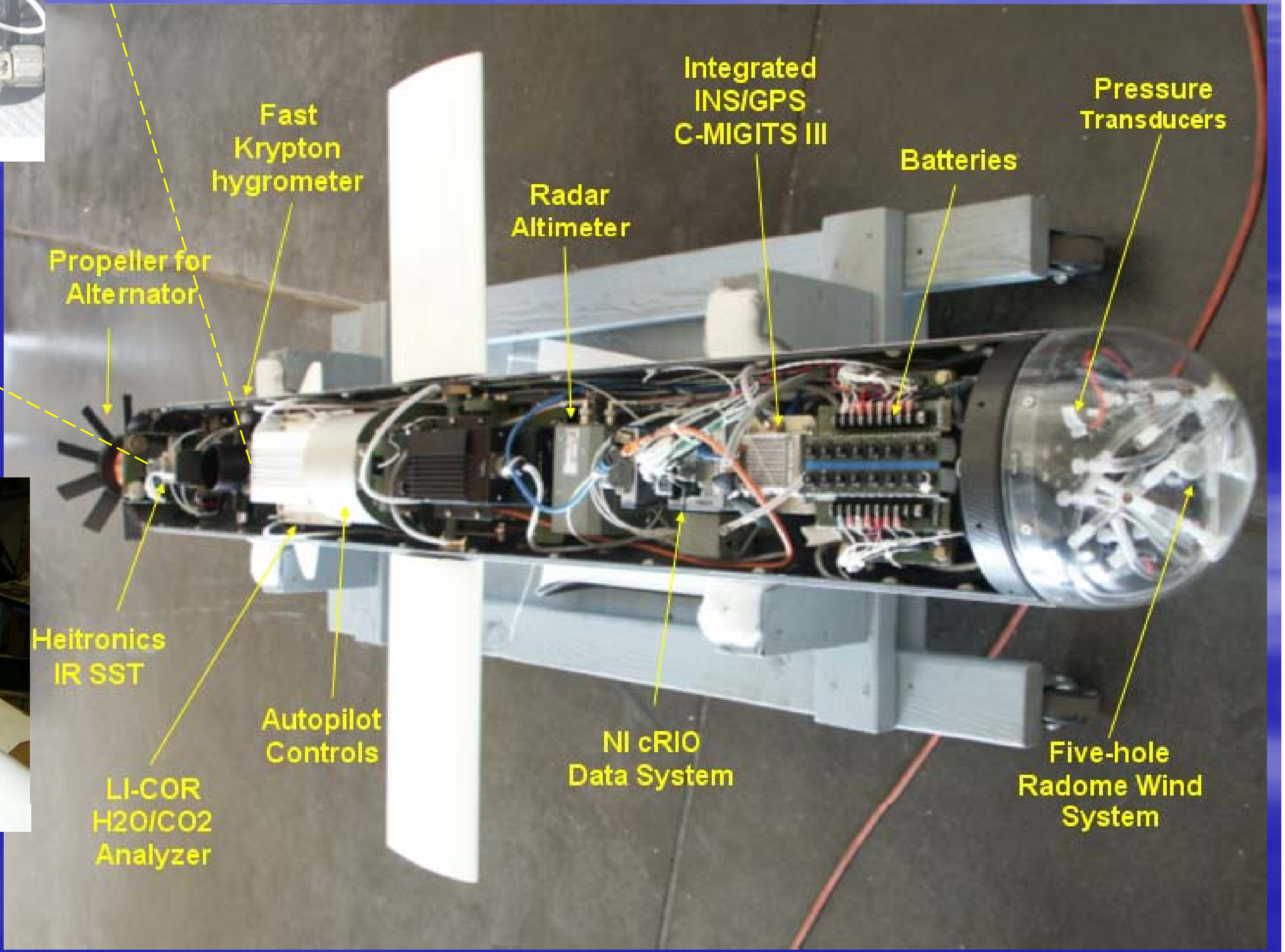
USN (CIRPAS) Twin Otter Research Aircraft

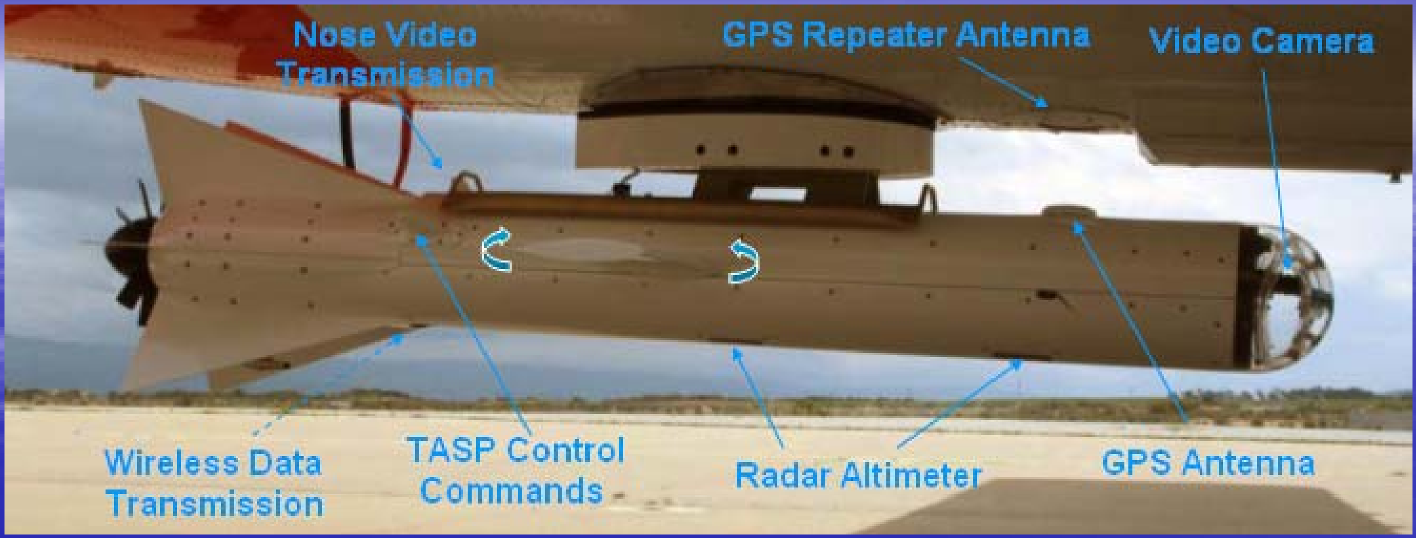
Note: Relative airspeed vector from 5-port radome pressures, i.e., in-situ "Cobra Probe." Navigation, motion, angles from GPS/Inertial



Instrument Layout

Mass=45 kg; D=0.23 m; L=2.2m; P=250W





- Wireless link between aircraft and CTV to send control commands

- **Active altitude control system** (Meggitt's) comprises a radar altimeter, a computer and a wing servo to detect and hold the prescribed altitude. Control authority is 250 ft from full wing up to full wing down (12 deg).

- Video from nose camera is transmitted wirelessly to tow aircraft for display in cockpit and at control station.

- Data from research instruments are recorded on CTV data system and transmitted via wireless Ethernet link to aircraft computer for *real-time* monitoring and redundant storage.

CTV Movie # 1 WMAV 24 MB

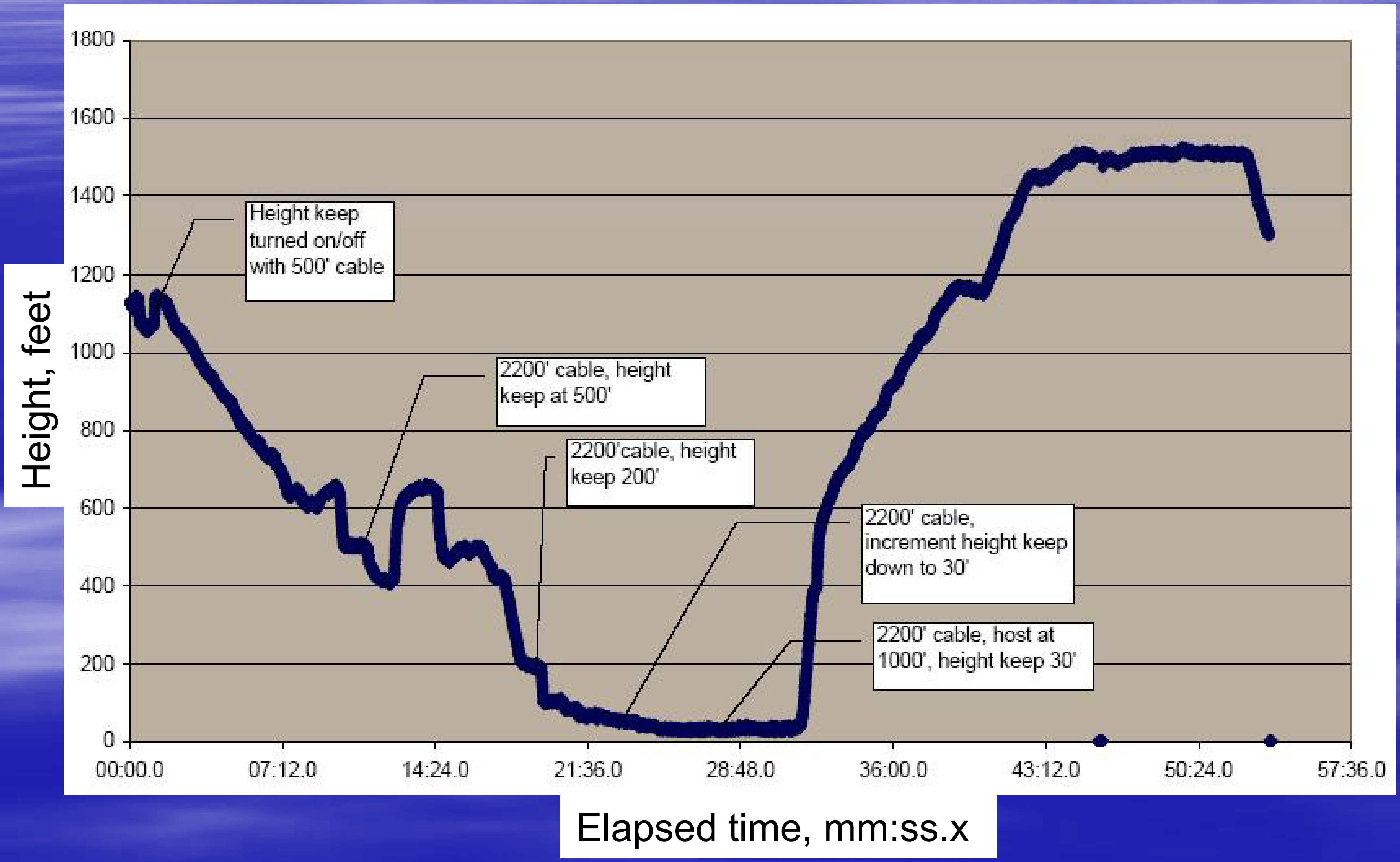
Controlled Towed Vehicle
CTV

April 2008

CTV Movie # 2 MPG 81 MB

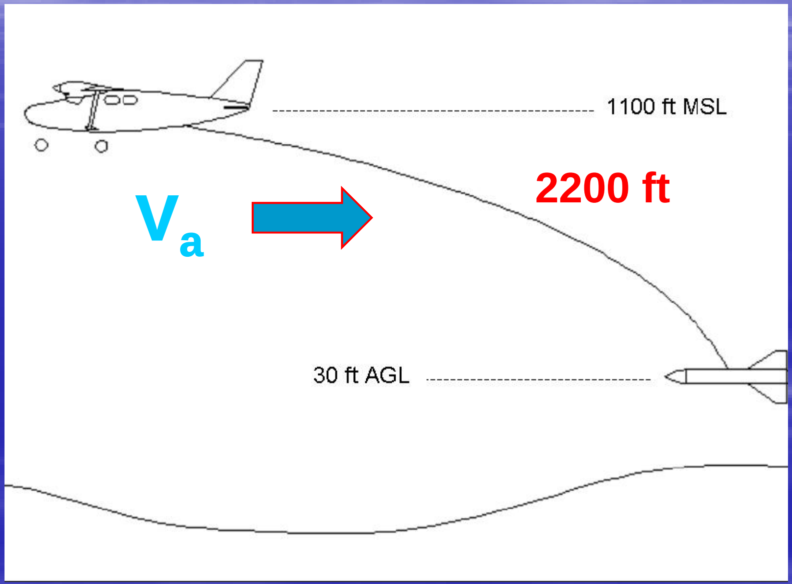
[redacted]

Radar Altimeter Height



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 prevent 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…

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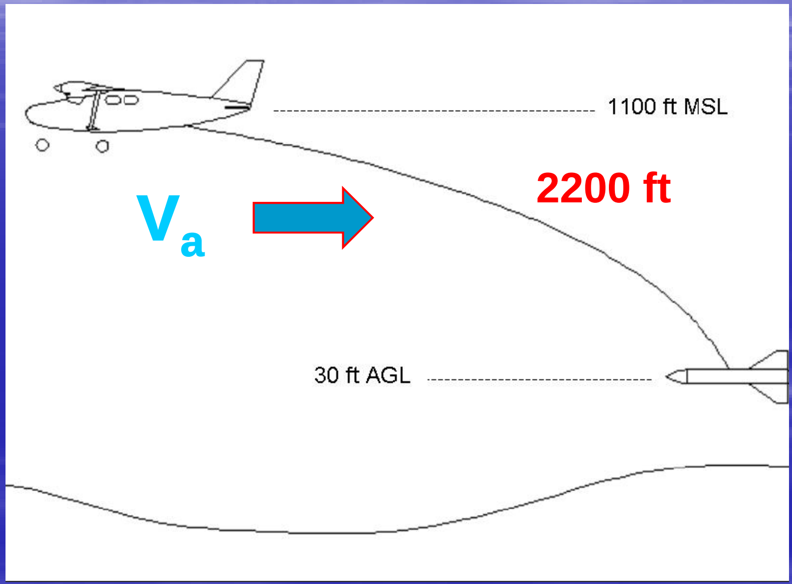

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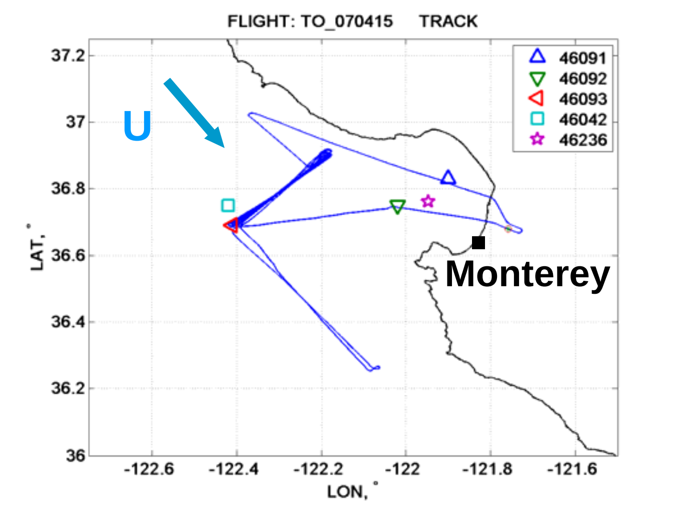
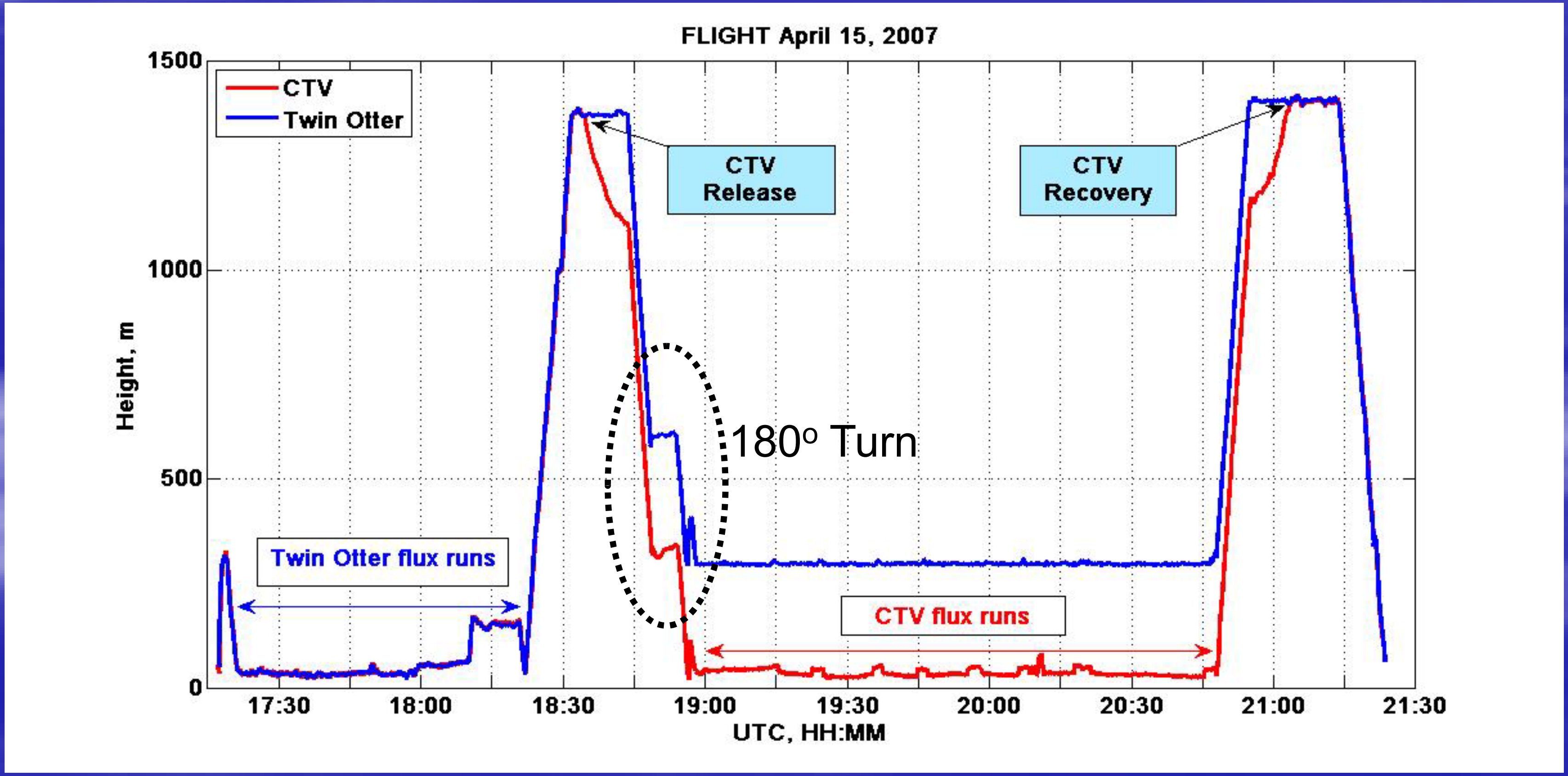
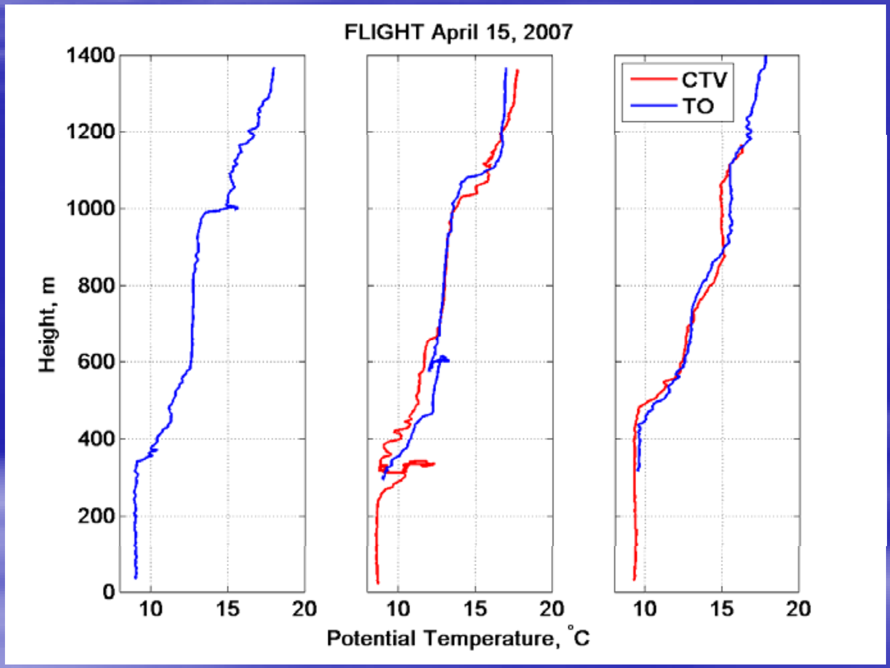
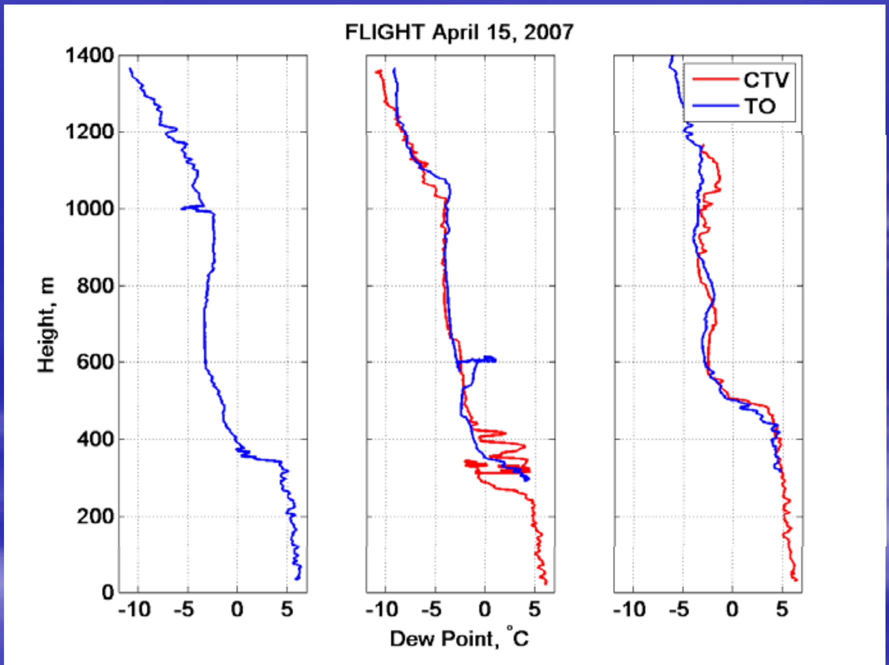
Flight of April 15, 2007



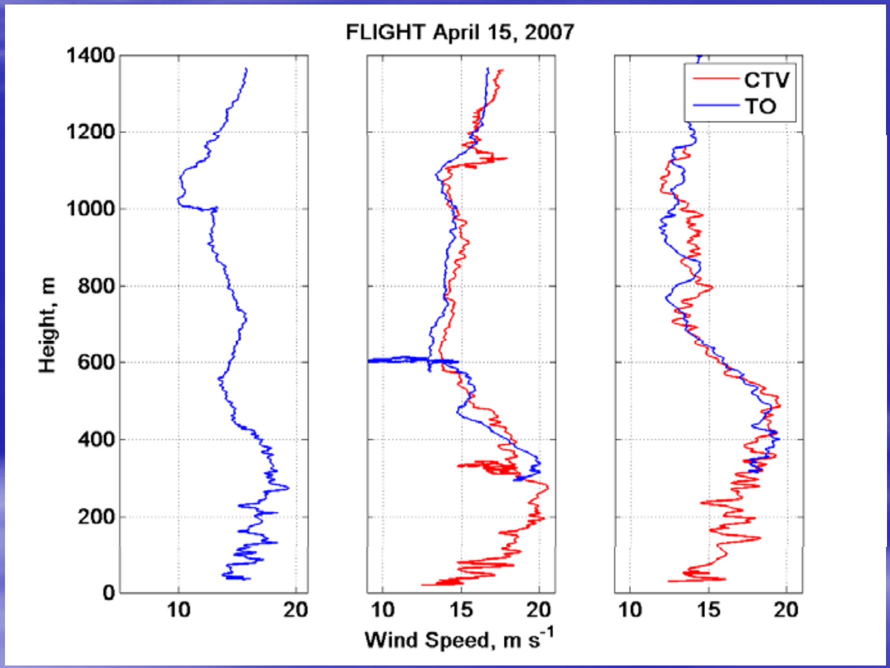


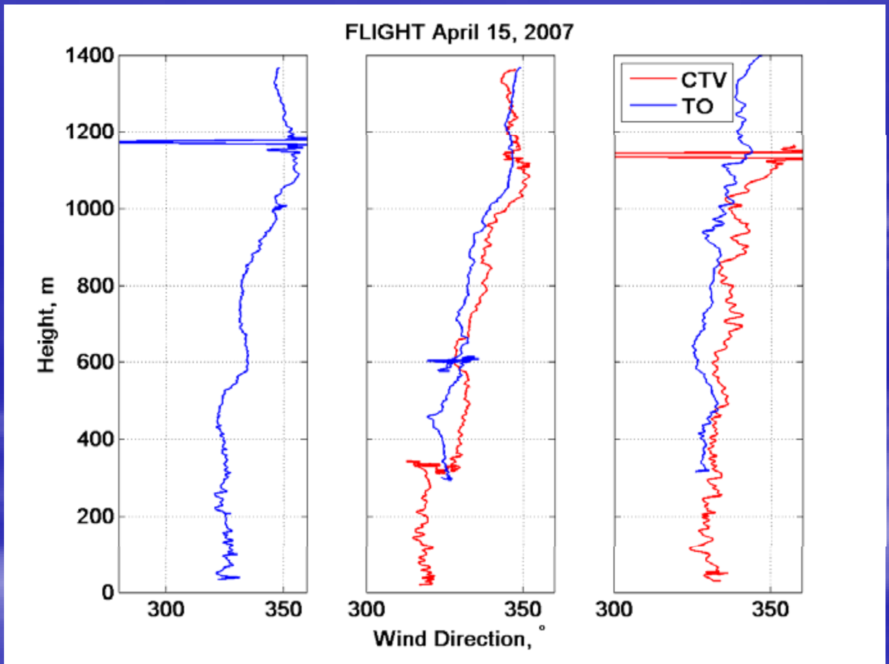
Temperature and Dewpoint Profiles





Wind Speed and Direction Profiles





Wind Measurements

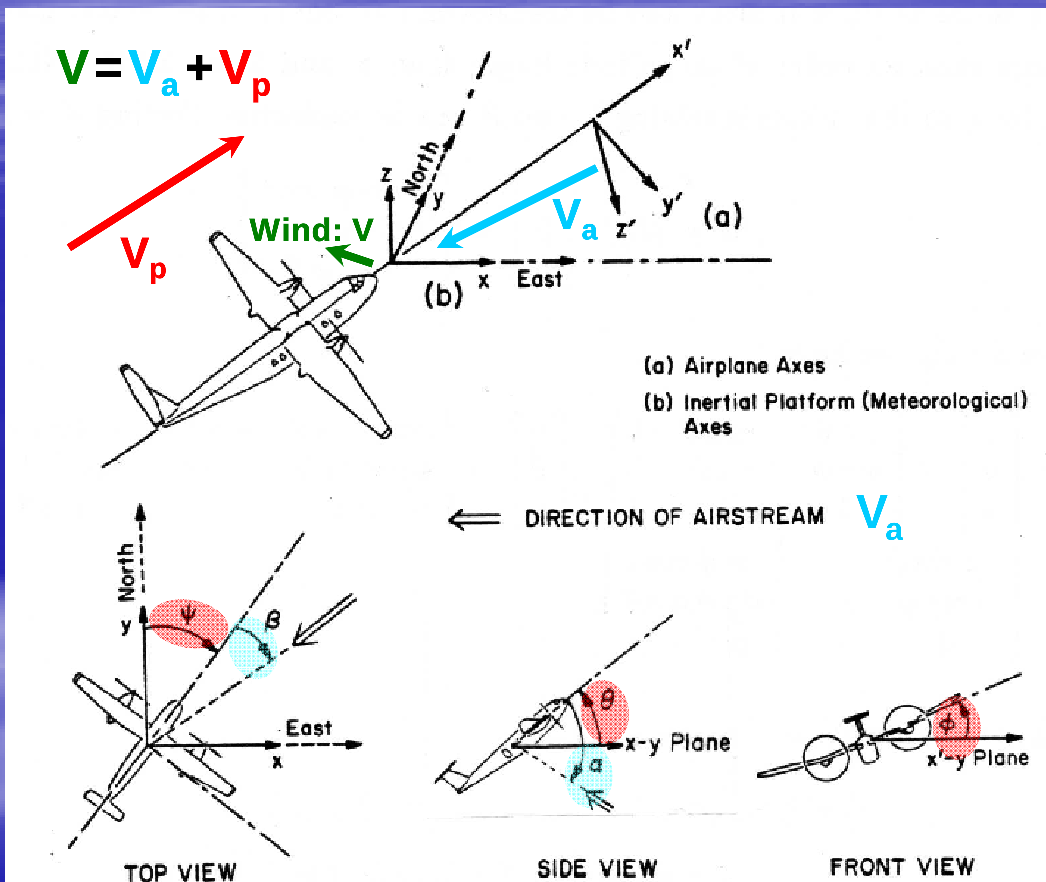


Figure from D.H. Lenschow and P. Spyers-Duran, NCAR/RAF Bulletin 23

$$u = u_p - U_a D \times [\sin\psi\cos\theta + \tan\beta(\cos\psi\cos\phi + \sin\psi\sin\theta\sin\phi) + \tan\alpha(\sin\psi\sin\theta\cos\phi - \cos\psi\sin\phi)] - L(\dot{\theta}\sin\theta\sin\psi - \dot{\psi}\cos\psi\cos\theta)$$

$$v = v_p - U_a D \times [\cos\psi\cos\theta - \tan\beta(\sin\psi\cos\phi - \cos\psi\sin\theta\sin\phi) + \tan\alpha(\cos\psi\sin\theta\cos\phi + \sin\psi\sin\phi)] - L(\dot{\psi}\sin\psi\cos\theta + \dot{\theta}\cos\psi\sin\theta),$$

$$w = w_p - U_a D[\sin\theta - \tan\beta\cos\theta\sin\phi - \tan\alpha\cos\theta\cos\phi] + L\dot{\theta}\cos\theta$$

where u_p and v_p are the east and north aircraft velocity components, respectively; U_a is the true airspeed; α, β, θ, ϕ, and ψ are the aircraft attack, sideslip, pitch, roll, and true heading angles, respectively; L is the distance separating the INS and gust probe along the aircraft's center line; $D = (1 + \tan^2\alpha + \tan^2\beta)^{-1/2}$; and $\dot{\psi} = d\psi/dt$ and $\dot{\theta} = d\theta/dt$; w_p is the aircraft vertical velocity.

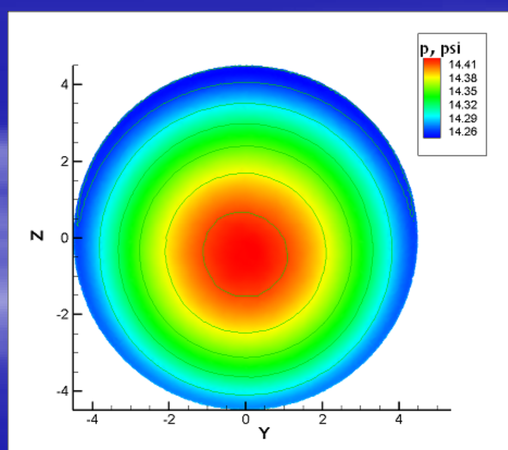
Serial data from INS/GPS C-MIGITS III unit.
Analog data (5-port radome gust system, P_s and T_r)

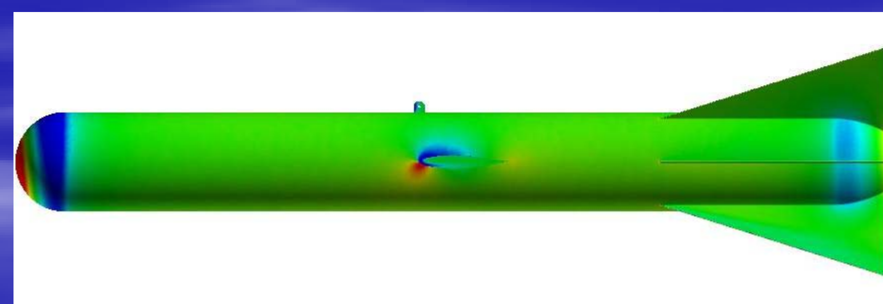
Wind Tunnel* Calibrations and CFD Modeling

5-port radome wind system

Attack=5°
Sideslip=0°

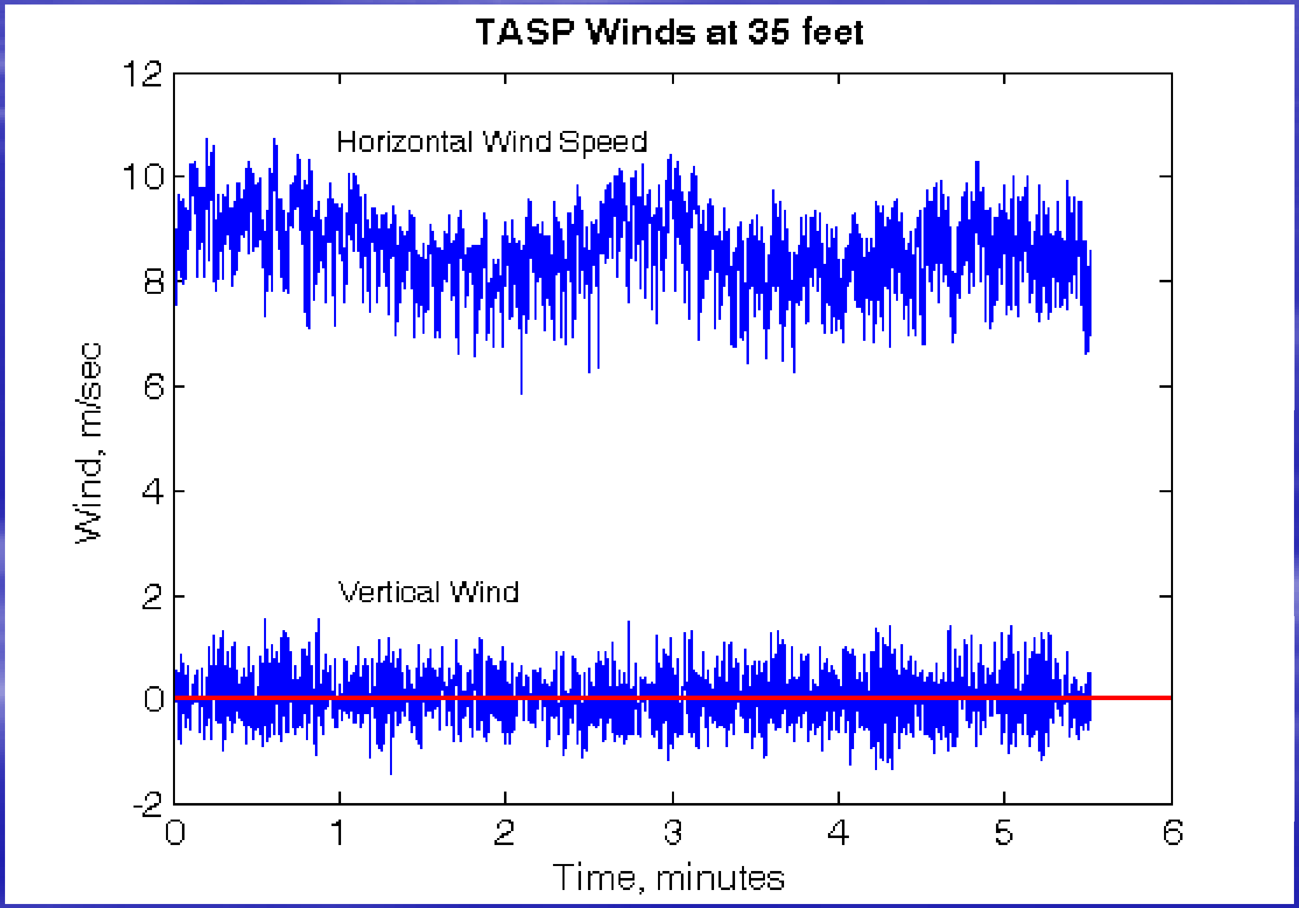
Static pressure port





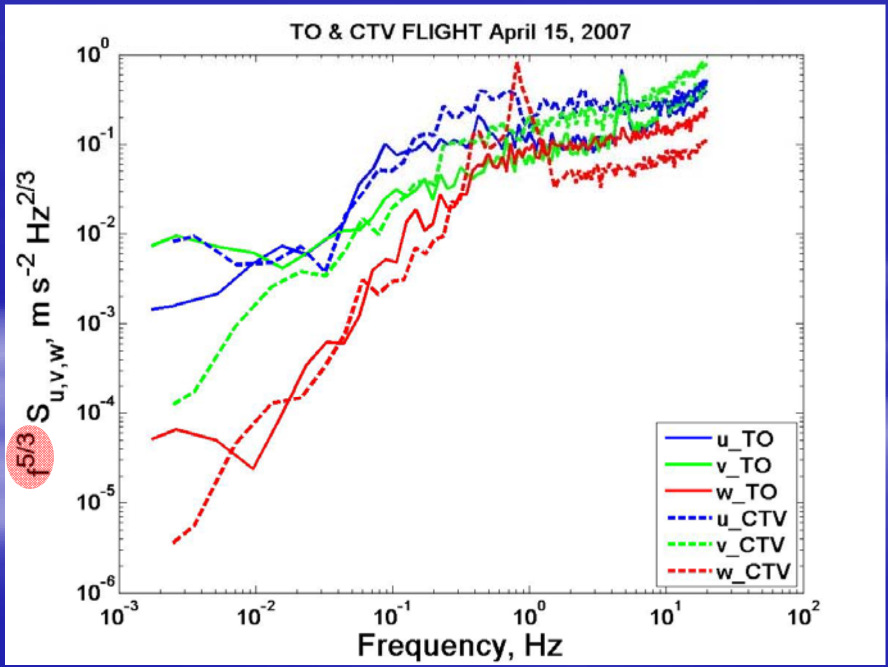
(*) Special thanks to Dr. Arena and his students for hosting us and helping us at Oklahoma State University's wind tunnel facility.

CTV Winds at 35 feet (10.6 m)

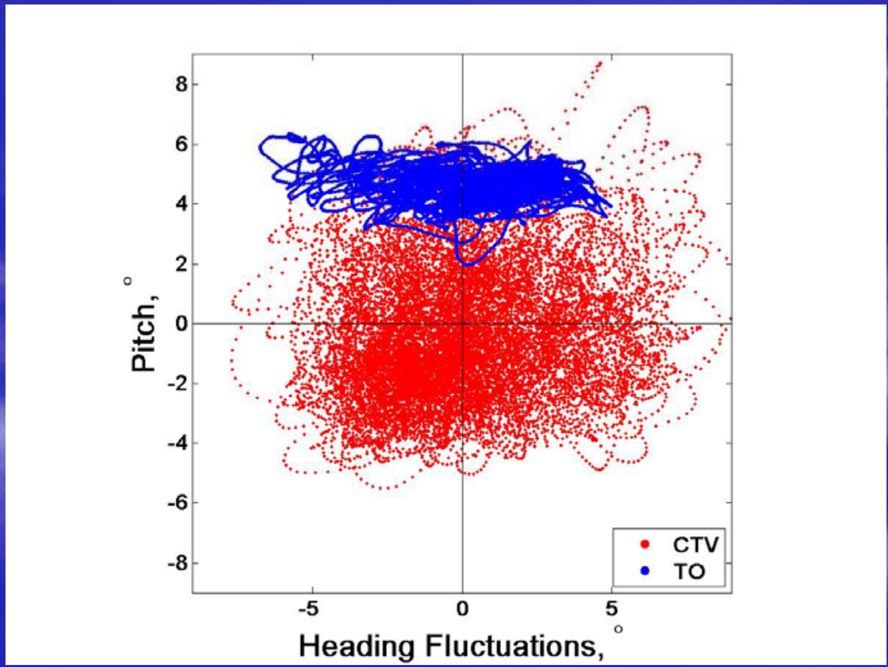


Wind Component Spectra (5/3-moment) and Platform Motions

Wind Spectra

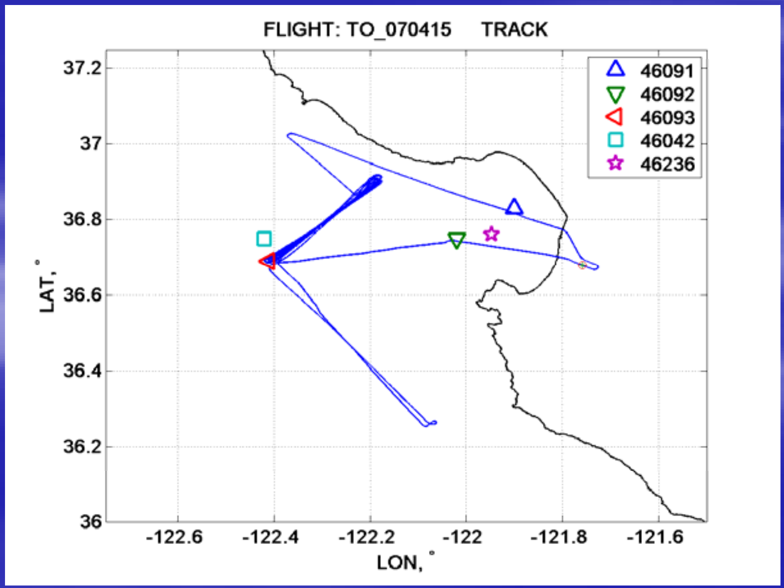


Attitude



Comparisons of Averaged data from ~ 33 m cross-wind runs

	T_a, °C	T_s, °C	T_d, °C	U, m s^{-1}	W_d, °	P, hPa	u_*,m s^{-1}	1000*C_D
CTV	10.1	9.6	6.4	14.5	322	1014.2	0.488	1.132
TO	9.6	9.5	6.0	13.9	323	1013.1	0.468	1.133
N46042	10.5	10.5	-	13.0	325	1015.9	-	-
M46093	10.5	10.5	-	12.6	320	-	-	-



Conclusions

- Towed drone technology is a viable means to obtain critical measurements near the ocean surface in high winds, especially in the hurricane environment.
- The CTV has had approximately 70 cycles-100 hours without mishap.
- More space, power and payload compared to most UAVs (UASs).
- Readily adapted to larger tow aircraft.
- Other sensors can be added or substituted – atmospheric chemistry (fires, volcanoes), aerosols, radiative transfer, waves, etc.
- Simultaneous measurements obtained from tow aircraft higher above.
- Warts: high-frequency motion contamination of winds; control system (being addressed in new phase of CTV development).

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