# Latest progresses in ShUREX* (2015-2017) data analyses

(Estimation of kinetic energy dissipation rates from Pitot, CWT and radar data)

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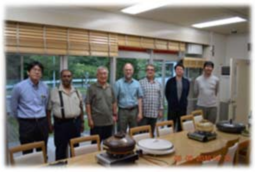
*ShUREX: Shigaraki- UAV – Radar Experiment

## Introduction to ShUREX campaigns

P.I.: Prof. Lakshmi Kantha (Colorado University, USA)

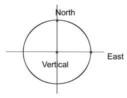


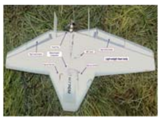
The ShUREX dream team!

## Instrumental set up (2016, 2017)

**MU Radar**

3 beams (0°,0°), (0°,10°), (90°,10°),

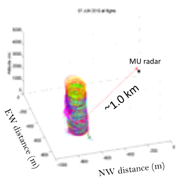


A **Datahawk UAV** equipped with mutiple sensors (**Kantha et al., 2017**).

| | |
|---|---|
| **Sensor type** | CWT / Pitot |
| **Sampling rate** | 800 Hz/ 400 Hz |

Number of useable flights (on Sep 2018): 39




Maximum height (UAV): 4-5 km

Acquisition time for one Doppler spectrum: 24.57 sec
Range sampling from 1.34 km to 20.35 km ($\Delta r = 150\ m$)

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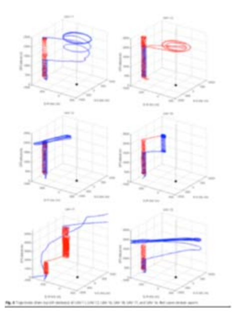
## Examples of UAV trajectories



After Kantha et al. 2017

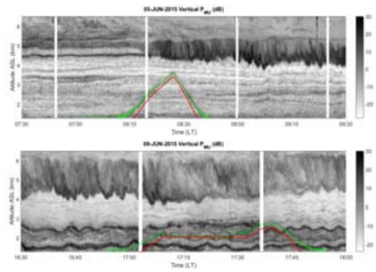


**Figure 3**: (a) Time-height cross-section of echo power $P_{MU}$ (dB) at vertical incidence after doing the Capon processing in the height range 1.27-6.5 km from 07:30 LT to 09:30 LT on 05 June 2015. (b) Same as (a) from 16:30 LT to 18:00 LT on 09 June 2015.

After Luce et al. 2018

## Focus of the presentation

Comparing **turbulence kinetic energy (TKE) dissipation rates $\varepsilon$** estimated from:

(1) relative air speeds measured by Pitot sensor (UAV)

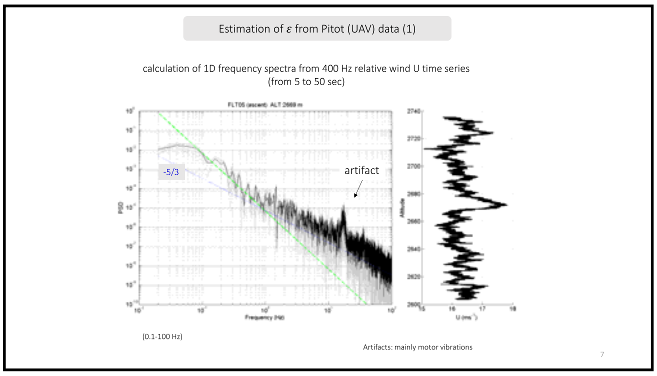
(2) MU radar Doppler spectral width using various models

(3) Temperature measurements by CWT sensors using a theoretical relationship between $C_T^2$ and $\varepsilon$

Part I: (1) and (2)

Part II: (1) and (3)

## Part I: radar – Pitot comparisons


Estimation of $\varepsilon$ from Pitot (UAV) data (1)
calculation of 1D frequency spectra from 400 Hz relative wind U time series
(from 5 to 50 sec)
FLT05 (ascent) ALT 2669 m
-5/3
artifact
Frequency (Hz)
(0.1-100 Hz)
Artifacts: mainly motor vibrations
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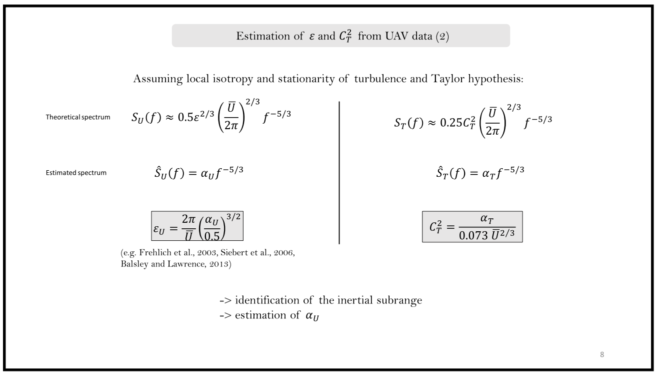
Estimation of $\varepsilon$ and $C_T^2$ from UAV data (2)
Assuming local isotropy and stationarity of turbulence and Taylor hypothesis:
Theoretical spectrum
$S_U(f) \approx 0.5\varepsilon^{2/3}\left(\frac{\bar{U}}{2\pi}\right)^{2/3} f^{-5/3}$
$S_T(f) \approx 0.25 C_T^2 \left(\frac{\bar{U}}{2\pi}\right)^{2/3} f^{-5/3}$
Estimated spectrum
$\hat{S}_U(f) = \alpha_U f^{-5/3}$
$\hat{S}_T(f) = \alpha_T f^{-5/3}$
$\varepsilon_U = \frac{2\pi}{\bar{U}}\left(\frac{\alpha_U}{0.5}\right)^{3/2}$
$C_T^2 = \frac{\alpha_T}{0.073\,\bar{U}^{2/3}}$
(e.g. Frehlich et al., 2003, Siebert et al., 2006, Balsley and Lawrence, 2013)
-> identification of the inertial subrange
-> estimation of $\alpha_U$
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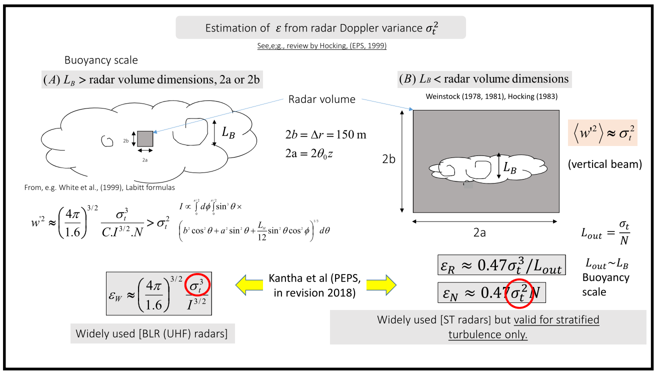
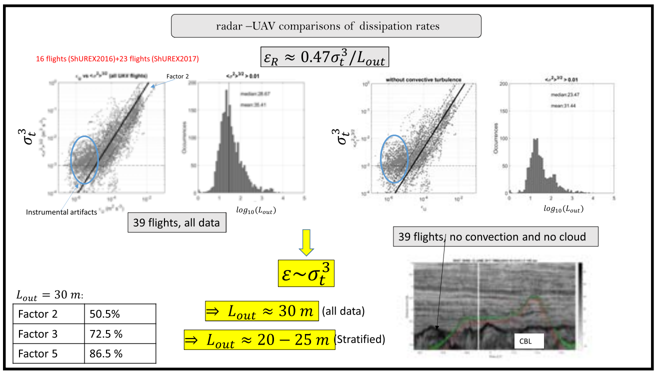
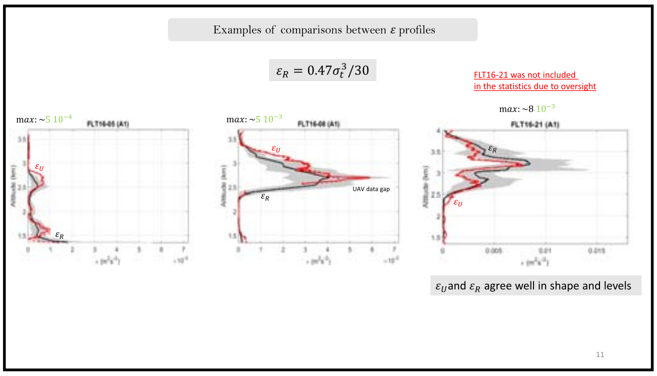

Estimation of $\varepsilon$ from radar Doppler variance $\sigma_t^2$
See e.g., review by Hocking, (EPS, 1999)
Buoyancy scale
(A) $L_B$ > radar volume dimensions, 2a or 2b
(B) $L_B$ < radar volume dimensions
Weinstock (1978, 1981), Hocking (1983)
Radar volume
$L_B$
$2b = \Delta r = 150$ m
$2a = 2\theta_0 z$
2b
2a
$\langle w'^2 \rangle \approx \sigma_t^2$
(vertical beam)
From, e.g. White et al., (1999), Labitt formulas
$L_{out} = \frac{\sigma_t}{N}$
$\varepsilon_R \approx 0.47\sigma_t^3/L_{out}$
$\varepsilon_N \approx 0.47\sigma_t^2 N$
$L_{out} \sim L_B$
Buoyancy scale
$\varepsilon_W \approx \left(\frac{4\pi}{1.6}\right)^{3/2} \frac{\sigma_t^3}{l^{3/2}}$
Kantha et al (PEPS, in revision 2018)
Widely used [BLR (UHF) radars]
Widely used [ST radars] but valid for stratified turbulence only.


radar –UAV comparisons of dissipation rates
16 flights (ShUREX2016)+23 flights (ShUREX2017)
$\varepsilon_R \approx 0.47\sigma_t^3/L_{out}$
Factor 2
without convective turbulence
Instrumental artifacts
39 flights, all data
39 flights, no convection and no cloud
$\varepsilon \sim \sigma_t^3$
$L_{out} = 30\ m$:
Factor 2 | 50.5%
Factor 3 | 72.5 %
Factor 5 | 86.5 %
$\Rightarrow L_{out} \approx 30\ m$ (all data)
$\Rightarrow L_{out} \approx 20-25\ m$ (Stratified)
CBL


Examples of comparisons between $\varepsilon$ profiles
$\varepsilon_R = 0.47\sigma_t^3/30$
FLT16-21 was not included in the statistics due to oversight
max: ~5 $10^{-4}$
max: ~5 $10^{-3}$
max: ~8 $10^{-3}$
UAV data gap
$\varepsilon_U$ and $\varepsilon_R$ agree well in shape and levels
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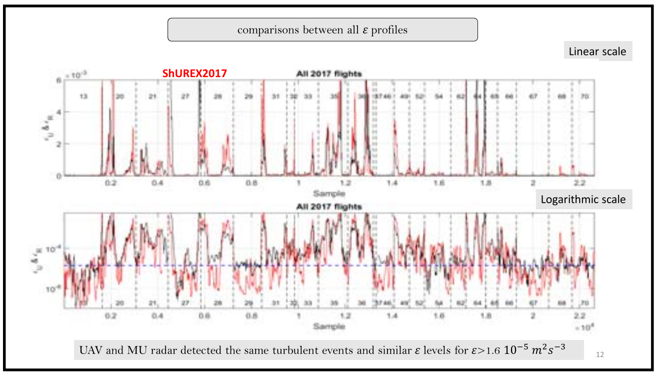
comparisons between all $\varepsilon$ profiles
Linear scale
ShUREX2017
All 2017 flights
Sample
Logarithmic scale
All 2017 flights
Sample
UAV and MU radar detected the same turbulent events and similar $\varepsilon$ levels for $\varepsilon$>1.6 $10^{-5}\ m^2s^{-3}$
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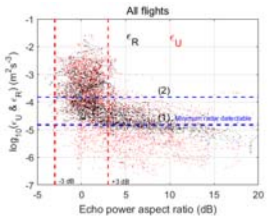
## $\varepsilon$ and aspect ratio (AR) of echo power




$AR = 10\,log10\left(\frac{P_V}{P_O}\right)$

| LR | (1) 0.014 $mW/kg$ $\varepsilon > 1.4\,10^{-5}\,m^2s^{-3}$ | (2) 0.14 $mW/kg$ $\varepsilon > 1.4\,10^{-4}\,m^2s^{-3}$ |
|---|---|---|
| AR < 3 dB | 74 % | **95 %** |
| AR < 5 dB | 86 % | **98 %** |

ICAO: turbulence felt by medium-size aircraft > 1 mW/kg (light turbulence)

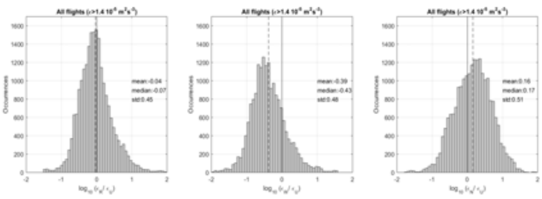
A large majority of $\varepsilon_{UAV}$ values is associated with isotropic echoes (weak aspect ratios) => An a posteriori justification of the use of Doppler variance from the vertical beam.



## comparisons with $\varepsilon_N$ and $\varepsilon_W$

Labitt/white formulation

Weinstock/Hocking formulation



$\varepsilon_r \approx 0.47\sigma_t^3/L_{out}$ | $\varepsilon_W \approx \left(\frac{4\pi}{1.6}\right)^{3/2}\frac{\sigma_t^3}{l^{3/2}}$ | $\varepsilon_N \approx 0.47\sigma_t^2 N$

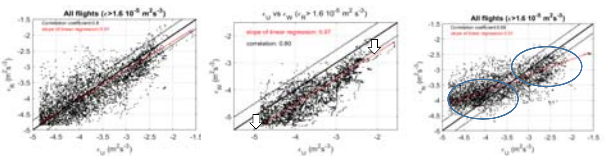
$<\varepsilon_r/\varepsilon_U> = 1$ (by definition)

$<\varepsilon_W/\varepsilon_U> = 0.4$

$<\varepsilon_N/\varepsilon_U> = 1.45$

## Comparisons between $\varepsilon$ estimates

$\varepsilon_R$ $\varepsilon_W$ $\varepsilon_N$



Scatter plot of the various $\varepsilon$ estimates and linear regression (with errors on x and y)

(1) Good agreement (regression slope ~0.9-1.0 and correlation ~0.8) between $\varepsilon_U$ and $\varepsilon_R$ $(or\ \varepsilon_W)$

(2) Disagreement between $\varepsilon_{UAV}$ and $\varepsilon_N$: It is high for low values and becomes lower for high values.



## Conclusions of part I

a) The UAV and radar captured the same turbulent events with peaks of $\varepsilon$ and $\sigma_t$ at the same altitudes and times. => quantitative comparisons could be made.

b) $\varepsilon_{UAV} \sim \sigma^3/L_{out}$ with $L_{out} \approx 30\,m$. Energy dissipation rates can be estimated from the sole Doppler variance. at least in the lower troposphere

c) The asymptotic models $\varepsilon_W$ and $\varepsilon_N$ provide quite consistent levels:
$\varepsilon_W \sim 0.4\,\varepsilon_{UAV}$, in average, slight underestimation but no bias,
$\varepsilon_N \sim 1.45\,\varepsilon_{UAV}$, in average, *BUT* overestimates for low values and underestimates for high values (~>0.3 mW/kg)

d) In addition, since $\varepsilon_R$ and $\varepsilon_W$ are relevant for turbulence generated by convections or shear flow instabilities but $\varepsilon_N$ is applicable to stratified turbulence only, the Weinstock model may not be suitable at least for tropospheric data.



## Part II: CWT – Pitot comparisons

## Estimation of $\varepsilon$ from $C_T^2$

For stratified turbulence (e.g. Ottersten, 1969; Gossard, 1982; Gavrilov et al. 2005):

$$\varepsilon_{CT2} = \left(\gamma \frac{g^2}{T^2}\frac{C_T^2}{N^2}\right)^{3/2}$$

Valid for dry or moist (unsaturated) air

$$\gamma = \frac{1}{\beta_\theta}\frac{P_r - Ri}{Ri} = \frac{1}{\beta_\theta}\frac{1-Rf}{Rf}$$

$\beta_\theta = 3.2$ (universal constant)

$Ri$: Richardson number, $P_r$= Turbulent Prandtl number
$Rf = {}^{Ri}/_{Pr}$: Flux Richardson number

Mixing efficiency coefficient:
$\gamma_{R_f} \equiv R_f/(1-R_f)$

mixing efficiency = $\frac{\text{Change in background potential energy due to mixing}}{\text{Energy expended}}$

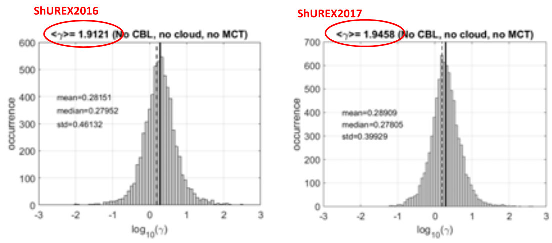
Gregg et al., 2018

Oceanic turbulence

1. It has long been understood that mixing efficiency is unlikely to be constant, but, because $K_\rho$ from tracers and microstructure evaluated with $\gamma_{R_f} = \gamma_{\chi\epsilon} = 0.2$ agree better than do coefficients and efficiencies from simulations and experiments. Reasons for this agreement are not understood, particularly in view of the loss of po-

## Statistical values of $\gamma$

$$\varepsilon = \left(\gamma \frac{g^2}{T^2}\frac{C_T^2}{N^2}\right)^{3/2}$$




Remarkable consistency between the results obtained from ShUREX2016 and ShUREX2017

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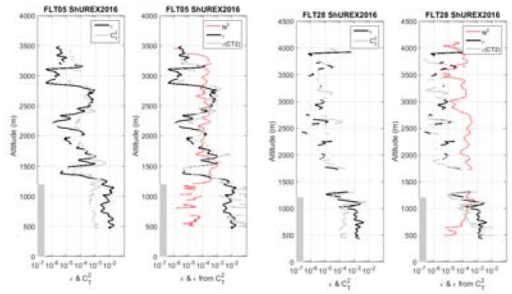
## Examples of comparisons between $\varepsilon_U$ and $\varepsilon_{CT2}$

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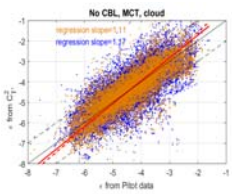
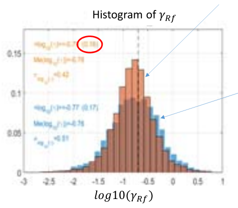
## Statistical values of mixing efficiency coefficient $\gamma_{Rf}$




$$\gamma_{Rf} \approx 0.16 \cong 0.20$$

The mixing coefficient is found to be $\sim cst$ and similar to oceanic values

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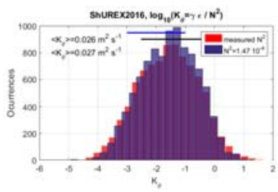
## Eddy diffusivity $K_\theta = 0.16\frac{\varepsilon}{N^2}$

In the literature: $K_\theta \approx 0.33\frac{\varepsilon}{N^2}$ (e.g. Lilly, 1974; Fukao et al., 1994, Naström and Eaton, 2005)



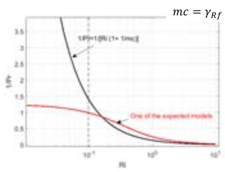

Black: After Alisse and Sidi (2000) for stratospheric turbulence (36 cases)
Blue: After Bertin et al. (1997), stratosphere (several cases)

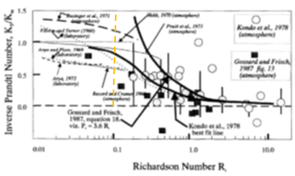
The statistical values of $K_\theta$ are similar to prior estimates from HR balloon data at stratospheric heights

## Conclusions of part II

1. TKE dissipation rates $\varepsilon$ estimated from wind and temperature data compare well with a mixing efficiency coefficient $\gamma_{Rf}$ of 0.16 (close to 0.2)
2. This result is not consistent with Prandtl number properties but…

$mc = \gamma_{Rf}$




For Ri >0.1, $\gamma_{Rf}$~0.16 provides reasonable agreements with laboratory experiments and theoretical expectations.
For Ri <0.1, large discrepancies. => **Is (effective) Ri <0.1 rare in lower tropospheric conditions (for stratified turbulence)?**

## Perspectives

Since $\varepsilon = \left(\gamma \frac{g^2}{T^2}\frac{C_T^2}{N^2}\right)^{3/2} = \left(\gamma \frac{C_n^2}{M^2} N^2\right)^{3/2}$ (Ottersten, 1969)

$C_n^2$ can be estimated from $\varepsilon$ making possible comparisons with $C_n^2$(radar)
⇒ Relevance of the radar estimates
⇒ Accurate calibration of $C_n^2$(radar)

(under processing)