EDR Implementation Update

Turbulence Mitigation Workshop IV

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NCAR/RAL

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NCAR

NSF

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- FAA: AWRP, Tammy Flowe
- IATA Turbulence Aware Program
- Manufacturers: Boeing, Teledyne, Honeywell, Airbus, ...
- Airlines: Delta, United, Southwest, Swiss, Lufthansa, Aer Lingus, Qantas, JAL, and many others
- …

Aircraft -based Turbulence Observations

- "Truth" about the turbulence situation drives ALL turbulence products.

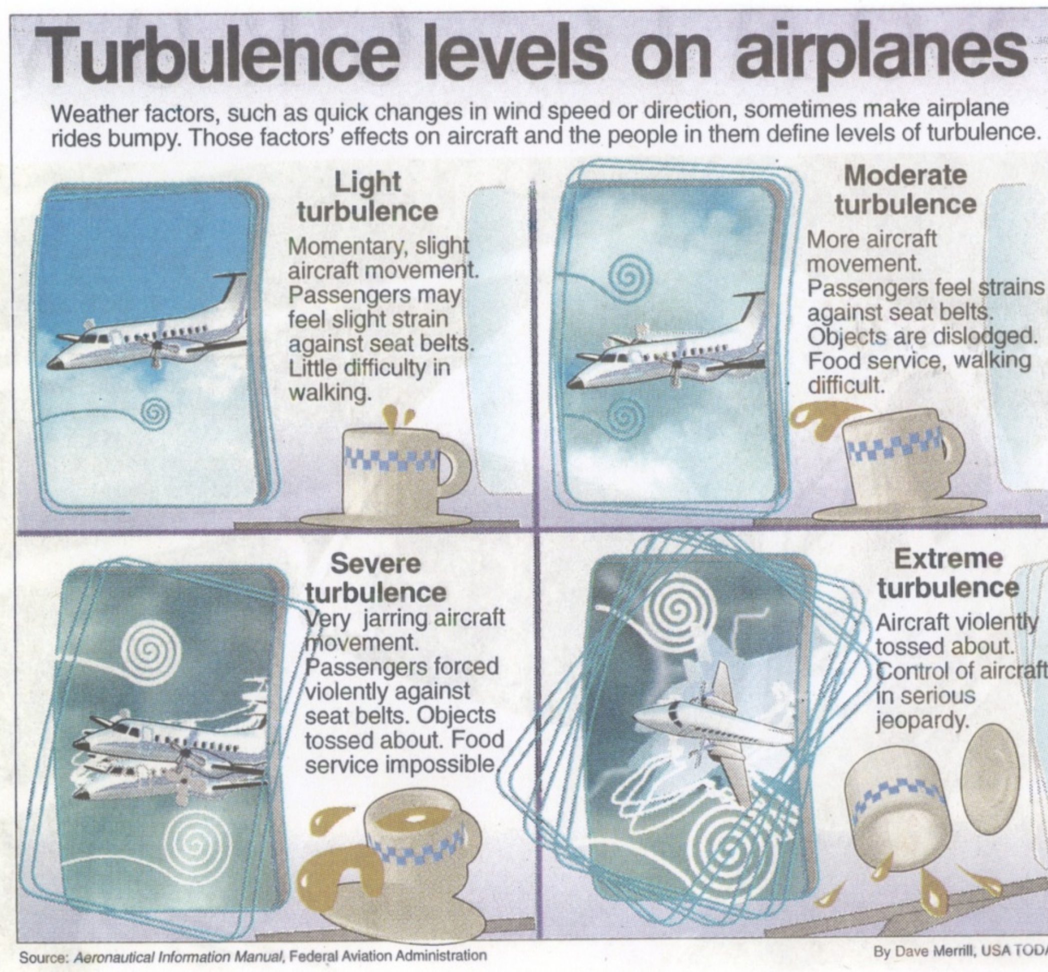
  No aircraft observations = No idea

- Basic research (climatologies, characterization, case studies)
- Product development (research, tuning)
- Evaluation/Verification of products
- Real-time ingest into products

PIREP/AIREP turbulence measurements

- Before insitu the only routine observations were pilot reports
  - Non-uniform measure in space and time
  - Generally low occurrence
  - Subjective and categorical (“light”, “moderate”, “severe”, “extreme”)
  - Serious position and time inaccuracies
  - Aircraft and flight condition dependent

- Better would be an automated atmospheric measure, i.e. aircraft independent



Turbulence levels on airplanes

Weather factors, such as quick changes in wind speed or direction, sometimes make airplane rides bumpy. Those factors’ effects on aircraft and the people in them define levels of turbulence.

Light turbulence
Momentary, slight aircraft movement. Passengers may feel slight strain against seat belts. Little difficulty in walking.

Moderate turbulence
More aircraft movement. Passengers feel strains against seat belts. Objects are dislodged. Food service, walking difficult.

Severe turbulence
Very jarring aircraft movement. Passengers forced violently against seat belts. Objects tossed about. Food service impossible.

Extreme turbulence
Aircraft violently tossed about. Control of aircraft in serious jeopardy.

Source: *Aeronautical Information Manual*, Federal Aviation Administration

By Dave Merrill, USA TODAY

PIREP/AIREP turbulence measurements

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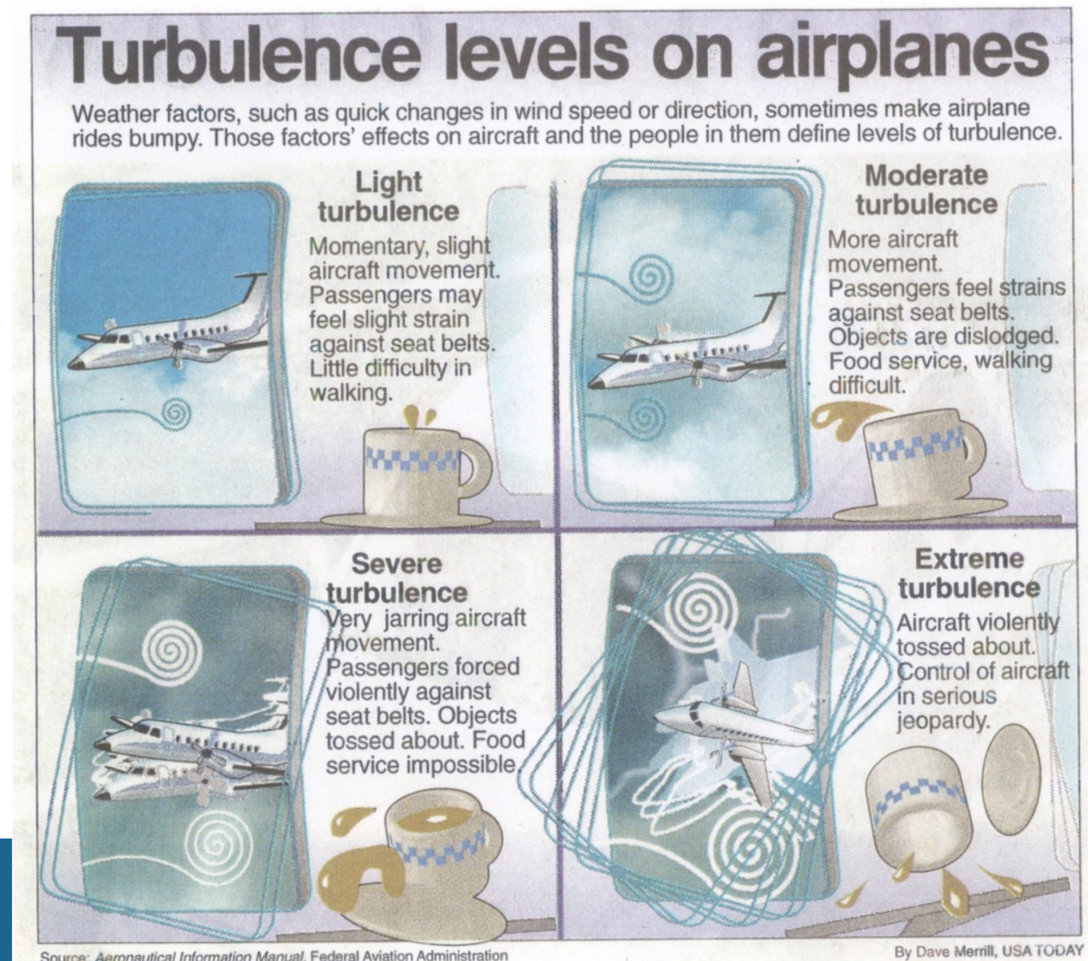
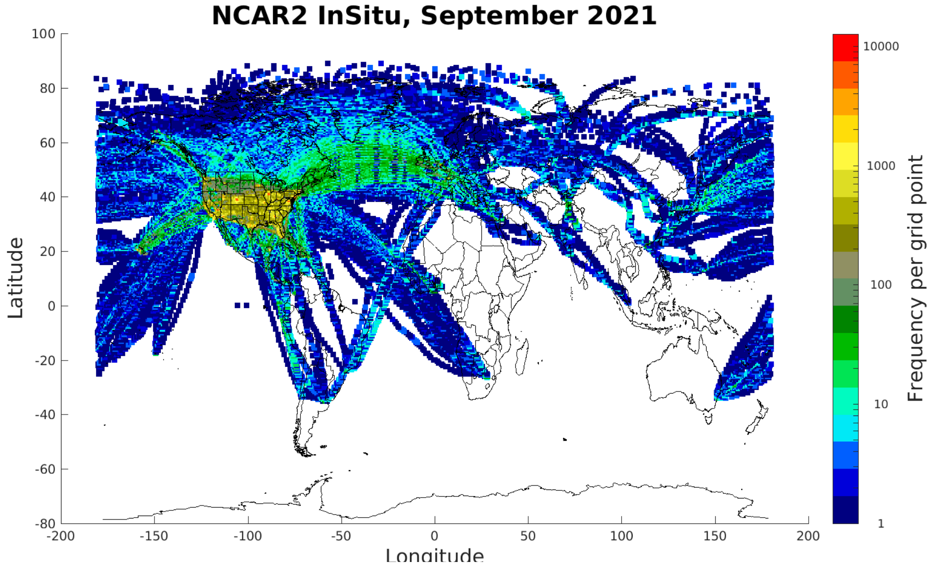
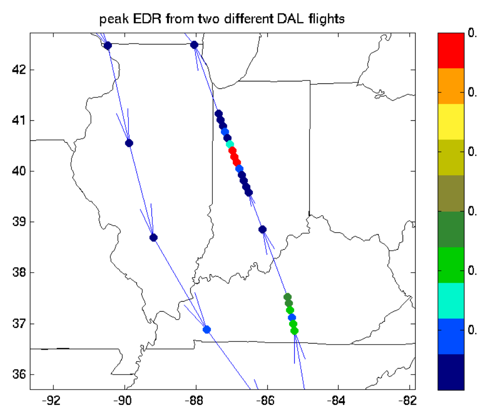
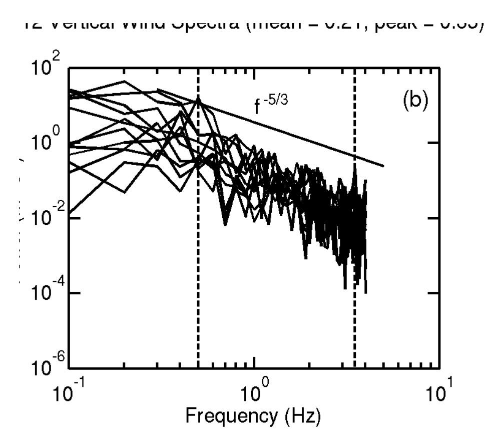


Automated InSitu Turbulence Reporting
NCAR Insitu EDR Algorithm

- To address these shortfalls, FAA sponsored NCAR to develop an <u>automated</u> InSitu Turbulence detection algorithm
  - Uniformly measured in time (though not always reported) every 1 minute
  - Frequent reporting (15/20 minute routine reporting plus event - triggered reports)
  - Objective and quantitative (based on existing aircraft censors)
  - Reliable and accurate position and time information
  - Measures EDR, an atmospheric turbulence intensity metric; not aircraft dependent.

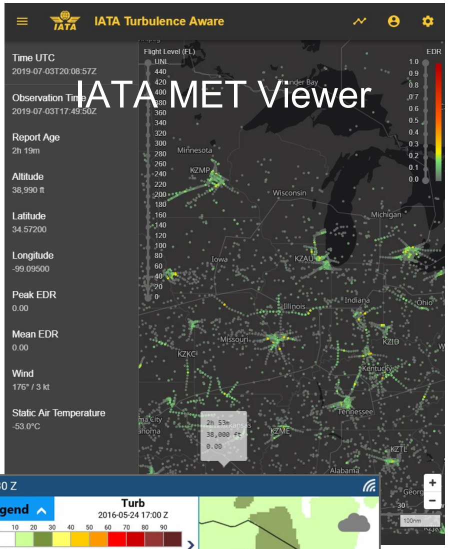


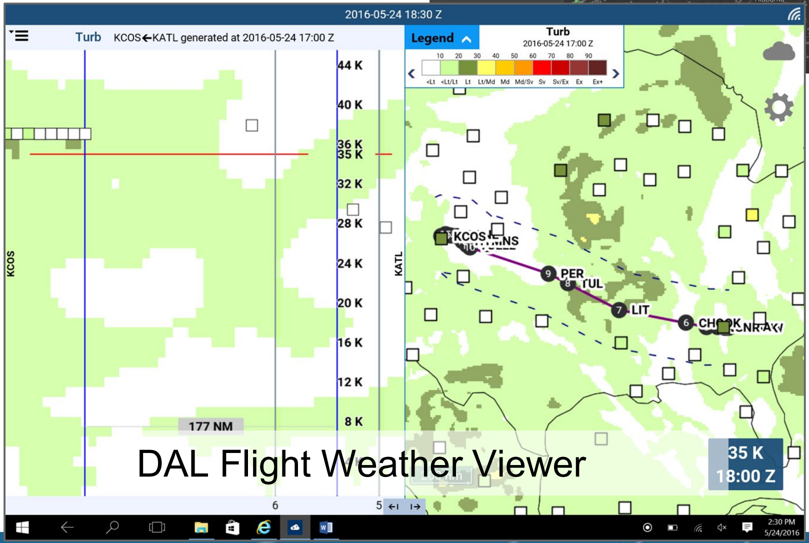




Operational Benefits

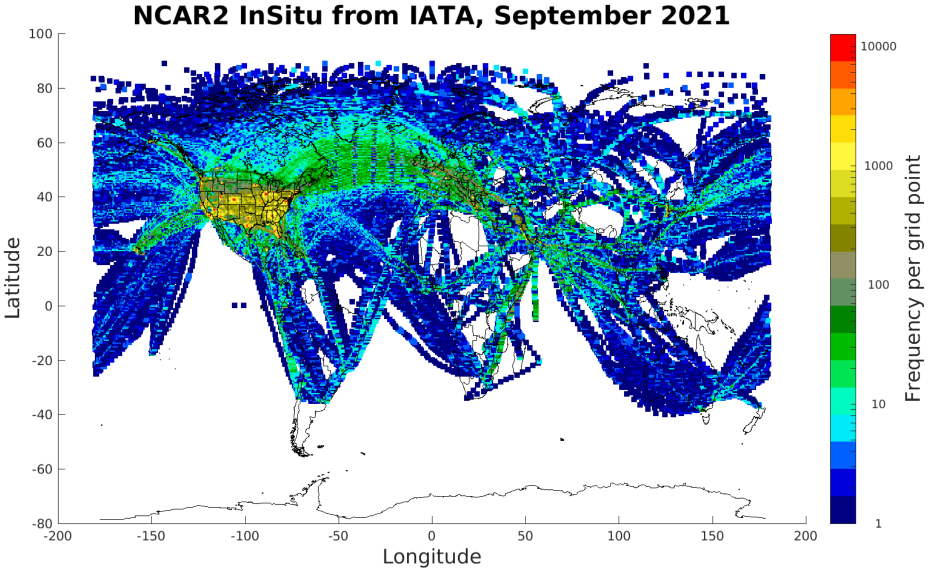
- Improved situational awareness for dispatchers and pilots, both from a strategic (e.g. GTG) and tactical (e.g. GTGN/in situ) standpoint.
  - Knowing better when to turn on the seatbelt sign and stow the beverage cart.
  - Fewer injuries/deaths
  - Wasting less fuel searching for a smooth ride.





NCAR Insitu EDR Algorithm Software Package Timeline

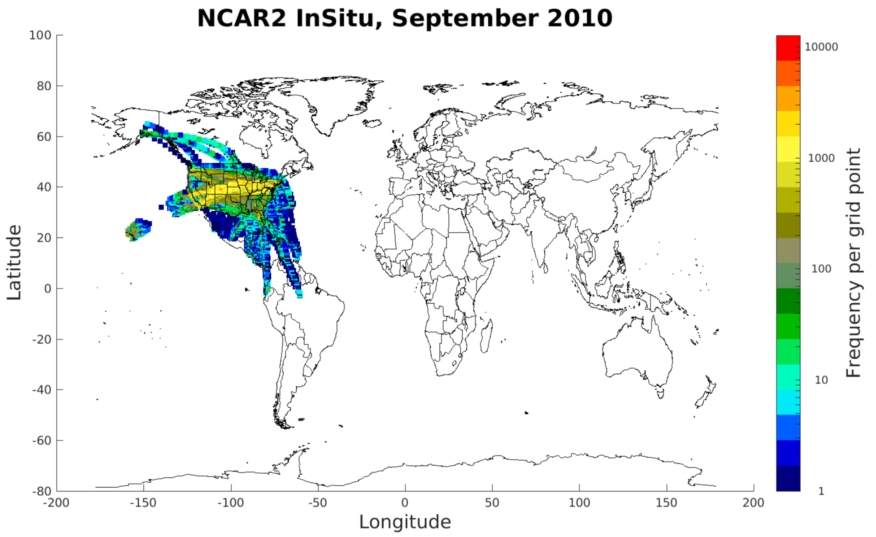
- In 1990s FAA sponsored development of an automated insitu atmospheric turbulence detection algorithm.
- Deployed version 1 (accelerometer-based) in early 2000s (UAL B737 & 757).
- Developed version 2 (vertical-wind-based) in mid 2000s and began deployment in 2008 (DAL B737NG).
- Updated version 2 to be easily adaptable to different aircraft types in 2016.
- Built 10 Hz version also in 2016 for 777 and 787.

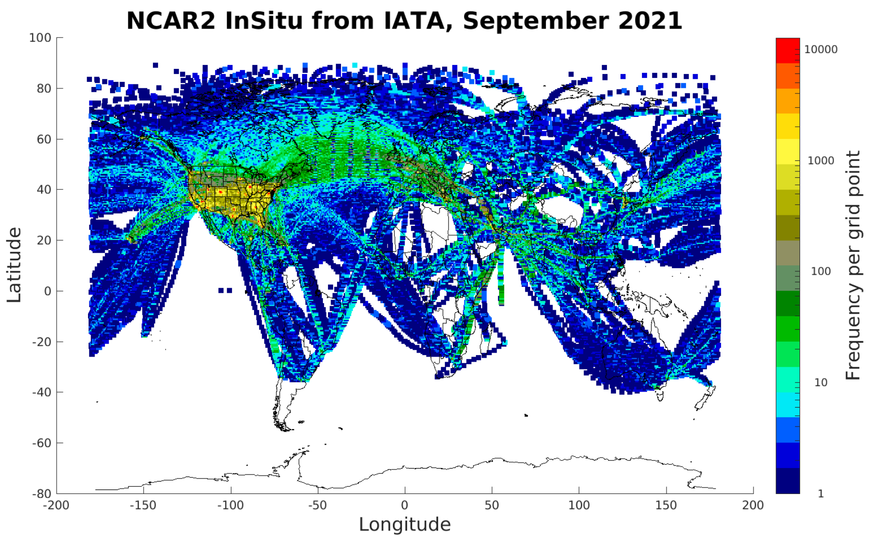


- Built tech transfer package in 2017 to simplify deployment including some support for other data rates.
- IATA incorporated into their tech transfer package in 2019.

NCAR Insitu EDR Algorithm: Current Facts

- Current Observations
  - ~1600 aircraft worldwide (1300 US based)
  - ~65K EDR reports per day received at NCAR (~75K at IATA)
- Current Aircraft Types
  - Boeing: 737NG, 737MAX, 767-300/400, 777-200/300, 787-8/9/10
  - Airbus: 319/20/21, 330-200/300/900
- Future
  - Boeing: 777X
  - Airbus: A350





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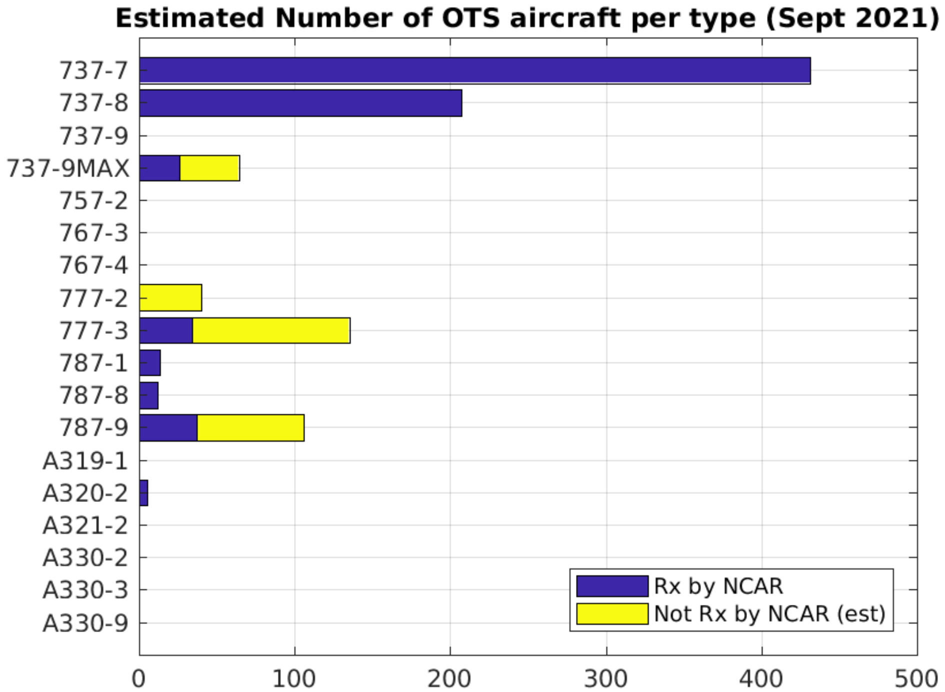
Automated InSitu Turbulence Reporting
Deployment Paths



All numbers are approximate

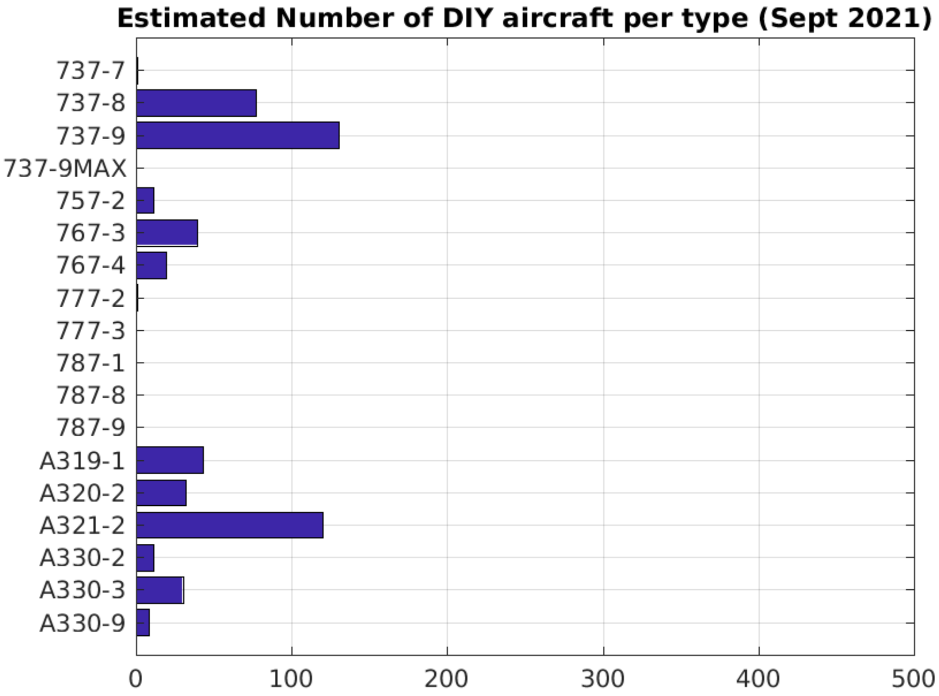
"Off the shelf" Deployment Paths

Teledyne:
- B737NG (DFDAU-91X)
- A320 (D10)
- Working on A330 (D13)

Boeing:
- 777
- 787
- 737MAX
- Working on 777X

Airbus:
- 350 (performing non-mandatory flight tests – now available)

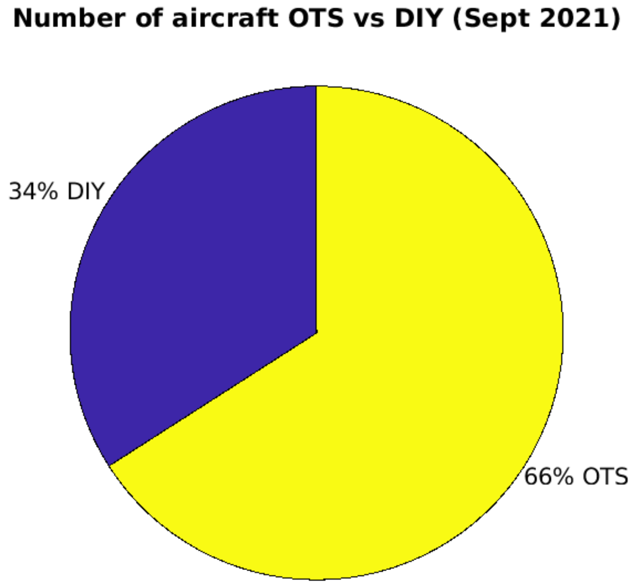
Automated In Situ Turbulence Reporting
Deployment Paths

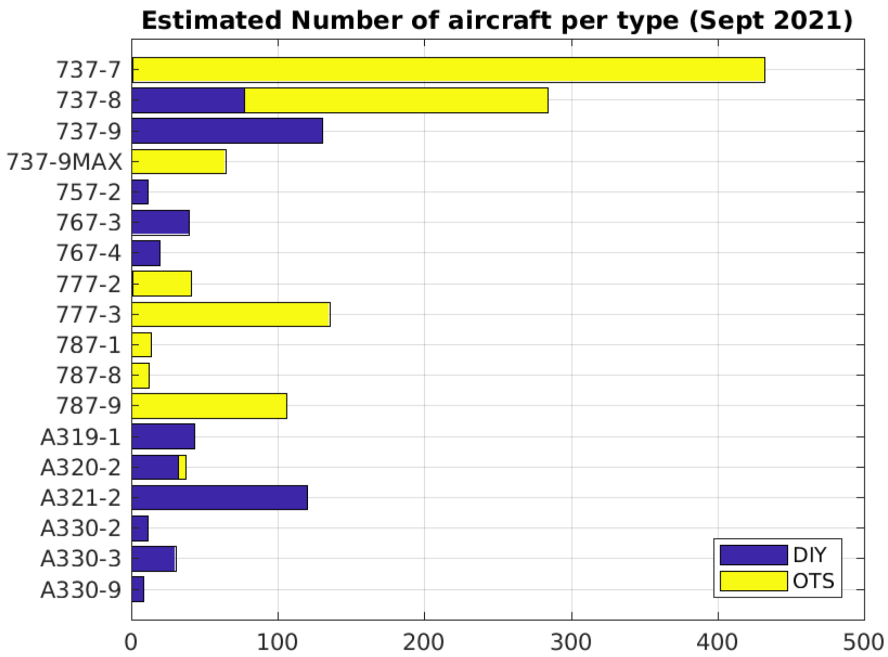


All numbers are approximate

- “Do-it-yourself” if using a Teledyne ACMS
  - Many Teledyne ACMS have the capability to allow the airline to integrate the software themselves.
  - Has been successfully done on
    - B737NG
    - B767-200/300
    - A319/20/21
    - A330-200/300/900
- Other DIY options
  - EFB
  - AID

Off-the-shelf VS Do-it-yourself Numbers





All numbers are approximate

NCAR InsituTT package

- C library implementation of EDR software and triggering logic
- EDR Support software (MATLAB)
  - Used for input data quality checks, tuning, and validation
- Sample data that can be used for bench testing, if available
- Ground-based software for ingest (decoding) and quality control
- Documentation
  - ICD, user's guide, etc.

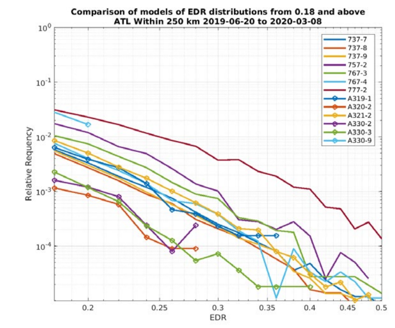
IATA Turbulence Aware

IATA has developed this program to help with EDR use from end-to-end: from getting the program started to EDR operational use

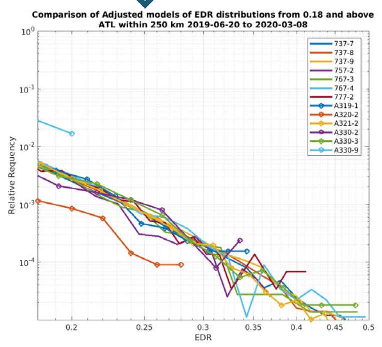
- Program development assistance:
  - Support for building the internal business case for an airline, including help with putting together the financials
  - Technical support including coordinating with NCAR, Boeing , Airbus and Teledyne
  - Training: Dispatcher, pilot, MET Viewer training
  - Free trial for new customers and select areas
- Tech transfer package:
  - Automated Turbulence Reporting - Industry Guidelines
  - NCAR2 EDR Algorithm: Technology Transfer Documentation (containing all that an airline needs to know to build a reporting capability)
  - Delta NCAR EDR Implementation Support Package for Teledyne boxes
  - Software and documentation for using/accessing EDR reports, interfacing with EDR database (API & SDK), and MET Viewer

Use Considerations: EDR Comparability

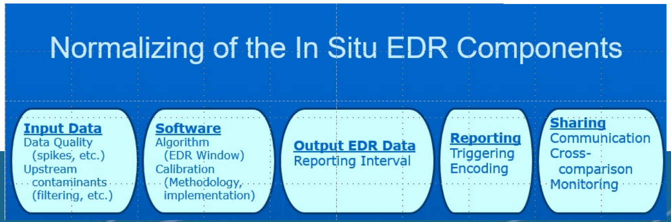
- In 2017, RTCA DO-370 was released: Guidelines for *In Situ* Eddy Dissipation Rate (EDR) Algorithm Performance
  - Provided testing procedure specification along with datasets to allow for testing the **algorithm** and **tuning methodology** (not implementation).
  - Why? There is not a feasible "golden EDR box" to test that an implementation is tuned properly and producing good EDRs.



Fleet Normalization

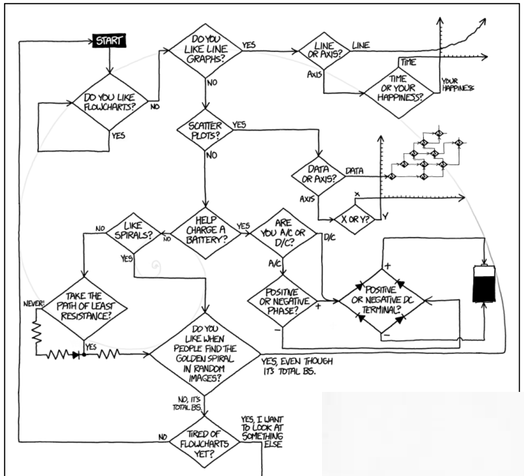


- Industry Turbulence Safety Action Team (ITSAT)
  - Working further on comparability
  - Side by side comparisons, …



Use Considerations: Thorny Issues

Control of data, Cost Sharing, Data Routing, Data Sharing

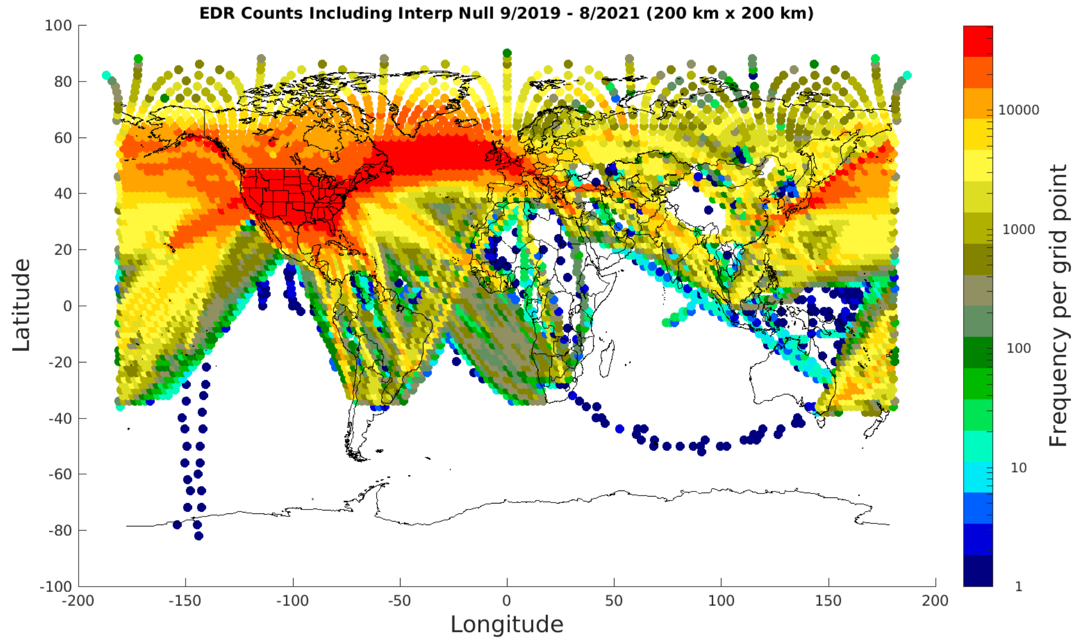


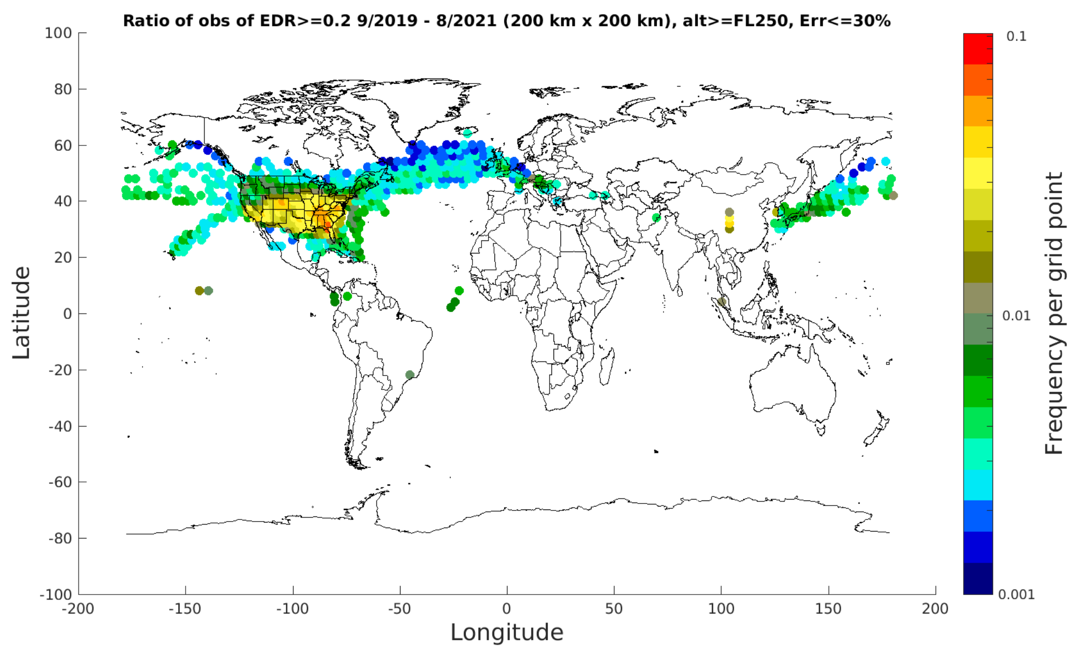
https://xkcd.com/1488/

- How can we better encourage the sharing of data with government agencies/met offices? ...research institutions?
- How is the distribution of the data controlled? (if freely available there is less incentive for others to invest to join in)
- What about the sharing of “significant” turbulence events?
- There are initial and recurring costs. How are these shared among the parties?

Quick Climatological Detour

- 2 year **preliminary** climatology of In Situ EDR
  - Top: Counts from 2 years including interpolate Nulls, FL250+ received at NCAR
    - Interpolated Nulls are substitute for EDRs that would be in dataset if it was downlinked.
    - All EDRs>=0.18 are downlinked.
  - Bottom: QC censored (relative errors<+/-30%) fraction of EDRs>=0.2
    - Because interpolated nulls are included, this should approximate the relative risk.





Extras

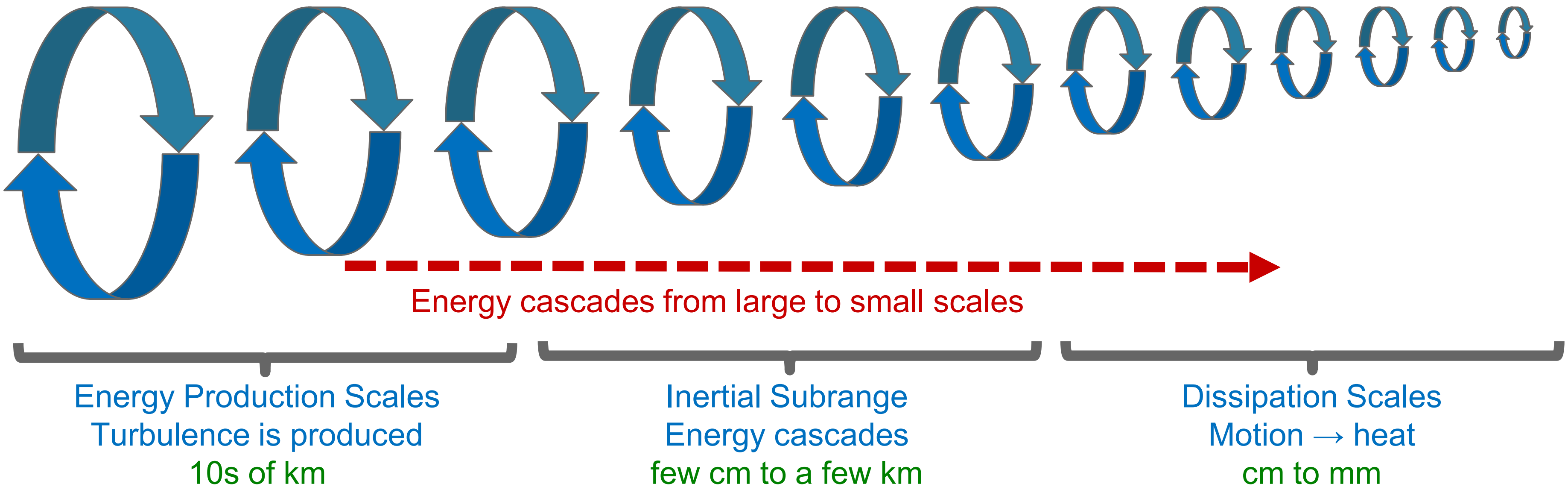
Turbulence and Its Estimation

- Turbulence: atmospheric motion which is defined by chaotic changes in pressure and velocity.

- EDR is an atmospheric turbulence intensity metric
  - Relevant for scales of turbulence which affect aircraft (very large or very small scales are not “felt” as “turbulence)
  - Is sufficient to fully characterize the atmospheric turbulence at these scales (no other parameters are needed).

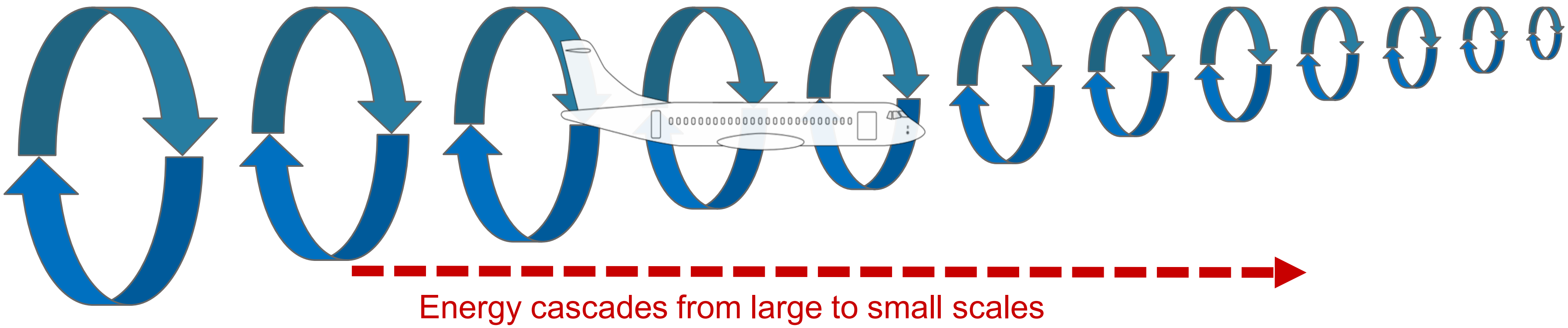
Turbulence and Its Estimation

From an atmospheric perspective, turbulence is made up of eddies of many sizes (or scales). Turbulence starts as larger scale eddies. The energy then cascades down to smaller and smaller eddies until the energy dissipates into heat because of viscosity.



Turbulence and Its Estimation

From an aviation perspective, turbulence is perceived only from scales within a certain range which, for most aircraft, falls within the “inertial subrange”.



Energy Production Scales	Inertial Subrange	Dissipation Scales
Turbulence is produced	Energy cascades	Motion → heat
10s of km	few cm to a few km	cm to mm
Aircraft/pilot can adapt. Not generally felt at turbulence.	Aircraft responds to scales from 10s m to few km with rapid pitch, roll, and vertical motions. Felt as turbulence.	Excites flexible modes of aircraft but typically small.

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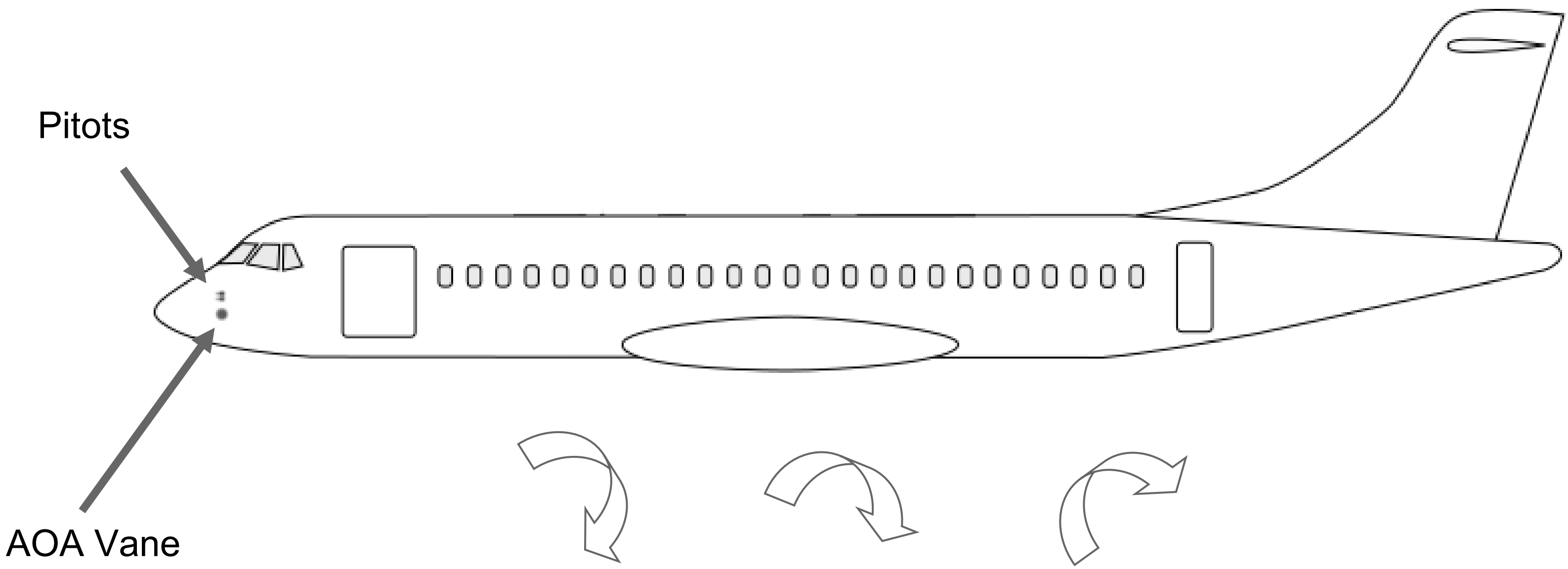
Some Atmospheric Turbulence Intensity Metrics

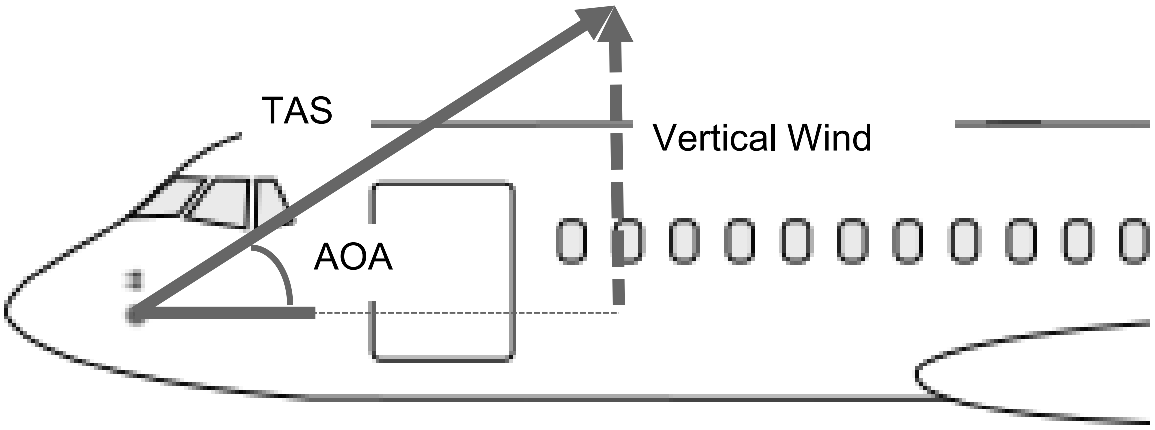
- Turbulence Kinetic Energy (TKE)
  - Essentially the variance of the winds.
  - Includes energy at all scales, even scales that do not effect aircraft (and in fact is generally dominated by those larger scales)
  - Generally would require other turbulence parameters (e.g. length scale) to interpret at aircraft scales.
- Energy (Eddy) Dissipation Rate (ε)
  - The rate of the dissipation of energy (conversion of motion to heat).
  - In the inertial subrange (which contains the scales of turbulence to which aircraft respond), ε can be used to soley characterize the turbulence.
  - We often refer to $\varepsilon^{1/3}$ as "EDR".

Wind Algorithm Approach



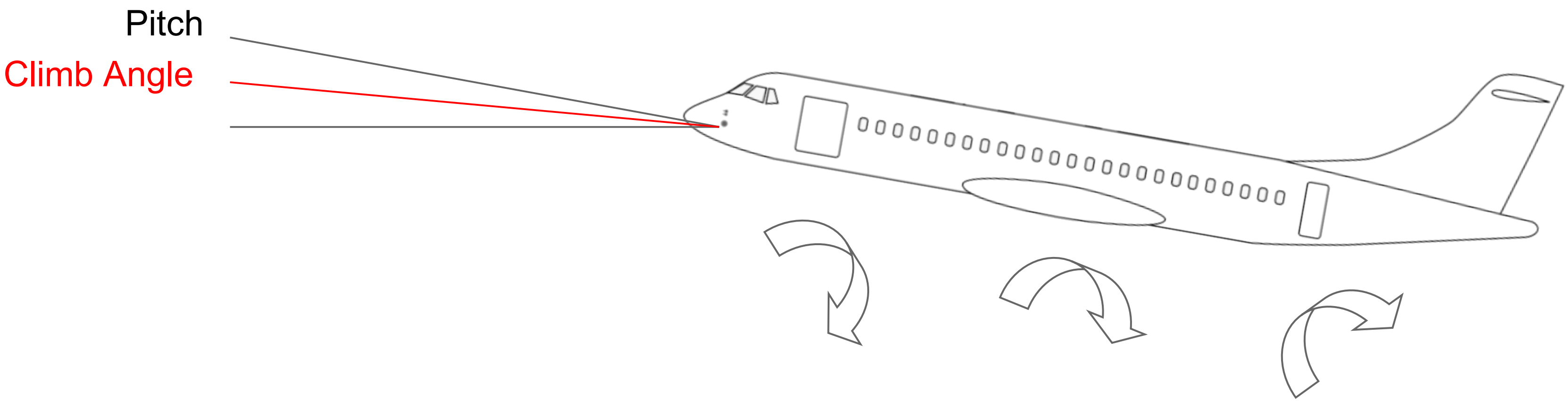
If aircraft is flying straight and level, AOA (body axis) gives direction of flow of air past the nose in longitudinal-vertical directions (geometric plane). TAS (derived from Pitots) provides speed in that plane. In essence, each aircraft has a sideways mounted anemometer attached to the nose.

Wind Algorithm Approach



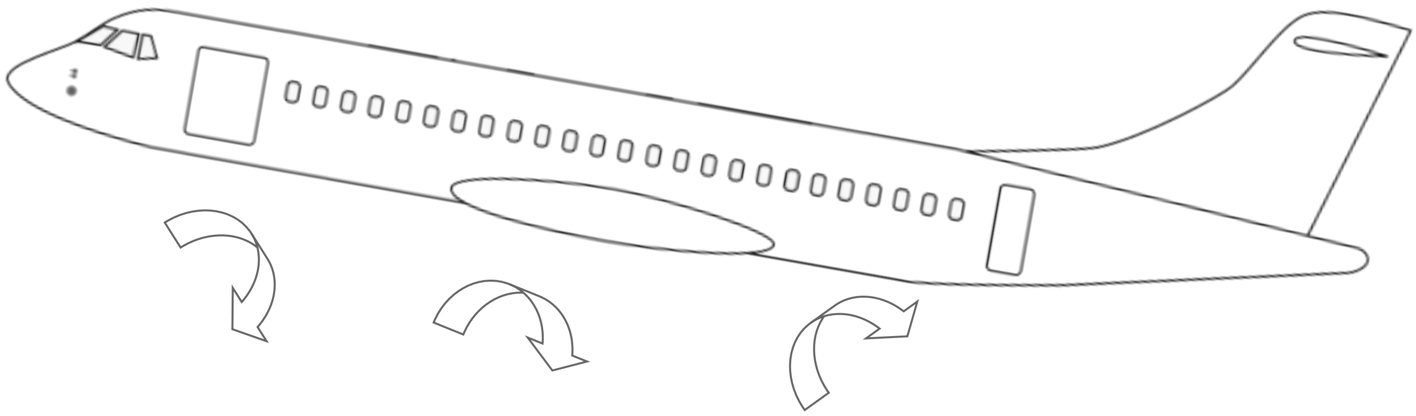
With the assumption of straight and level flight, using simple trigonometry, we can determine the magnitude of the vertical wind.

Wind Algorithm Approach



Since the aircraft does not fly straight and level, in reality, the equations to compute the vertical wind are more complicated. Corrections are included for pitch, pitch rate, vertical motion (inertial vertical velocity), and roll. There are all used solely to adjust for the fact that the "anemometer" is moving and is not oriented in a fixed direction.

Wind Algorithm Approach



Once a vertical wind time-series is estimated, we can estimate the turbulence in an aircraft-independent way.

Note 1: There are some aircraft-dependent parameters involved to **compute** the EDR, but they relate to the conversion from indicated AOA to body axis AOA, length of the aircraft, and the signal processing applied to the EDR algorithm input up-stream from the algorithm.

Note 2: The response (i.e. accelerations) of the aircraft to the turbulence is not used.

EDR Calculation

To compute EDR from vertical winds

- We first do some quality control

- We then find the value of EDR which "best" fits the data within a frequency range which is within the inertial subrange.

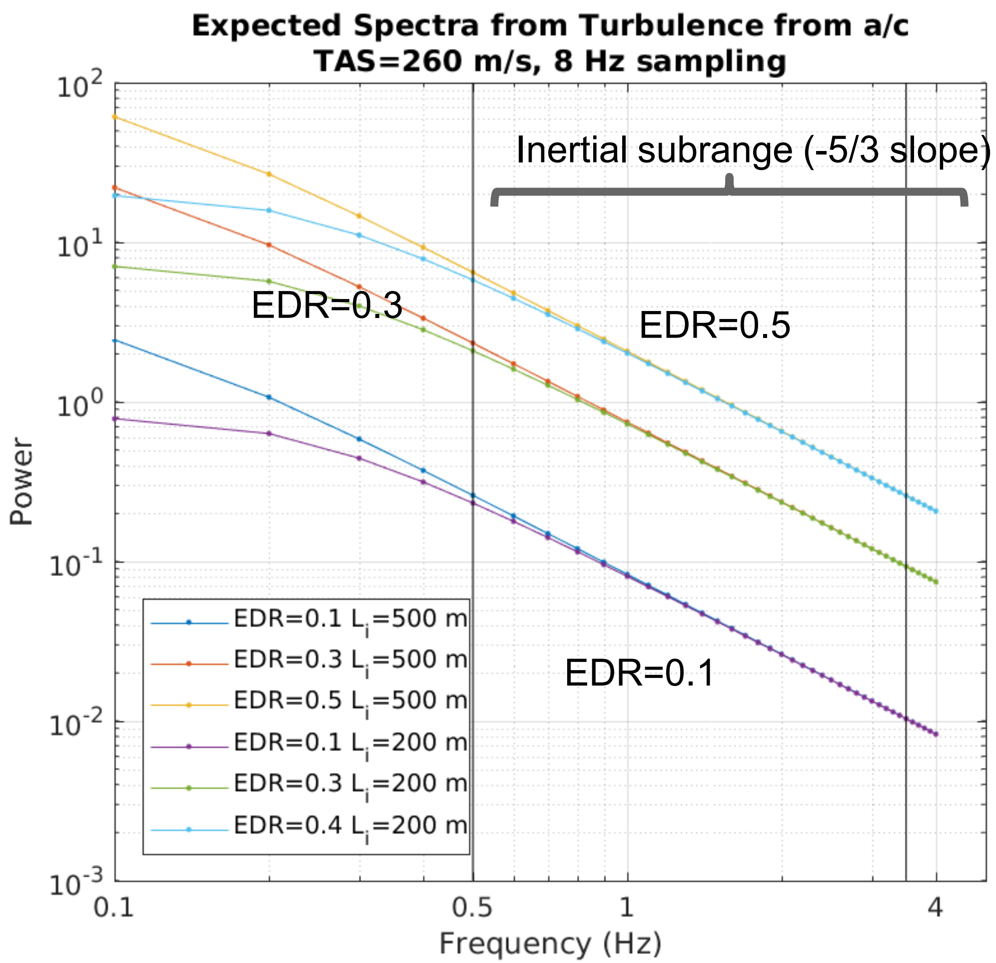
- The "best" fit is performed using a statistical method called "maximum likelihood", which has optimal performance properties.

EDR Calculation - Detailed

To compute EDR from vertical winds, we first do some quality control, and then compute the power spectrum of the vertical winds (Fourier Transform).

Turbulence is well approximated by the so-called von Karman turbulence spectrum. The figure to the right shows the idealized spectra from turbulence of 3 different intensity levels and 2 different (inner) length scales.

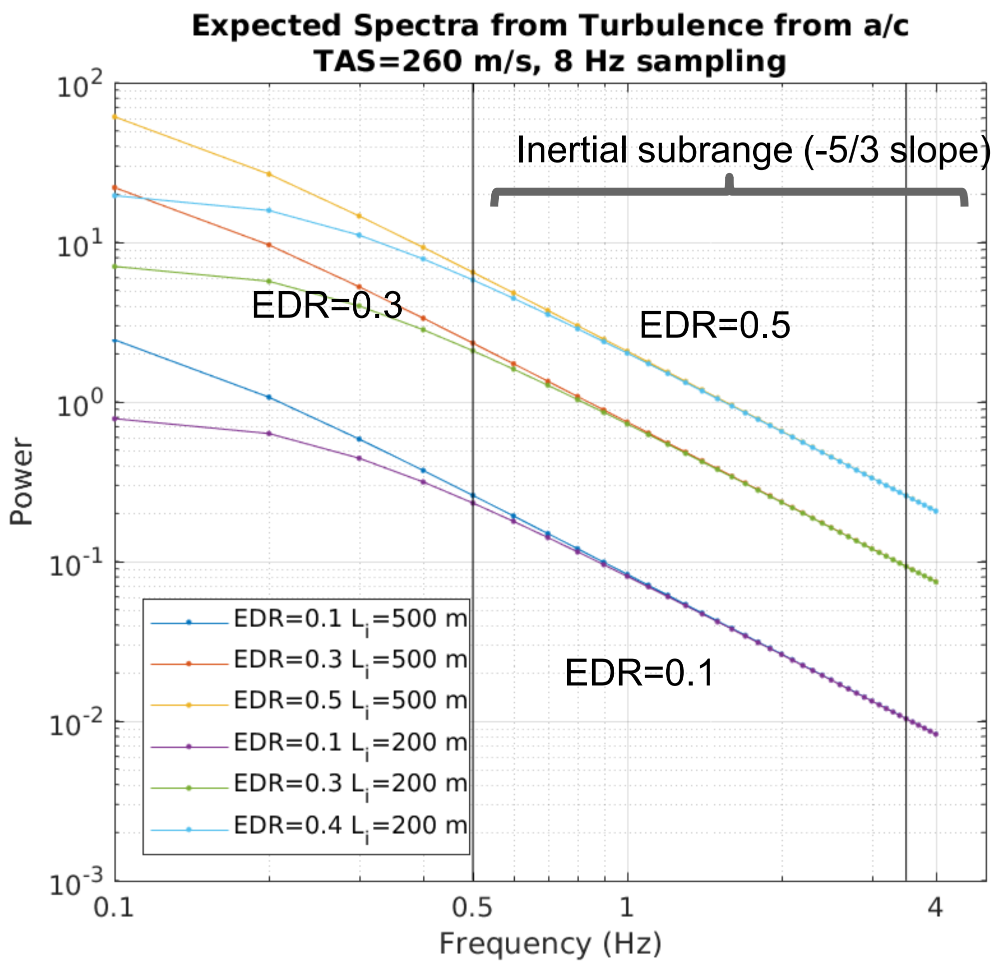
For von Karman turbulence, there are 2 unknowns: EDR (which dictates the height), and the length scale (which dictates the location of the bend).



EDR Calculation

The NCAR algorithm only uses the data between 0.5 and 3.5 Hz (vertical black lines), ignoring the part of the spectrum where we would need to know the length scale. (Length scales have generally been found to be at **least** 200 to 500 m).

The EDR is found by determining which level of EDR best fits the data.

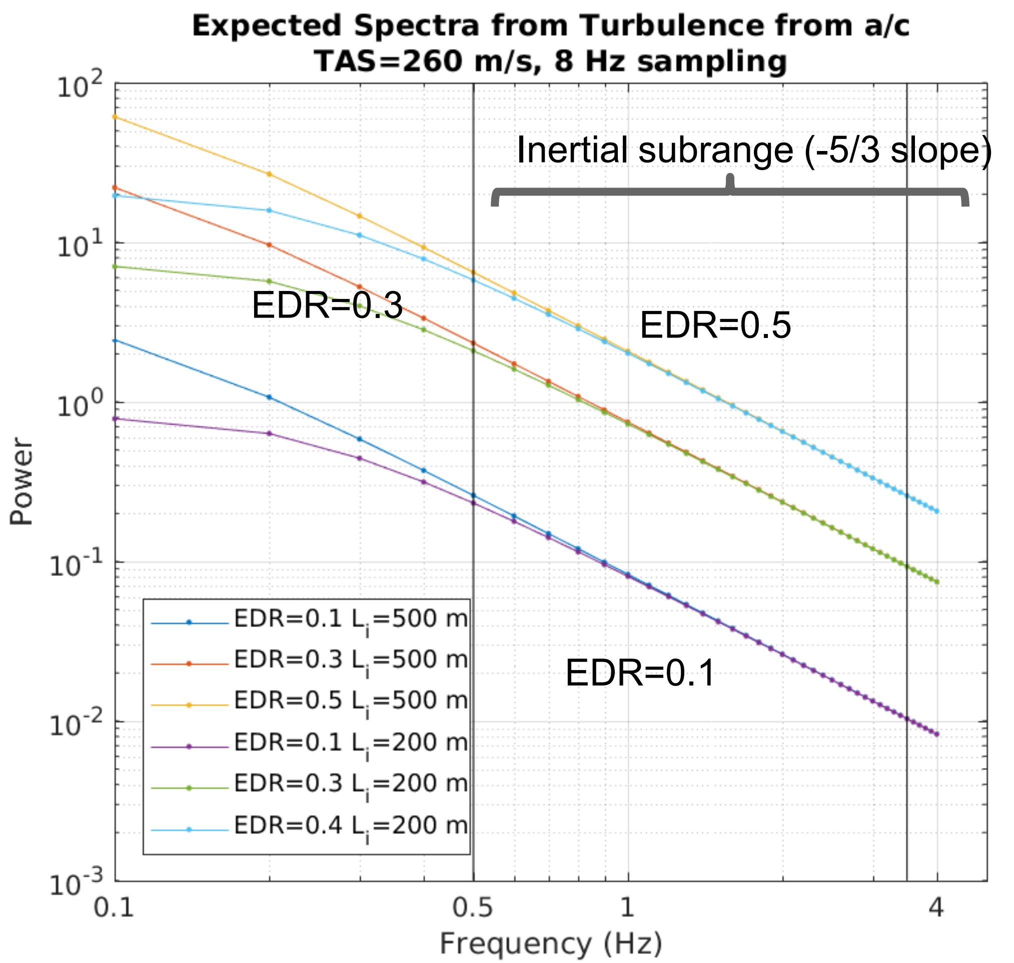


EDR Calculation

Note 1: The algorithm is not very sensitive to the choice of cutoffs as long as the left cutoff steers the algorithm away from the bend, and the right steers the algorithm away from contamination that can occur especially at the higher frequencies

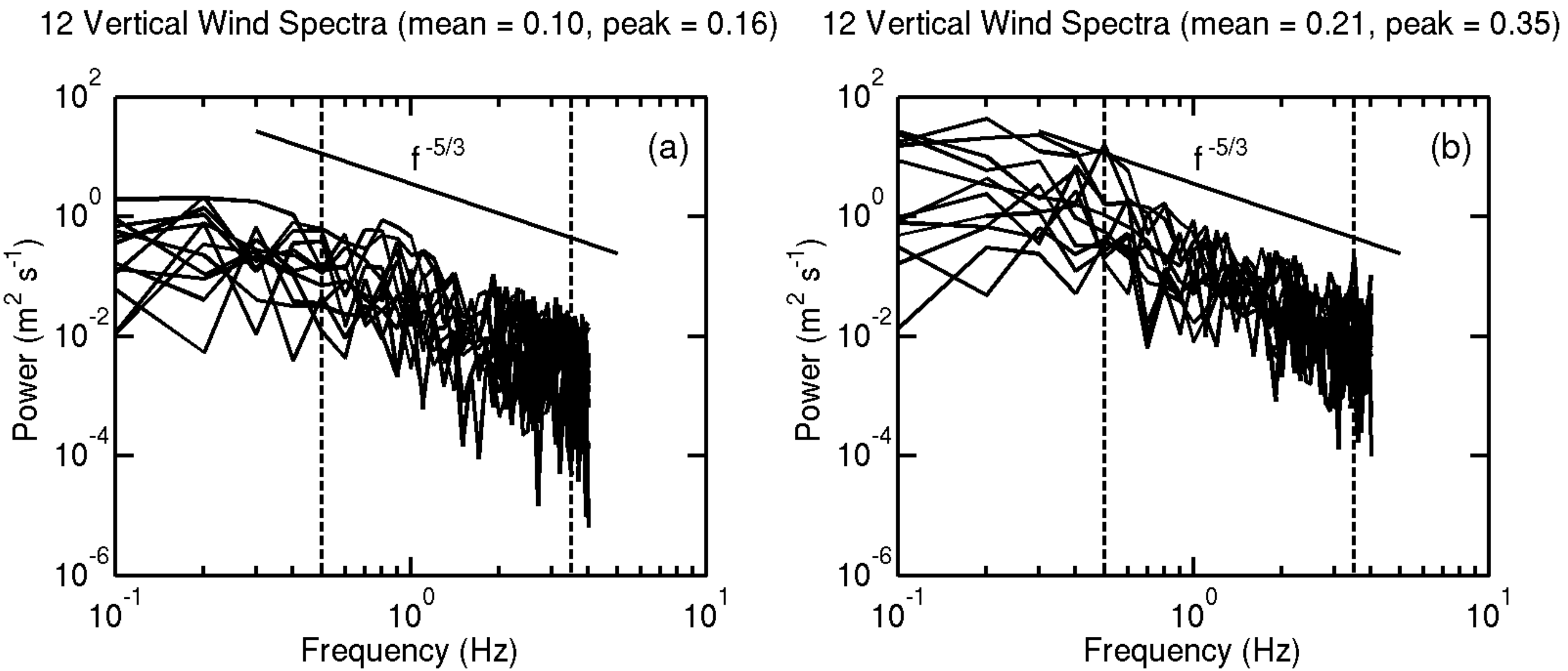
Note 2: Spectral contamination because of up-stream and algorithm signal processing are accounted for.

Note 3: see next slide…



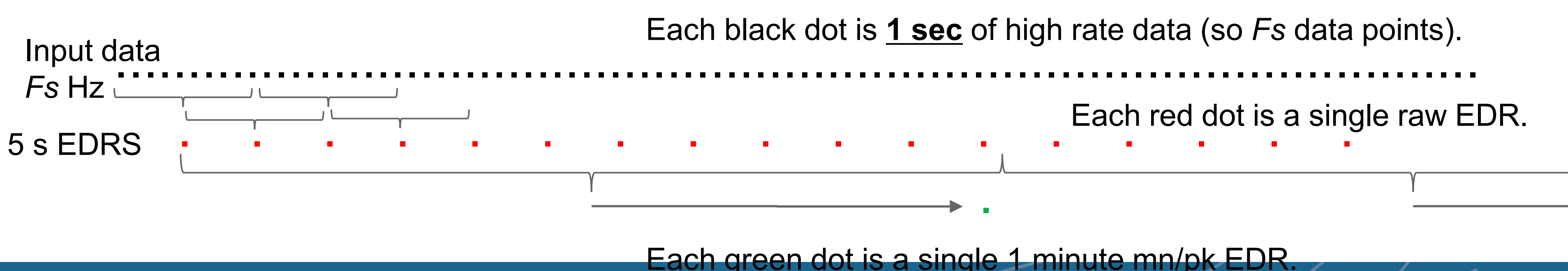
Note 3: “real ” data is quite a bit noisier

Example output from the winds-based EDR algorithm for two different turbulence levels [peak=0.16 $m^{2/3} s^{-1}$ panel (a) and peak=0.35 $m^{2/3} s^{-1}$ panel (b)]. For both cases the individual 12 spectra developed over a one-minute time interval are shown as well as a reference $f^{-5/3}$ line and the algorithm cutoff frequencies of 0.5 Hz and 3.5 Hz.



Current Data Rate Flow

- High-rate input data comes in at *Fs* Hz. On-board, data is typically at 8 or 10 Hz.
- Compute raw EDRs <u>using</u> 10 seconds of data.
- Compute new EDRs every 5 sec so there is a 50% overlap between EDRs.
- Every minute, compute a mean and peak EDR from the 12 raw EDRs computed as discussed in previous slides.

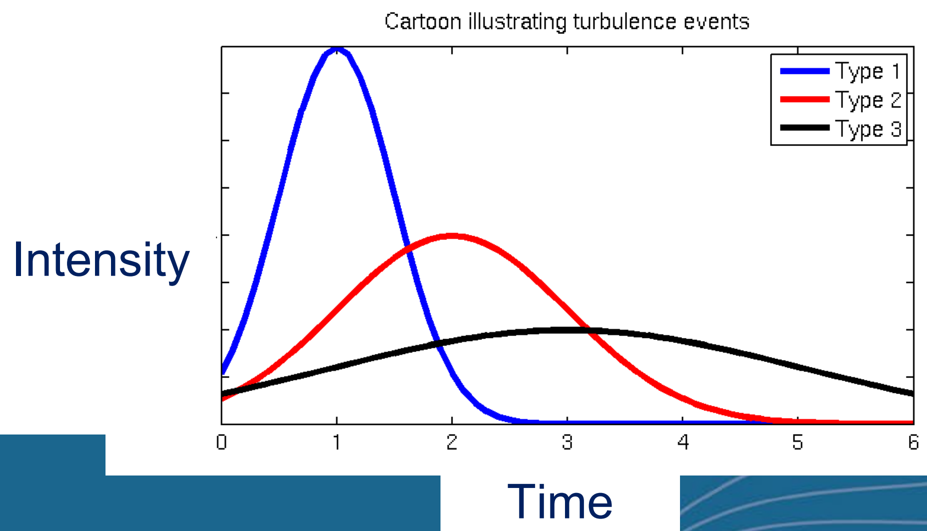


Reporting

- It was decided to go to event-triggered logic. When an “event” is identified, the logic triggers the downlink of a report.
- Because it is important to also know where the algorithm is working properly and there is *not* turbulence, routine reports consisting of 1 measurement are also downlinked at a specific time interval.
  - These routine reports are also downlinked after takeoff and landing.

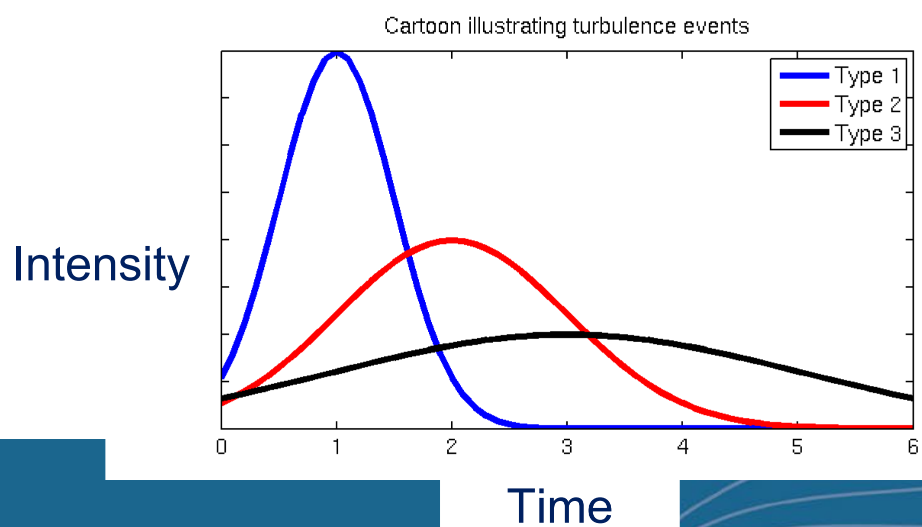
What is an “event”?

- Events are of 3 types (see cartoon below):
  - Type 1: Higher intensity experienced.
  - Type 2: Fairly consistent medium intensity experienced over the last 6 minutes.
  - Type 3: Consistent lower intensity experienced over the last 6 minutes.



Events defined more formally

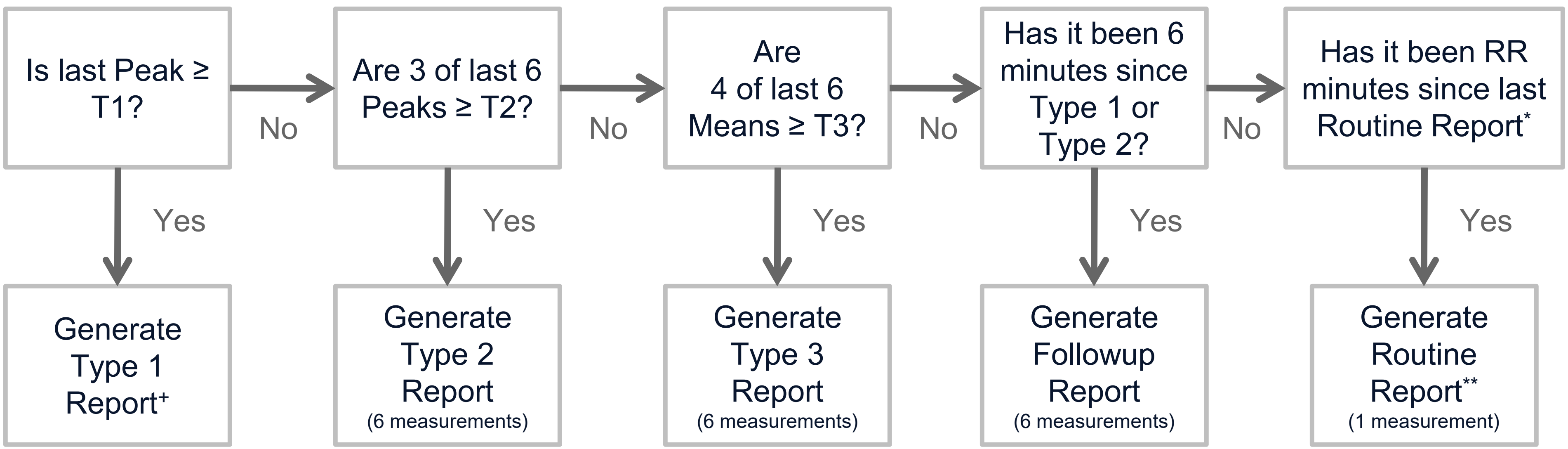
- Events are:
  - Type 1: peak EDR ≥ T1 from the last minute. Note that 6 minutes later a followup report is also generated.
  - Type 2: peak EDR ≥ T2 for at least 3 out of the last 6 minutes. Note that 6 minutes later a followup report is also generated.
  - Type 3: *mean* EDR ≥ T3 for at least 4 out of the last 6 minutes. *No* followup report.



* Followup reports are generated after type 1 and 2 events so that users can see "both sides" of the event (before and after) . Otherwise, users would only see data before the event. They always contain 6 measurements.

Overview of Report Hierarchy

Every minute a mean and peak EDR is generated by the *Insitu* Turbulence Algorithm. The following logic is used to determine *when* to generate and downlink a report.

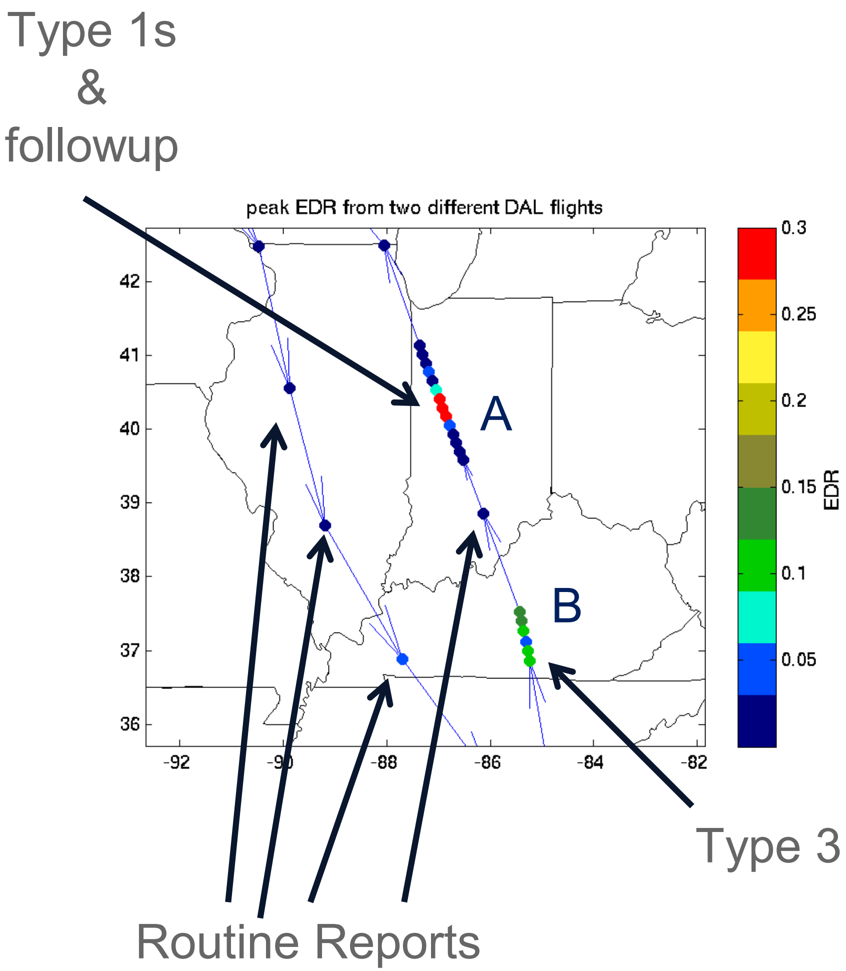


[+]Type 1 reports generally contain 6 measurements, but may have less to avoid duplication.

[*]Routine Reports may sometimes contain a measurement that will later be reported again.

[**]Routine Reports are also generated at beginning (after 1^{st} minute) and end of each flight.

Example



- This plot shows the locations of EDRs for 2 different flights. The color indicates the peak EDR. The blue arrows indicate the aircraft track.
- Measurements from 3 type 1 reports plus a followup report is shown as region A.
- Measurements from 1 type 3 report is shown as region B.
- The isolated measurements (usually 15 minute spacing) are from routine reports

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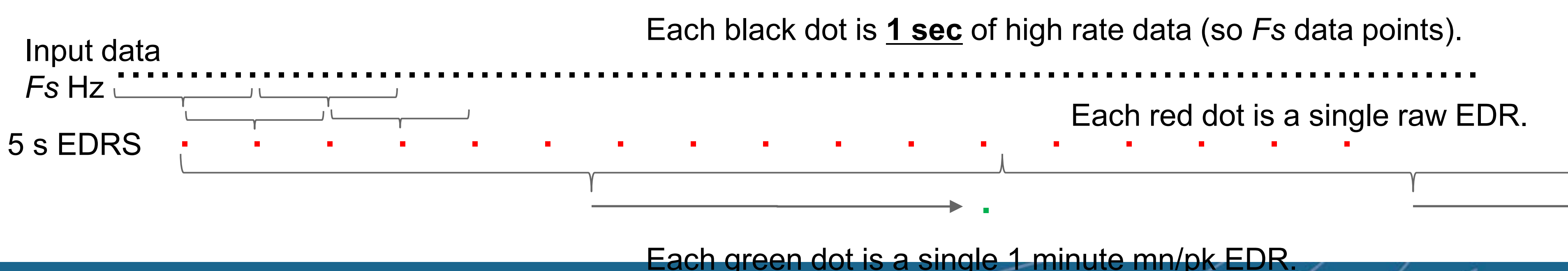
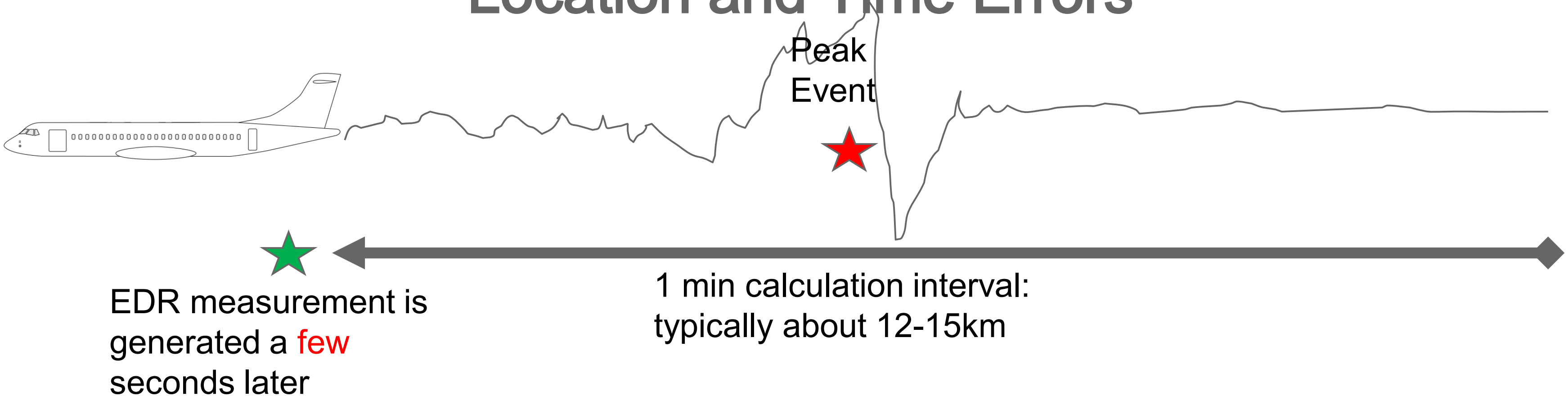
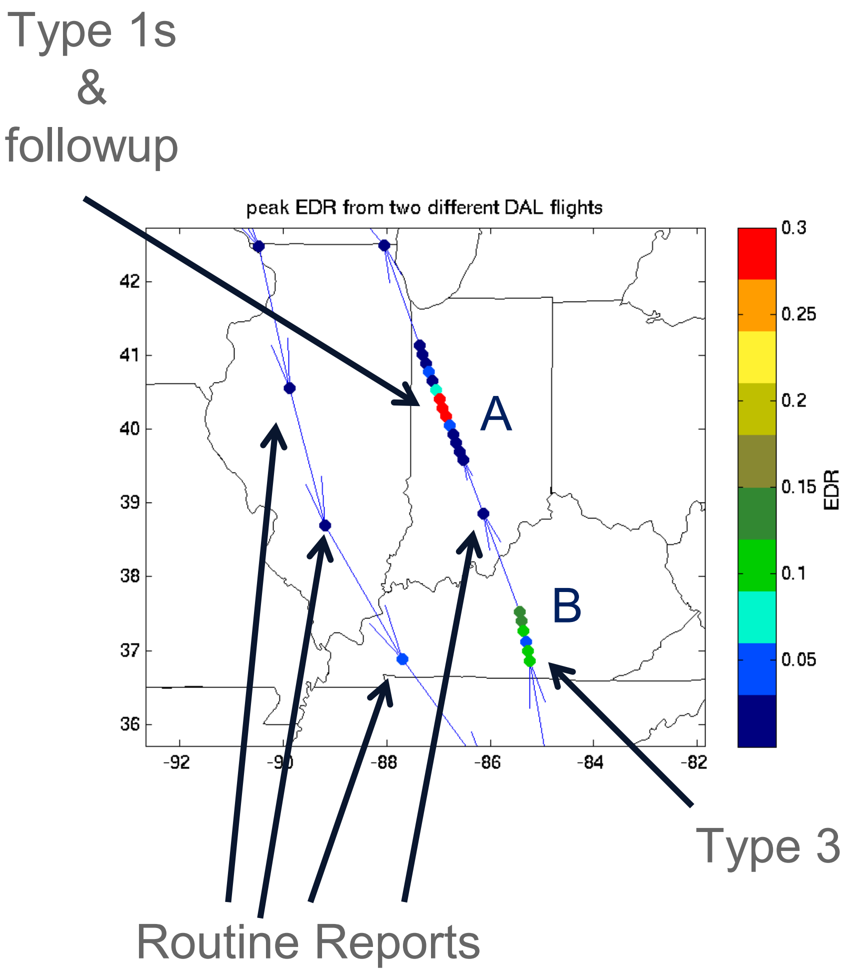


Location and Time Errors



- EDRs are computed over a time interval, though the peak may be from a very localized location.
- Location/time of the event vs the location/time of the event is complicated. Distinct from the precision/accuracy of the lat/lon/alt/time.

Reporting is not simple



- This plot shows the locations of EDRs for 2 different flights. The color indicates the peak EDR. The blue arrows indicate the aircraft track.
- It was thought that in quiet conditions, we would want less resolution but in turbulent conditions we would want more resolution.

Intensity Error of a single EDR

- Turbulence estimation is really a statistical process: trying to estimate *variation* using a small number of samples (the aircraft is typically moving fast through a space)
- As can be seen at right, absolute errors in the estimation of a singe 10 s EDR increases with EDR value: i.e. makes more sense to think of errors as relative errors.
- This is for *homogeneous* turbulence (over the 10 s).

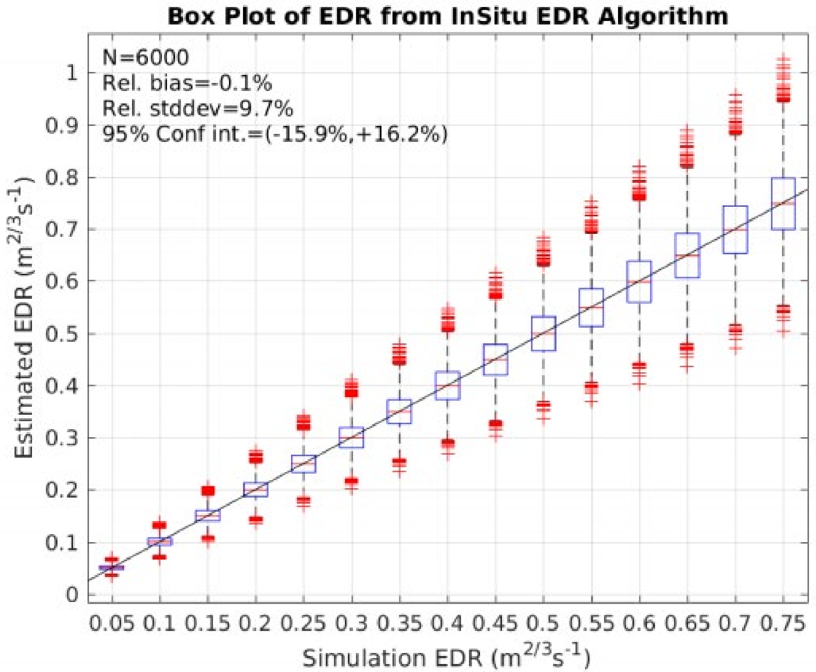


Figure 3: Box plot of the performance of the *In Situ* EDR estimator, for varying values of the simulation input EDR (*x*-axis). N=6,000 vertical wind time-series were used for each value of simulation input EDR. The solid black line shows the y=x reference line. The relative statistics of bias, standard deviation, and 95% confidence interval for the simulation input EDR of 0.3 $m^{2/3}s^{-1}$ are provided at the top left. The relative statistics are calculated relative to the simulation input (0.3 $m^{2/3}s^{-1}$). However, they are representative for all simulation input EDRs.

…Of the mean EDR

- For homogeneous turbulence, the 1–minute mean errors are similar to understand.

- When the turbulence is not homogenous, then what is the reference point against which we evaluate the mean?

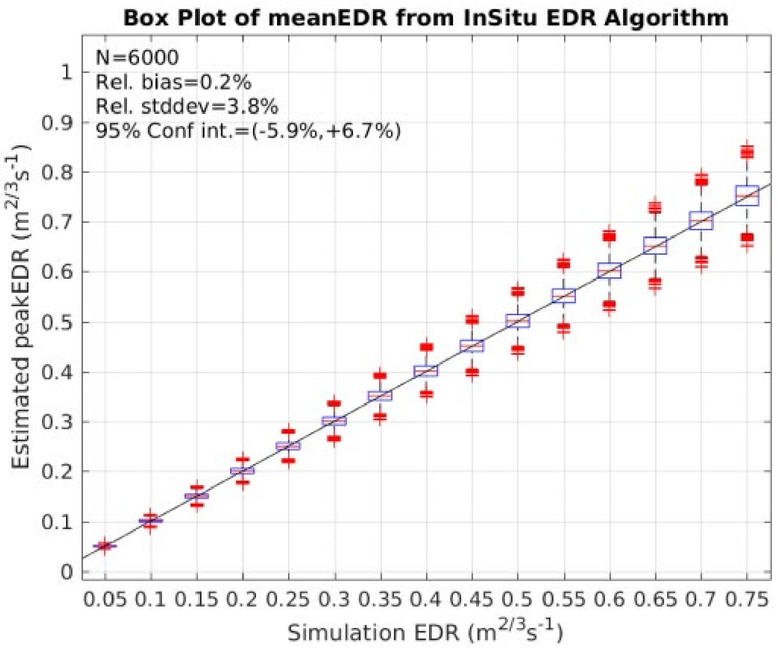


Figure 4: Box plot of the performance of the *In Situ* Mean EDR estimator, for varying values of the simulation input EDR (*x*-axis). N=6,000 vertical wind time-series were used for each value of simulation input EDR. The solid black line shows the y=x reference line. The relative statistics of bias, standard deviation, and 95% confidence interval for the simulation input EDR of 0.3 $m^{2/3}s^{-1}$ are provided at the top left. The relative statistics are calculated relative to the simulation input (0.3 $m^{2/3}s^{-1}$). However, they are representative for all simulation input EDRs.

…Of the peak EDR

- More complicated because in homogenous, you get a relative bias *compared* to the true homogenous EDR, and that bias depends on your EDR interval (e.g. 5 vs 10 seconds).
- When it is not homogenous, then things get more complicated. Peak EDR errors get much larger as the length of the event shortens.
  - E.g., if the event is just a few seconds, the 95% confidence interval is close to +/-90%.

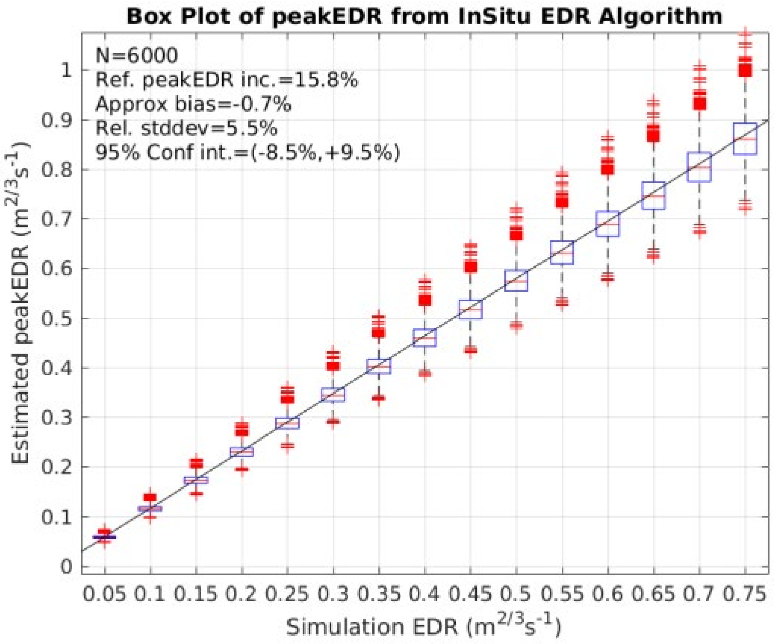


Figure 5:: Box plot of the performance of the *In Situ* Peak EDR estimator, for varying values of the simulation input EDR (*x*-axis). N=6,000 vertical wind time-series were used for each value of simulation input EDR. The relative statistics of bias, standard deviation, and 95% confidence interval for the simulation input EDR of 0.3 $m^{2/3}s^{-1}$ are provided at the top left. The *relative standard deviation* and *95% confidence interval* are relative to the average Peak EDR. However, they are representative for all simulation input EDRs. The solid black line shows the expected average Peak EDR based on the *reference peak EDR increase* for each simulation input EDR.