



An Unusual Structure for a Feedforward Gust Load Alleviation Controller

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Knowledge for Tomorrow



Gusts and Turbulence Cause Loads and Passenger Discomfort

Induced additional loads must be taken into account in the design of the structure

- various standardized cases must be demonstrated for certification
- on all these cases the maximum loads on each part of the structure are determined
- additional safety margins are applied
- the structure shall be designed to withstand the maximum loads + safety factors

➔ Reducing the loads acting on the aircraft enables weight savings and thereby also more efficient aircraft

Additionally when encountering gusts or turbulence

- undesired aircraft motions can be induced by the change in aerodynamic forces and moments (+ coupling with flexibility of the structure)
 - can become a safety threat (e.g. for passengers or cabin crew personnel that would not be seated or with their seat belts unfastened)
 - causes discomfort and passenger anxiety



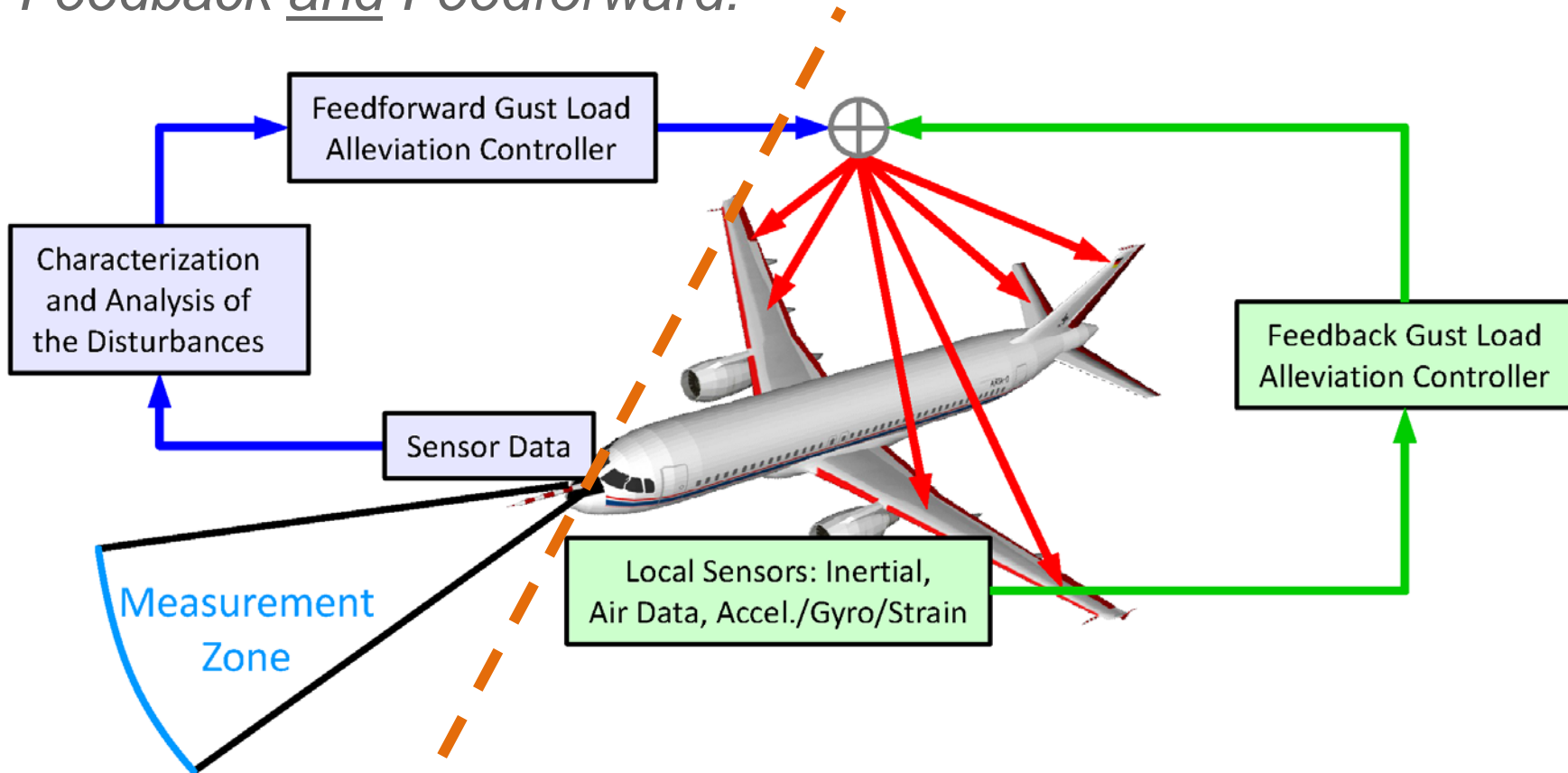
How Can We Reduce the Loads?

- Procedures (e.g. fly at lower speed when in turbulence)
- Passive load alleviation
- Active load alleviation
 - Specific control algorithms
 - Additional local sensors (accelerometers, gyros, strain-gauges, etc...)
 - Possibly remote wind sensors (e.g. Doppler LIDAR), which permit to anticipate the future disturbances



Active Load Alleviation: Feedback vs. Feedforward?

→ *Feedback and Feedforward!*

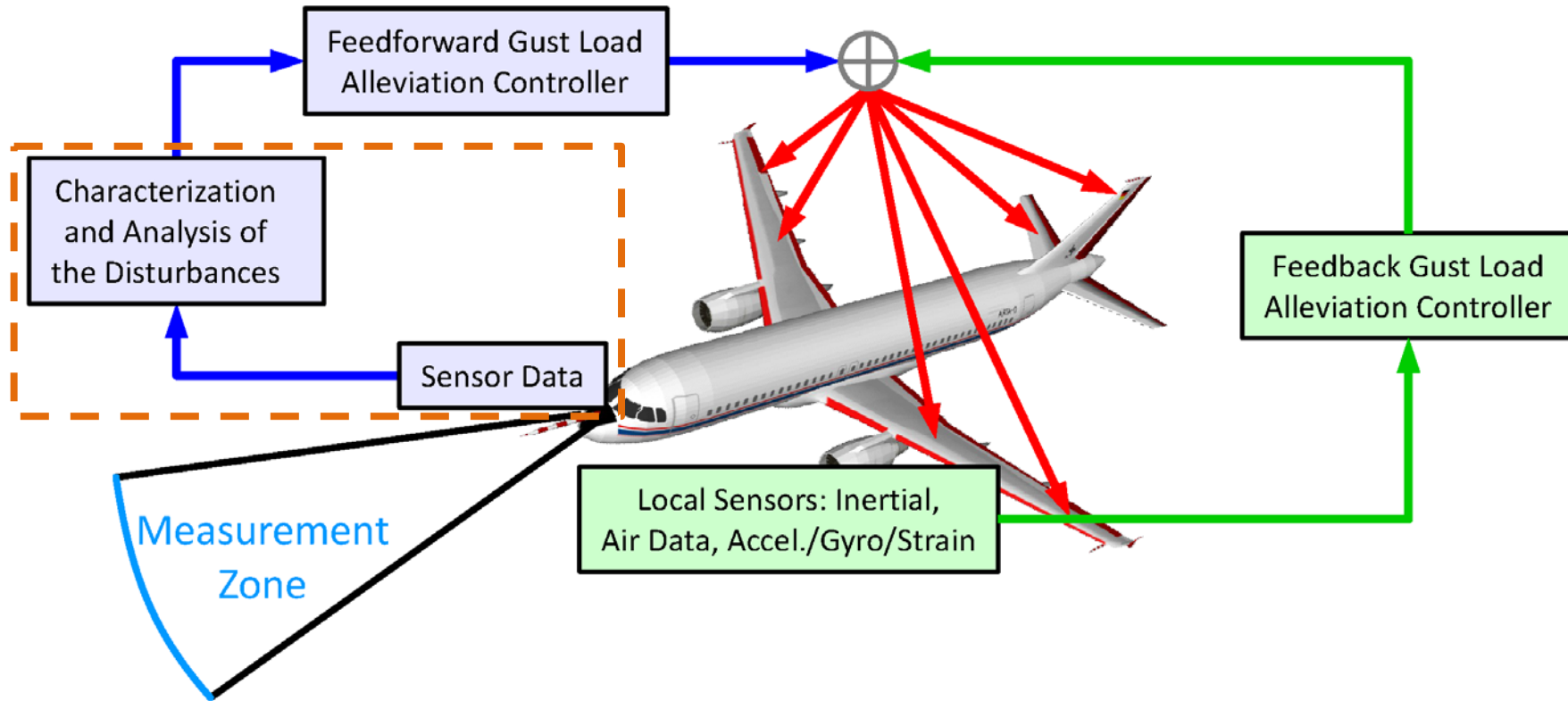


Not possible to act on the flexible modes
Anticipation is possible

Possible to act on the flexible modes (e.g. damp them)
No anticipation



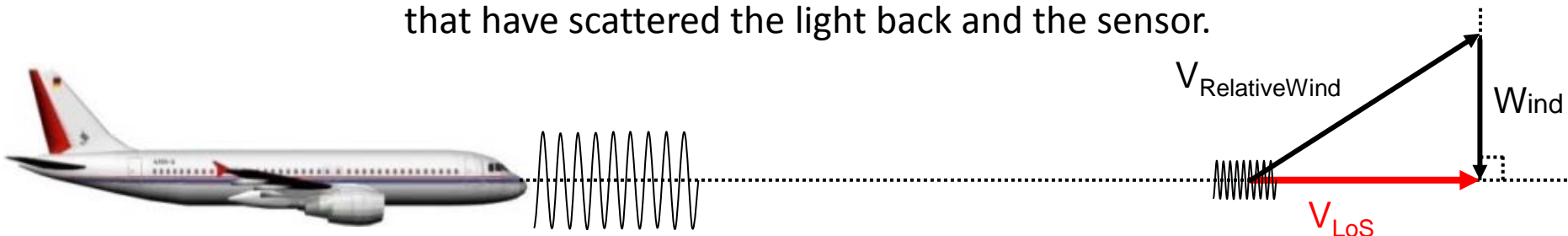
Active Load Alleviation: Feedback vs. Feedforward?



Doppler LIDAR Sensors for Gust/Turbulence Detection

Doppler LIDAR

- Based on the backscattering of light on particle(s)/molecules of the air
- Doppler-shift → relative line-of-sight velocity between the particle(s)/molecules that have scattered the light back and the sensor.



- Relative wind components perpendicular to LoS are lost
Note: the vertical component at locations ahead of the aircraft is the most interesting wind information for load alleviation
- Problem can be solved:
 - By taking several measurements with various locations and under various angles
 - By combining these measurements to extract the transversal wind components *

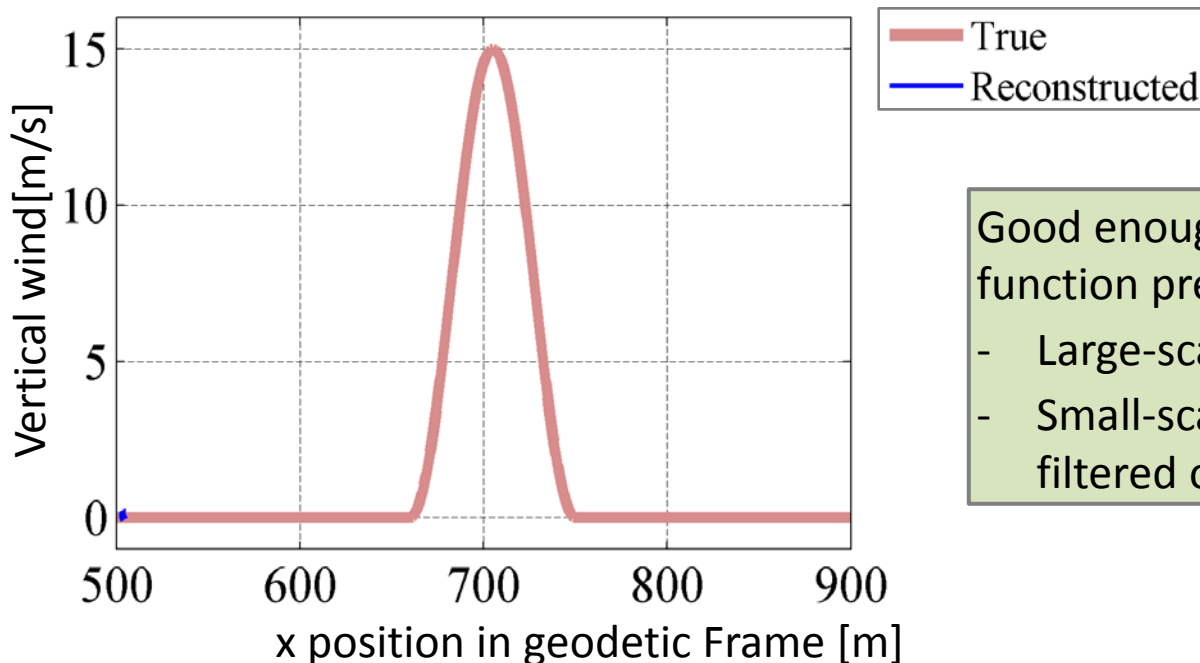
* N. Fezans, J. Schwithal, D. Fischenberg, "In-flight remote sensing and identification of gusts, turbulence, and wake vortices using a Doppler LIDAR," CEAS Aeronautical Journal, 2017, doi: 10.1007/s13272-017-0240-9.



Doppler LIDAR Sensors for Gust/Turbulence Detection

*Results: 1-cosine gust characterization**

- Fully coupled and flexible flight dynamics model
- Free-form parametric wind model
- Tikhonov regularization (smoothing)
- Near real-time performance on regular PC (non-optimized single-threaded code)



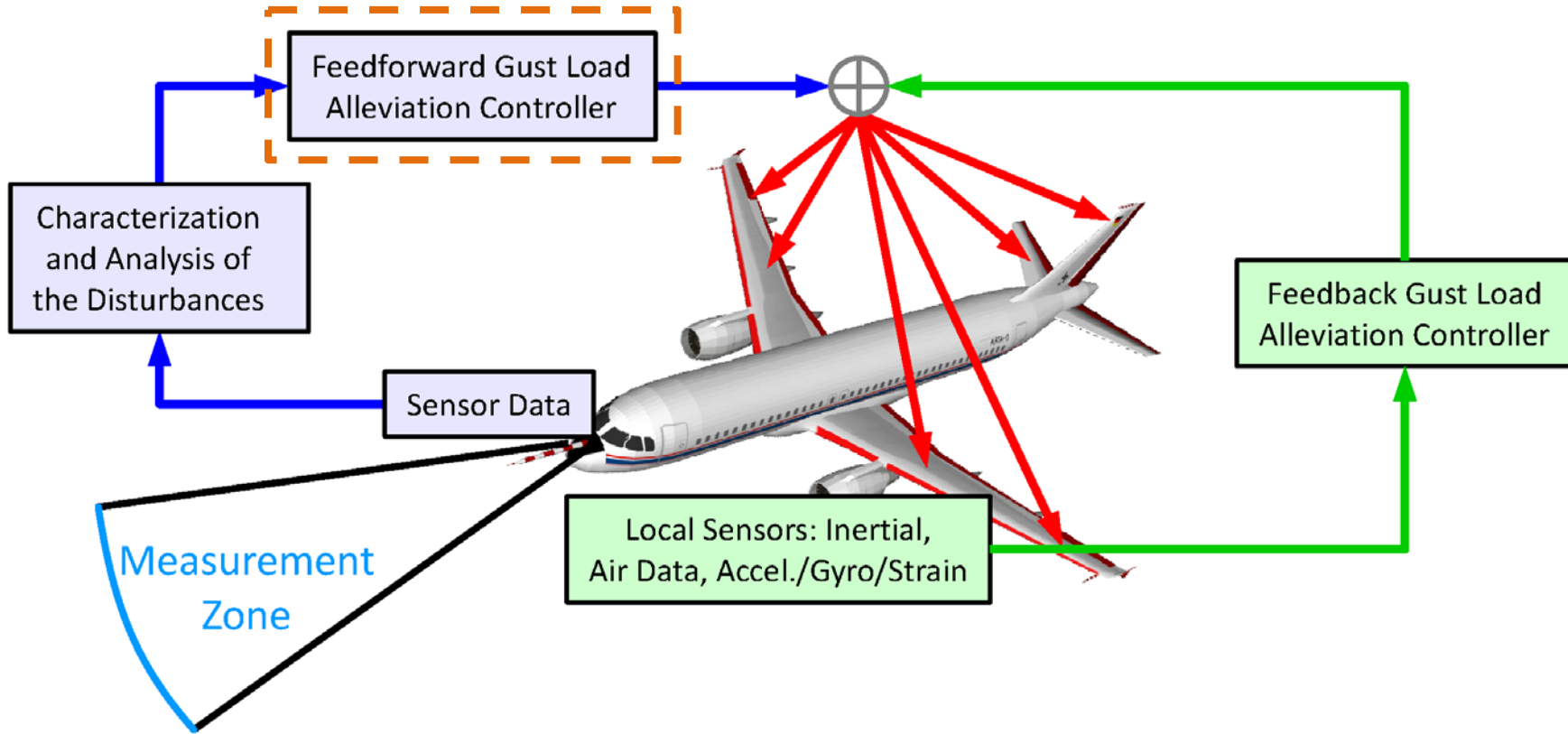
Good enough for the load alleviation function presented hereafter:

- Large-scale wind variations well detected
- Small-scale variations must still be filtered out

* N. Fezans, J. Schwithal, D. Fischenberg, "In-flight remote sensing and identification of gusts, turbulence, and wake vortices using a Doppler LIDAR," CEAS Aeronautical Journal, 2017, doi: 10.1007/s13272-017-0240-9.

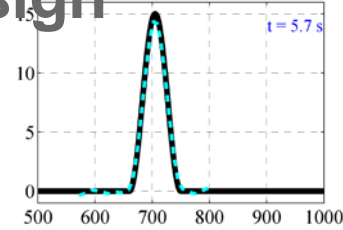


Active Load Alleviation: Feedback vs. Feedforward?



Satisfying Strong Allocation Constraints by Design

Reconstructed wind profile ahead of the aircraft



Wind profile analysis and decomposition

Controller #1:

- *Low frequencies*
 - *Large amplitudes*
- *Pitching actions*

Controller #2:

- *Medium frequencies*
 - *Small to medium amplitudes*
- *Symmetrical deflections of ailerons (no spoilers)*

Controller #3:

- *Medium frequencies*
 - *Medium to large amplitudes*
- *Symmetrical deflections of ailerons and spoilers*

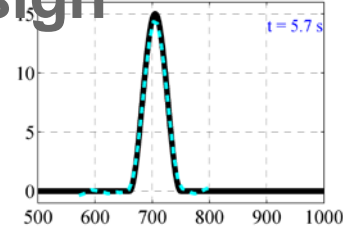
Gathering and combining commands

Feedforward load alleviation commands



Satisfying Strong Allocation Constraints by Design

Reconstructed wind profile ahead of the aircraft



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 - Medium to large amplitudes
- **Symmetrical deflections of ailerons and spoilers**

The synthesis of each controller only needs to focus on a smaller problem (simple constraints, simple goal, and few tuning parameters).

Advanced tools (e.g. from the linear and robust control theories) can be used for each of these feedforward control design problems.

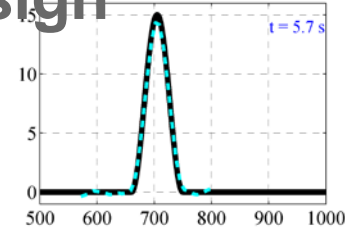
Feedforward load alleviation commands



Satisfying Strong Allocation Constraints by Design

It's a kind of magic...

Reconstructed wind profile ahead of the aircraft



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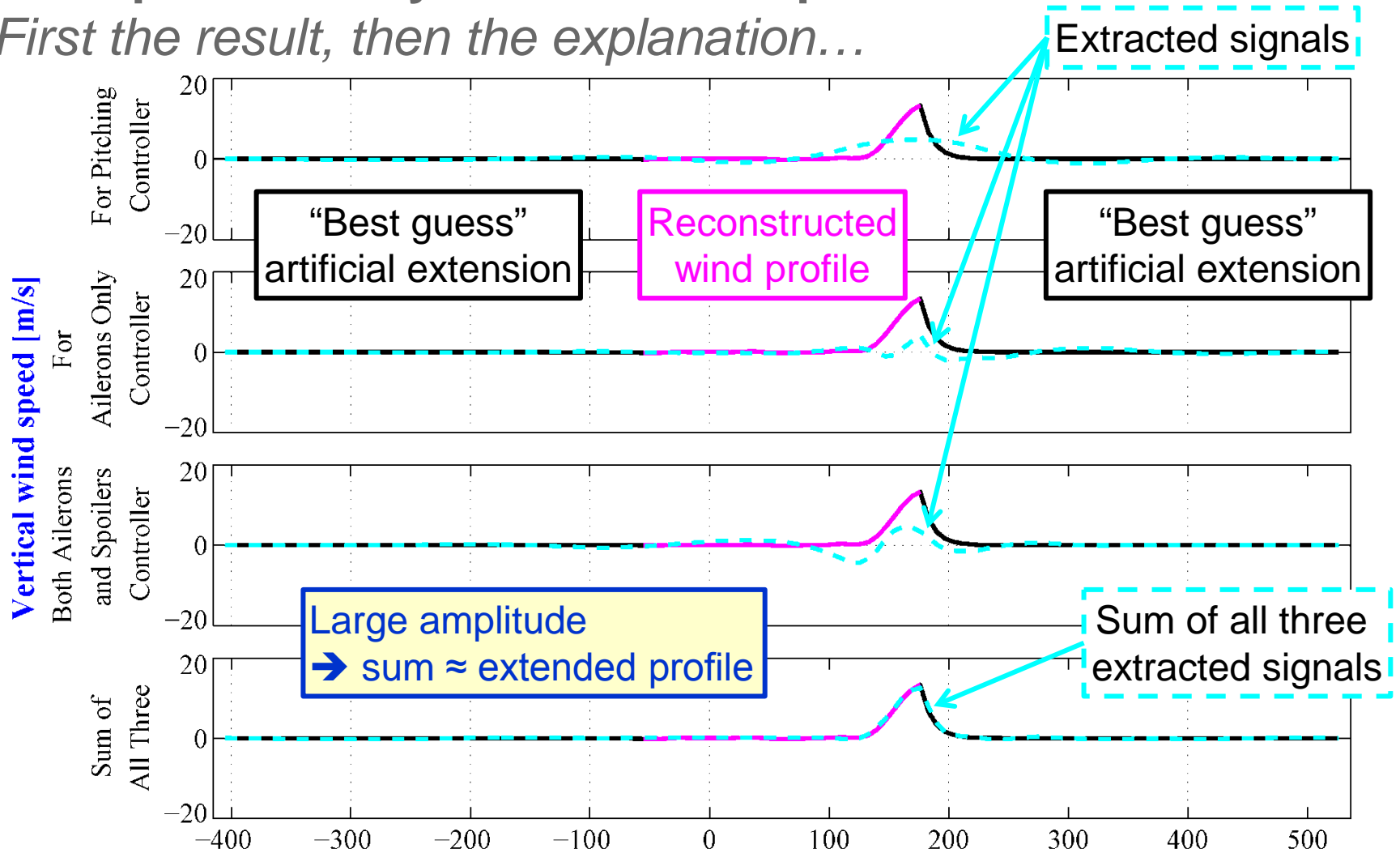
Gathering and combining commands

Feedforward load alleviation commands



Wind profile analysis and decomposition

First the result, then the explanation...

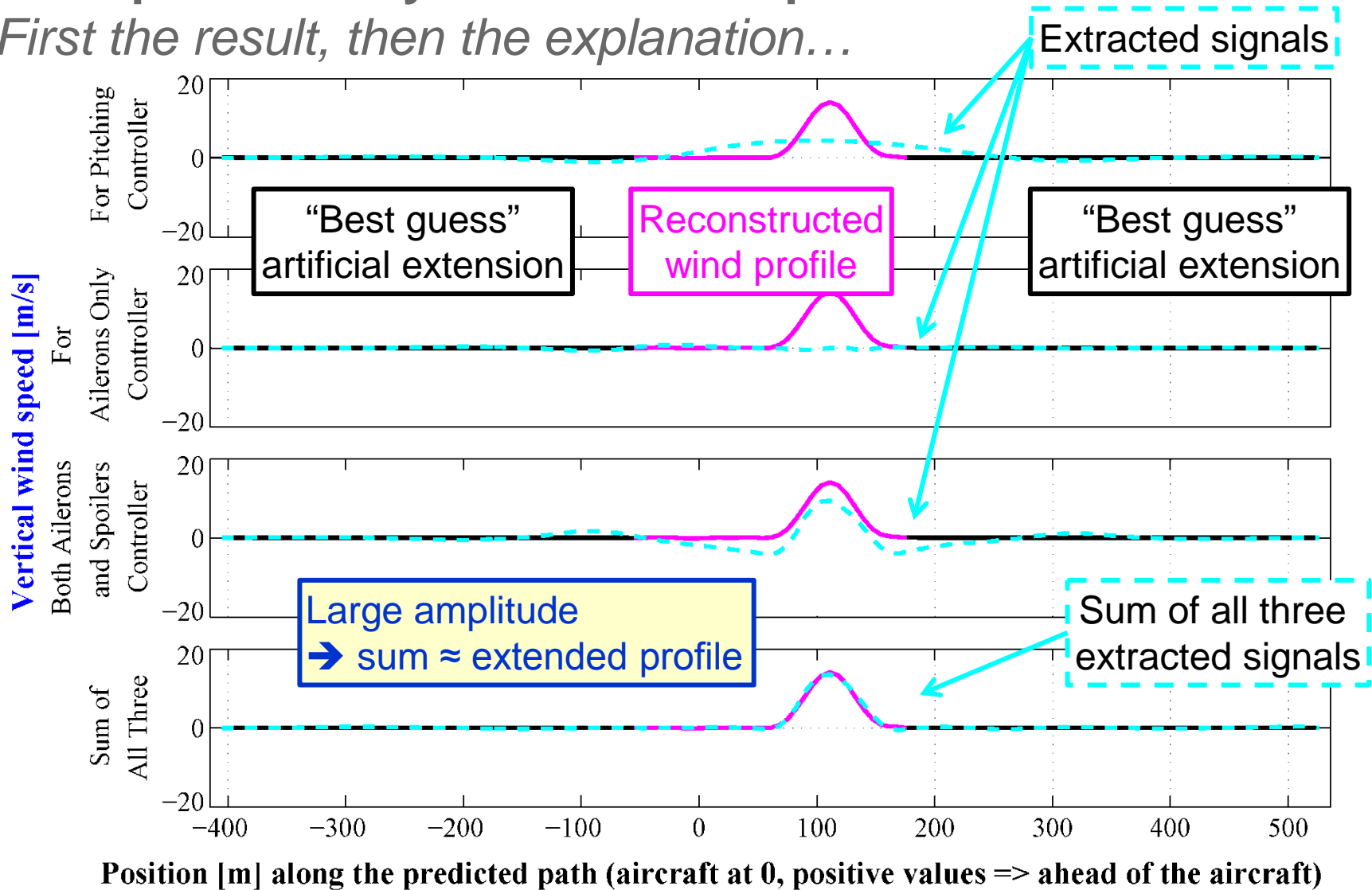


Position [m] along the predicted path (aircraft at 0, positive values => ahead of the aircraft)



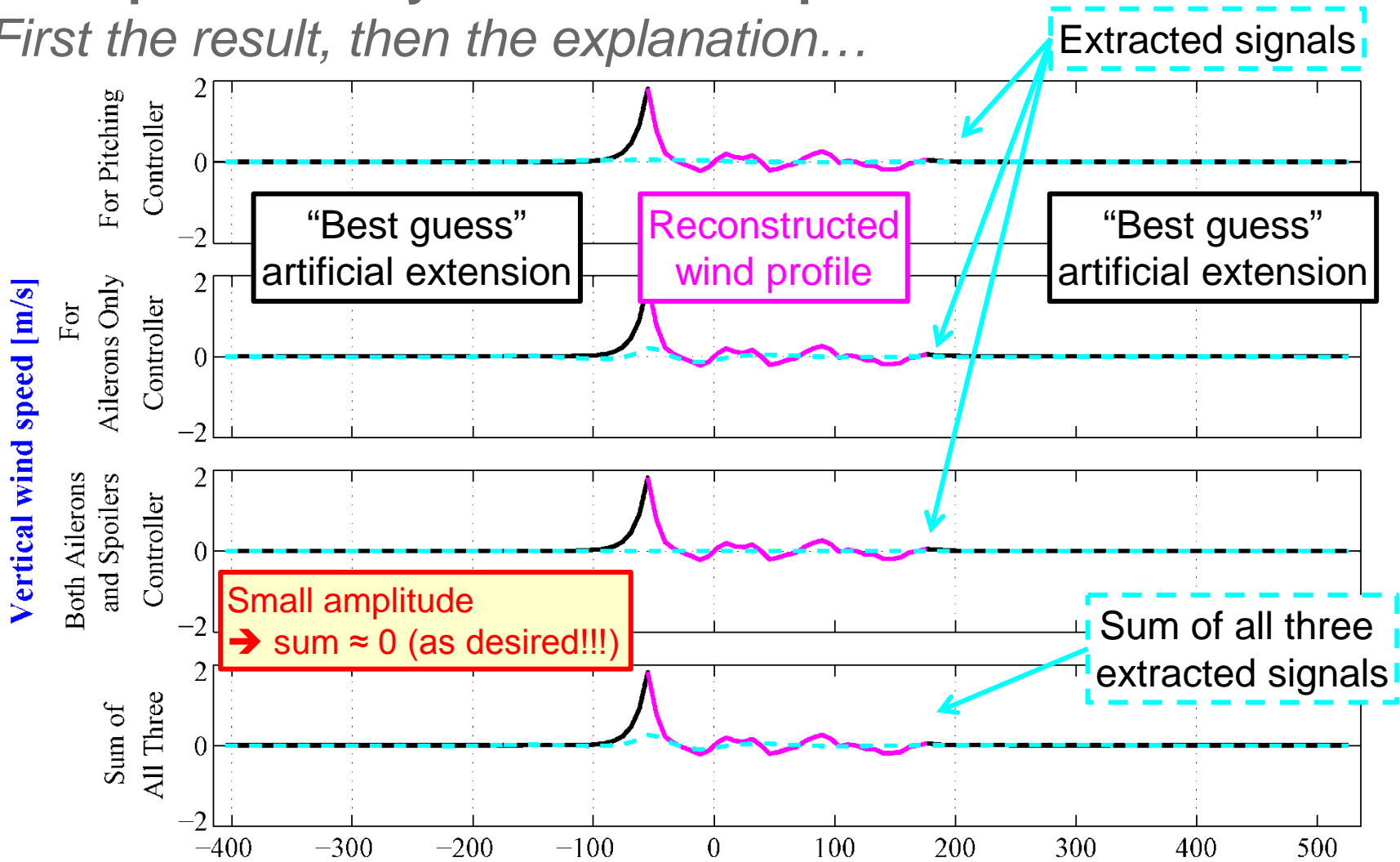
Wind profile analysis and decomposition

First the result, then the explanation...



Wind profile analysis and decomposition

First the result, then the explanation...



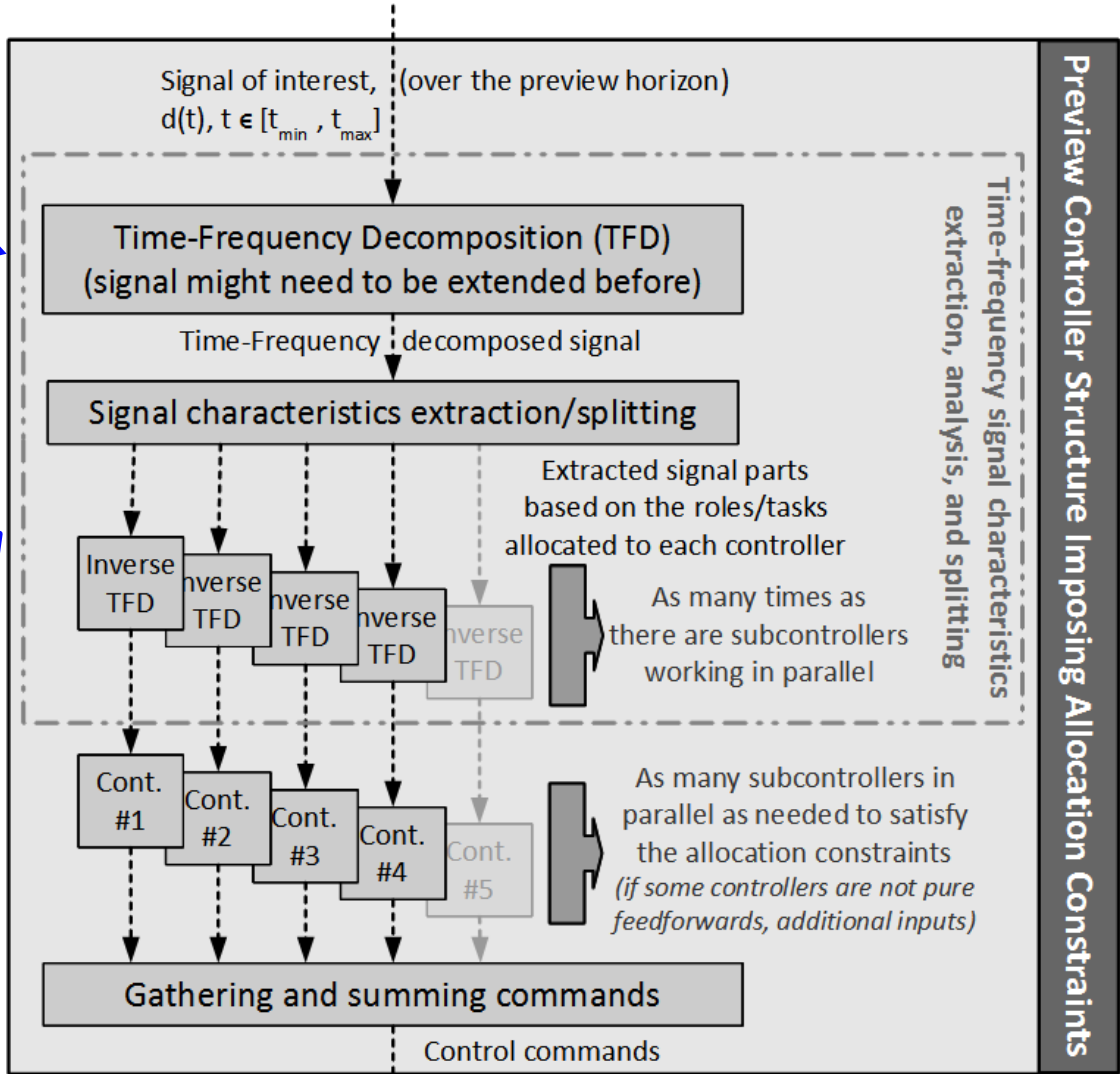
Position [m] along the predicted path (aircraft at 0, positive values => ahead of the aircraft)



Wind profile analysis and decomposition

Which Time-Frequency Technique?

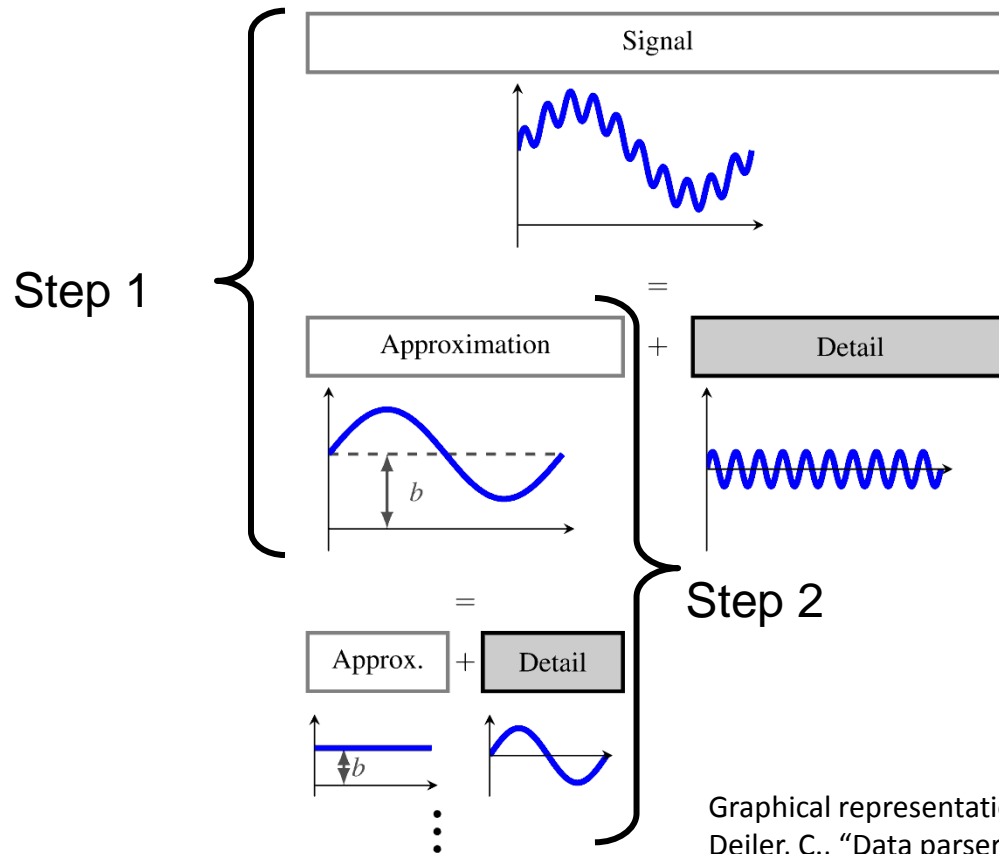
How to perform the extraction?



Wind profile analysis and decomposition

Which Time-Frequency Technique?

- FOWT: Fast Orthogonal Wavelet Transform - wavelet base used: bior3.9
(remark: *actually a time-scale and not a time-frequency technique*)



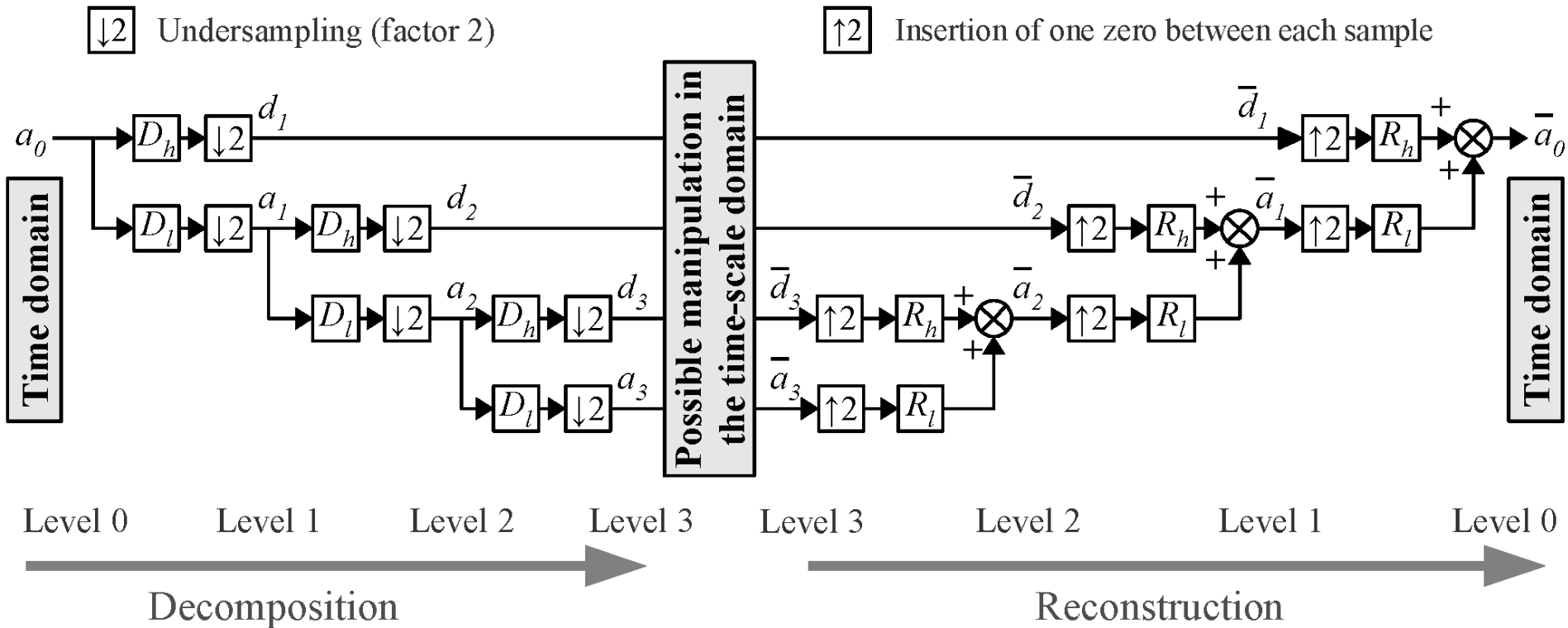
Graphical representation taken with permission from:
Deiler, C., "Data parser approaches for (online) parameter estimation,"
CEAS Aeronautical Journal, Vol. 5, No. 3, 2014, pp. 345–357.



Wind profile analysis and decomposition

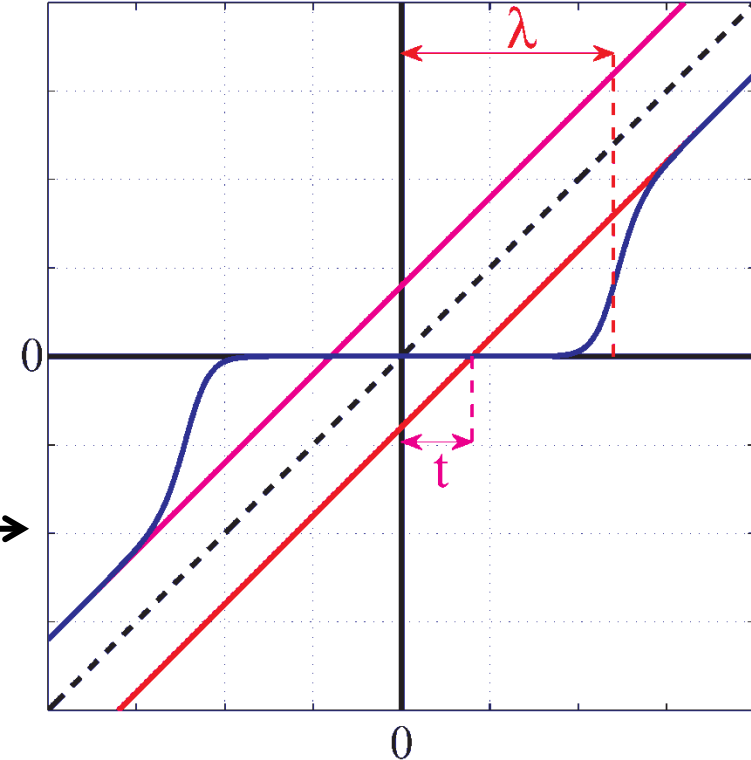
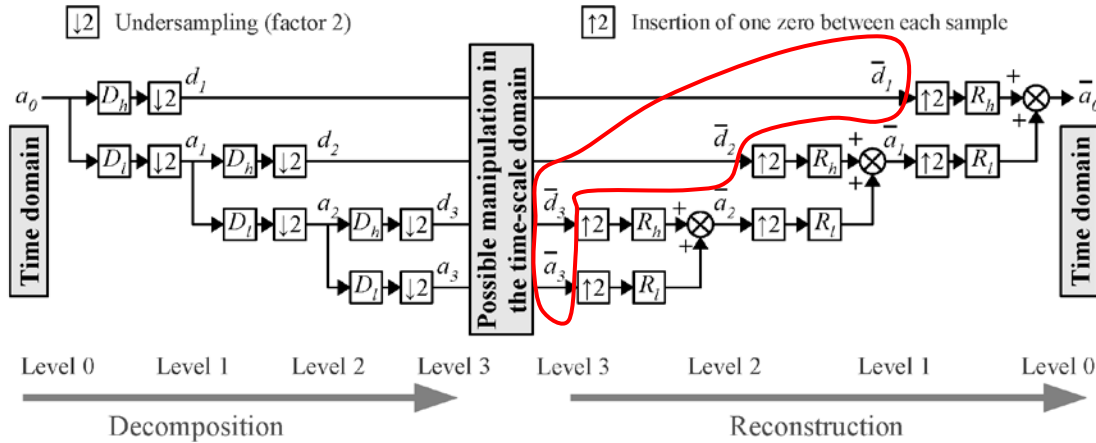
Which Time-Frequency Technique?

- FOWT: Fast Orthogonal Wavelet Transform (base used: bior3.9)
(remark: actually a time-scale and not a time-frequency technique)
- Implemented as a filter bank



Wind profile analysis and decomposition

Which Time-Frequency Technique?



Coefficients are passed through some shrinkage function, before reconstructing the signals s.

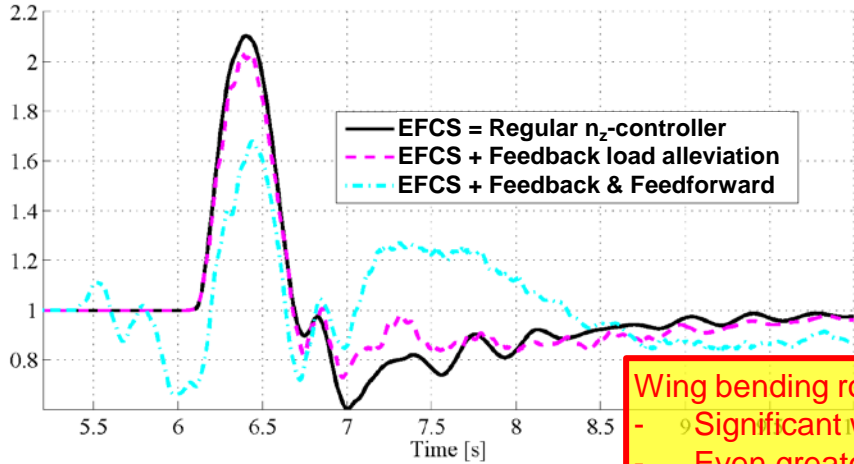
Used function: Smooth Sigmoid-Based Shrinkage (SSBS)



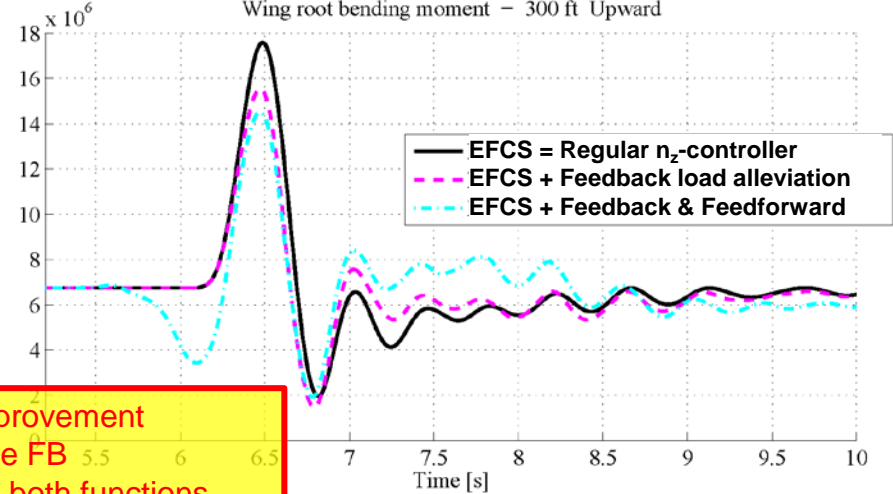
Results – Time Simulation 300 ft Gust

UPWARD

Load factor n_z – 300 ft Upward



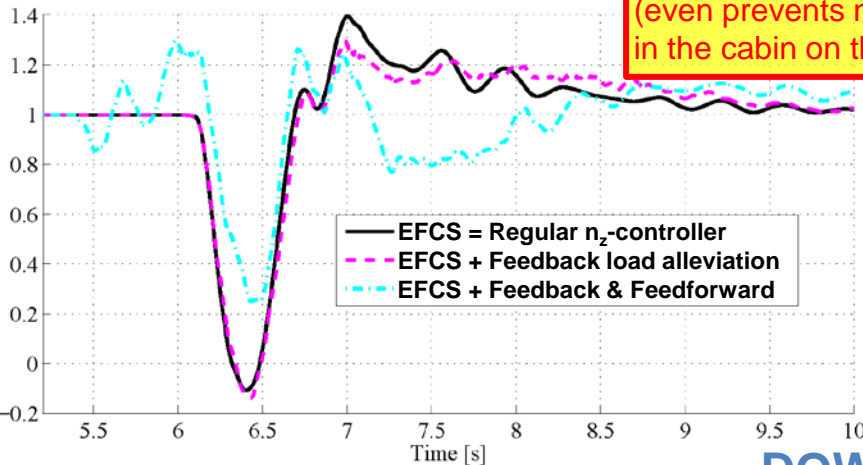
Wing root bending moment – 300 ft Upward



Wing bending root improvement
 - Significant with the FB
 - Even greater with both functions
 FF anticipation permits to strongly alleviate max accelerations in the cabin (even prevents negative load factor in the cabin on the downward case)

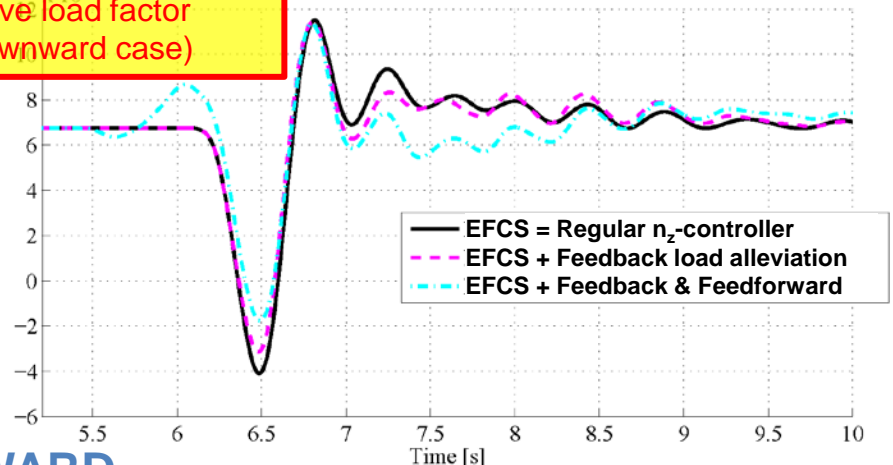
Nz

Load factor n_z – 300 ft Downward



Wing root bending moment

Wing root bending moment – 300 ft Downward



DOWNWARD



Summary and Outlook

An unusual feedforward controller structure was presented

- For cases where a portion of a signal (e.g. disturbance) is known in advance
- Partly based on time-frequency/scale signal processing technique
- Permits to easily specify and design a controller that necessarily satisfies some time-frequency-based allocation constraints
- Designed specifically for the considered application (feedforward load alleviation based on a Doppler LIDAR sensor and an explicit gust/turbulence estimation)
- Certainly useful for many other applications

Outlook

- Further improvements?
- Attempt to tune the parameters of the signal decomposition, characteristics extraction, and splitting (i.e. level selection, wavelet shrinkage parameters, etc.) directly in the controller(s) design?
 - integrated tuning of all parameters (of the preprocessing step and of all controllers)

