



Advances in Distributed Propulsor Acoustic Modeling

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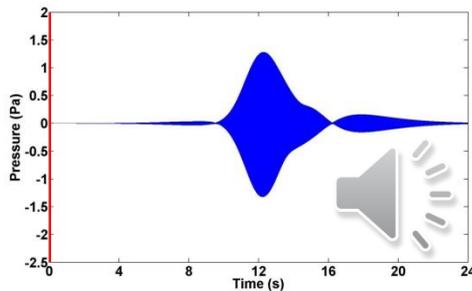
AHS International – AIAA – NASA
2015 Transformative Vertical Flight Workshop
NASA Ames Research Center
3-4 August 2015

From 2014 we found...

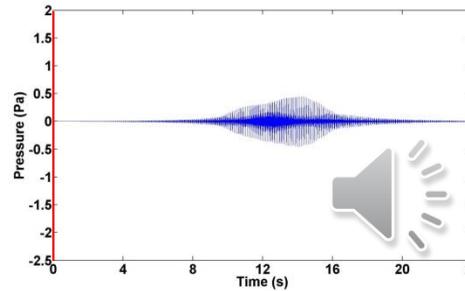
- Metrics like average source power not sufficient to reflect annoyance
- Lacking a good metric, we need the ability to create the noise signatures to investigate human annoyance

Distributed Electric Propulsion – LEAPTech Concept with 18 propellers

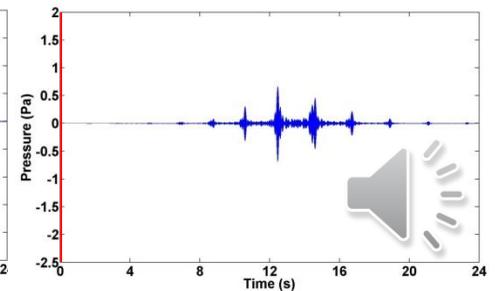
Average source power same for all configurations below, yet sound very different



Coherent



Spread Frequency (10Hz)



Spread Frequency (0.5Hz)



Simple models neglecting unsteadiness of the sources are not suitable for use in human annoyance studies that are intended to lead to low noise design strategies.



- Objective & Approach
- SCEPTOR CAS Project
 - Effect of motor control and atmospheric turbulence on LEAPTech spread frequency strategy
- DELIVER CAS Project
 - Effect of body and rotor drag, atmospheric turbulence and imbalance on quadcopter noise
- Conclusions



Objective & Approach

Objective

- **Demonstrate the level of model detail necessary to produce high-fidelity auralizations.**
- Develop annoyance model for these types of vehicles to guide low annoyance designs.

Approach

- **Systematically add real-world unsteady effects associated with particular flight vehicles and their operations to underlying physics-based auralizations.**
- Perform psychoacoustic testing to understand human response to distributed electric propulsor noise.

SCEPTOR – Auralization of LEAPTech System

HEIST Wing

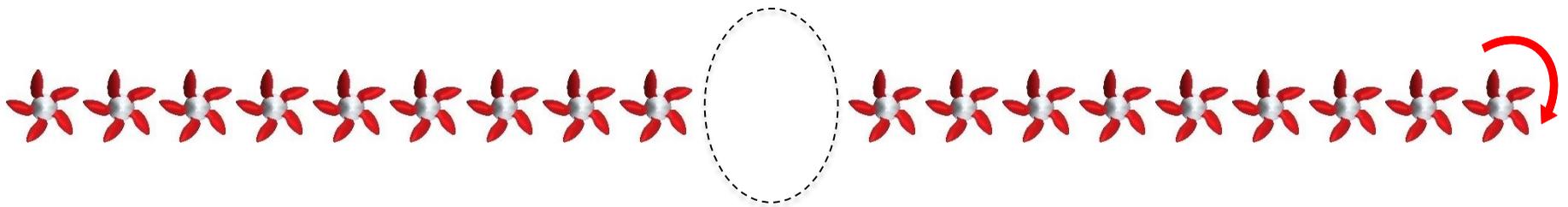


Some Modeling Constraints

- Constant tip speed irrespective of number of props
- Port/starboard RPM symmetry
- Prop rotation in same direction

Auralization Approach

- **Source noise directivity derived from Gutin model**
 - Relative contribution of each harmonic verified using ANOPP Propeller Analysis System (PAS) coupled with F1A acoustic analysis
- **Simple model**
 - Vary number of props and spread frequency/phase
- **Higher fidelity model**
 - Introduces unsteadiness

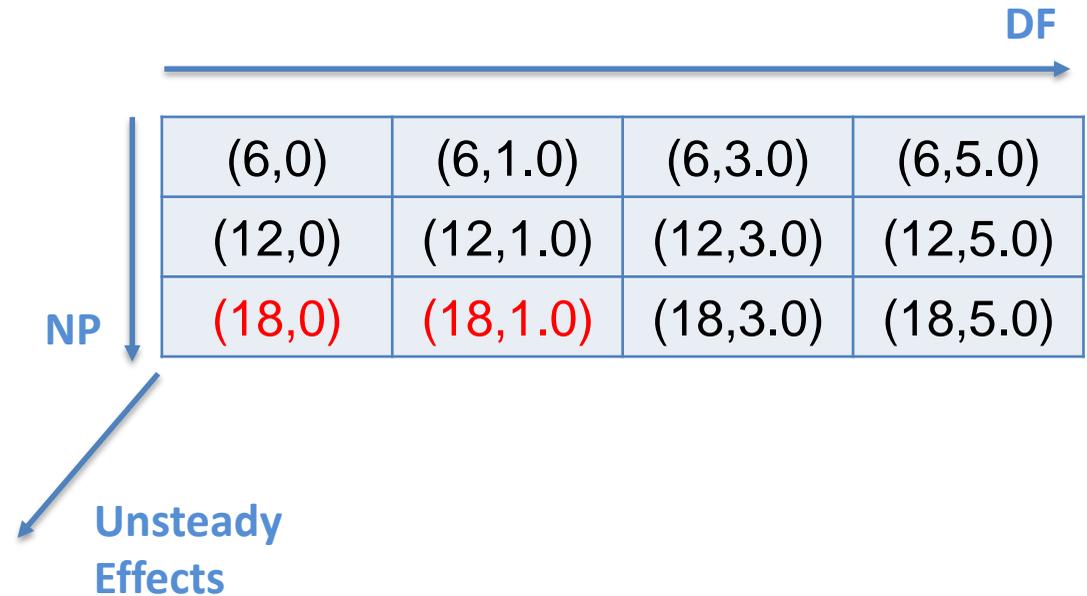




LEAPTech Acoustic Design Space

Design Space

- **Electric propulsion opens up several dimensions in the design space**
 - Scalability - electric motors open design to changes in size and number of props
 - Controllability – Digital controllers provide precise control of phase and frequency
- **Baseline design parameters:**
 - NP: number of props (6-18)
 - ΔF : Step in prop BPF (0-5Hz ~ 10% max variation)
 - ΔP : Step in prop phase (0-180°/NP) [$\Delta F=0$ only]
- **Unsteady design parameters:**
 - Motor control – Tight or loose (complexity/cost tradeoff)
 - Atmospheric turbulence



Some Example Design Choices (and their effect on spatial distribution)

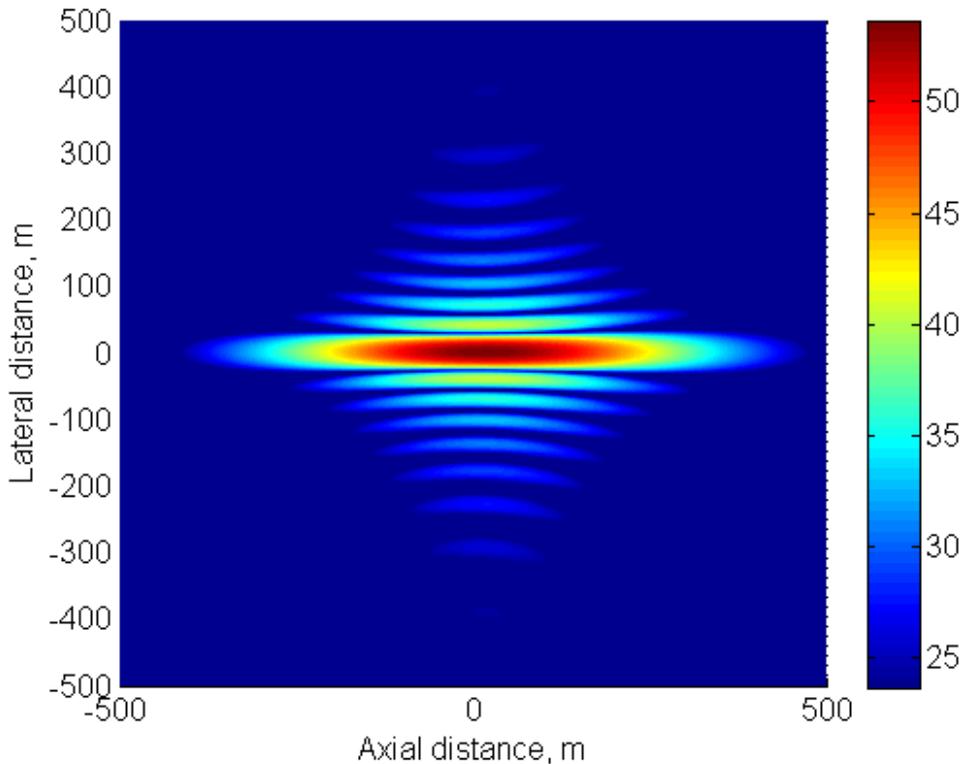


Uniform Frequency (DF=0) - Steady Conditions

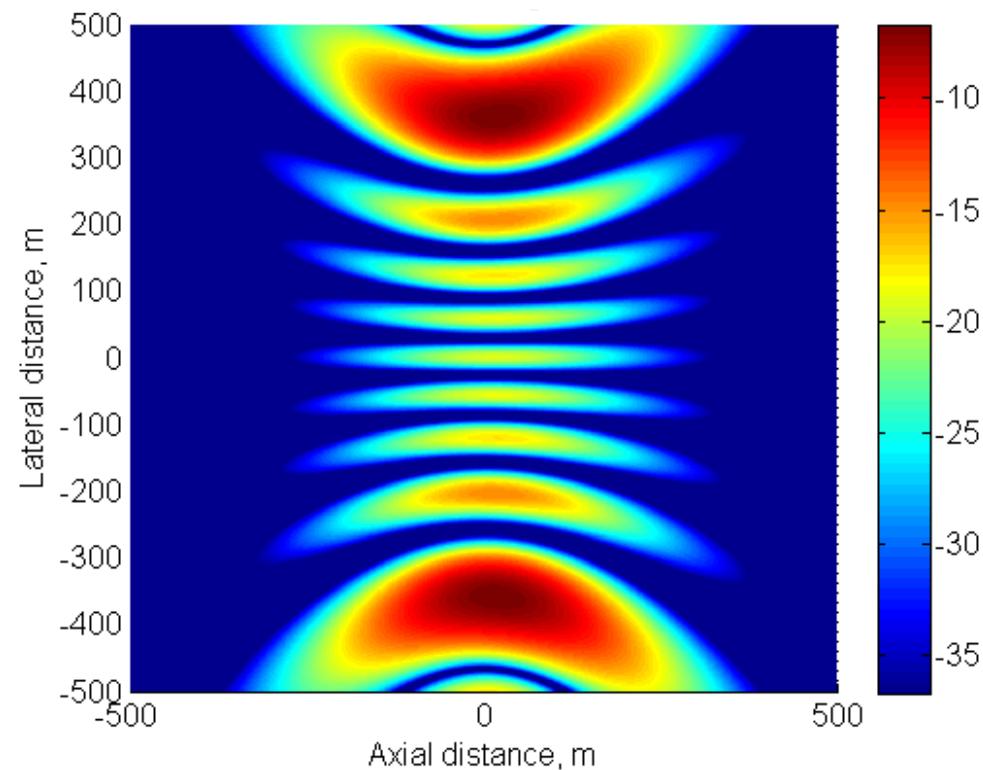
Baseline

(Relative to Max Baseline)

NP=18; DF=0; Synchronized; DP=0



NP=18; DF=0; Synchronized; DP=36°



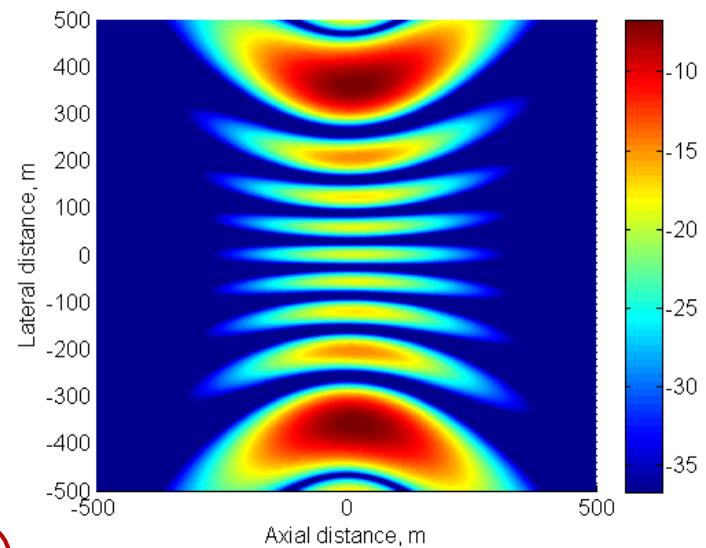
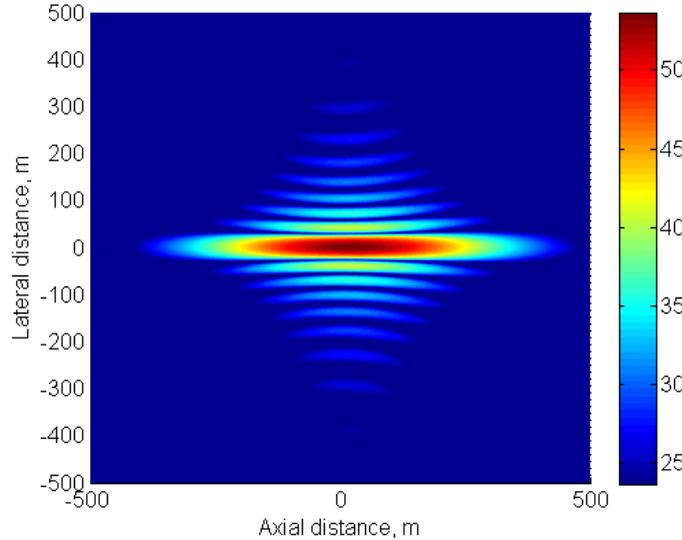
- Sound can be 'steered' dynamically
- Total integrated sound power the same

Some Example Design Choices (and their effect on spatial distribution)

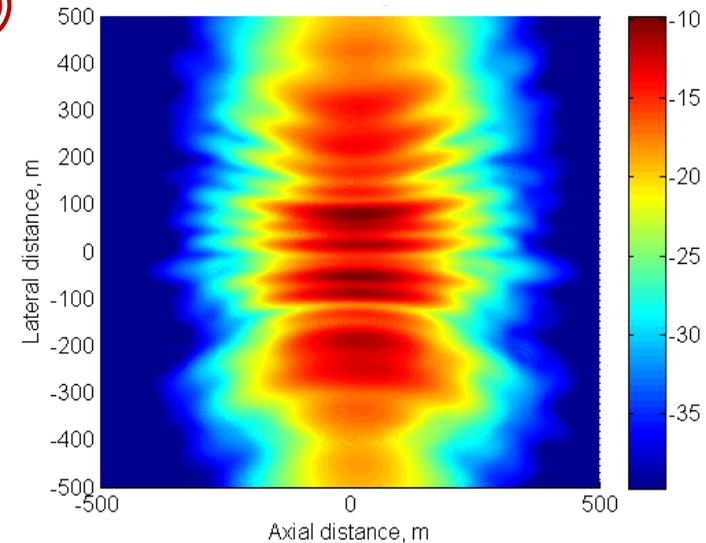
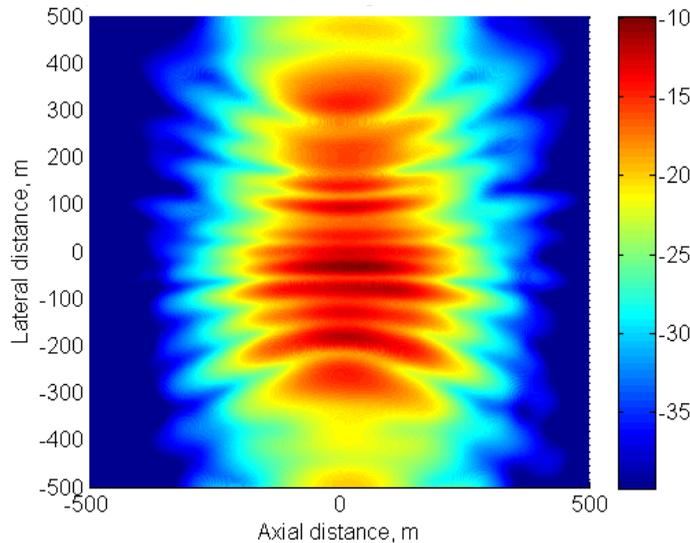


Uniform Frequency (DF=0) - Unsteady Condition (Loose motor control: 1% Freq Error)

Steady



Unsteady



Minor changes in max level. Major changes in spatial distribution.

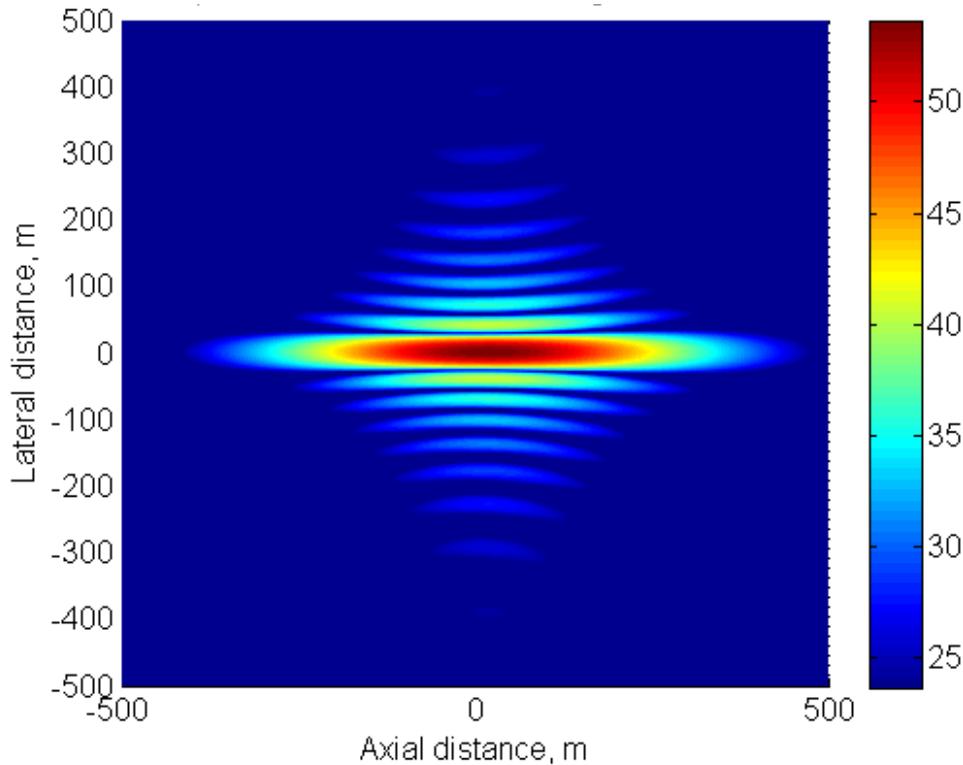
Some Example Design Choices (and their effect on spatial distribution)



Spread Frequency (DF=1) - Steady Conditions

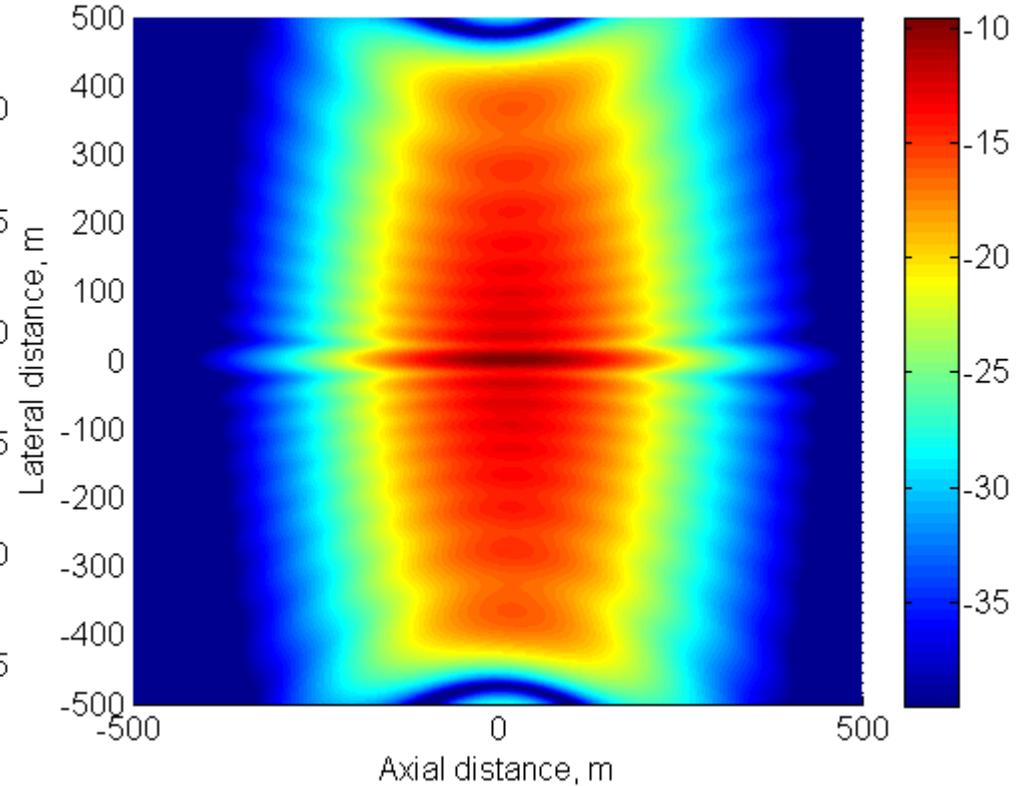
Baseline

NP=18; DF=0; Synchronized; DP=0



(Relative to Max Baseline)

NP=18; DF=1; Unsynchronized; DP=0



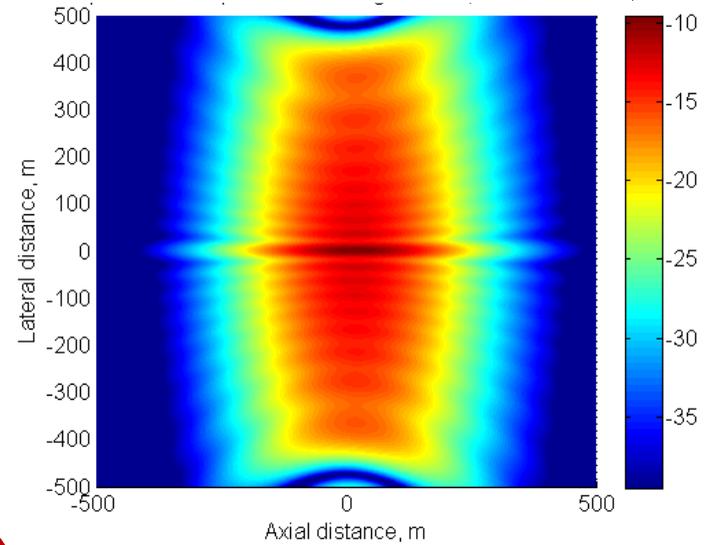
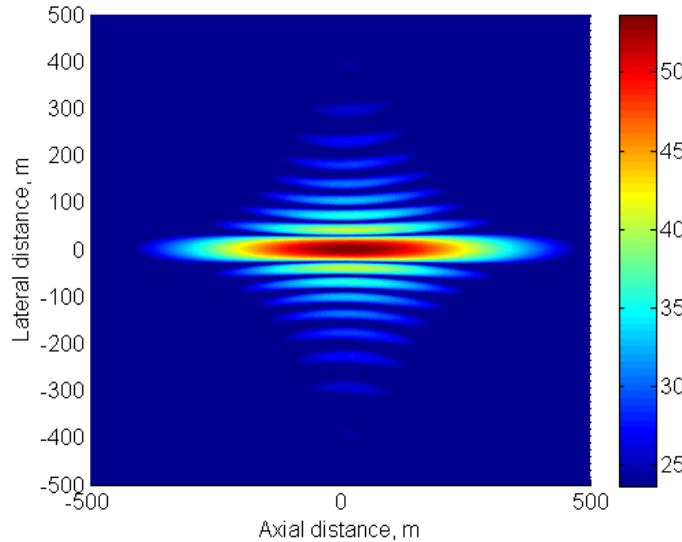
Major change in spatial distribution.

Some Example Design Choices (and their effect on spatial distribution)

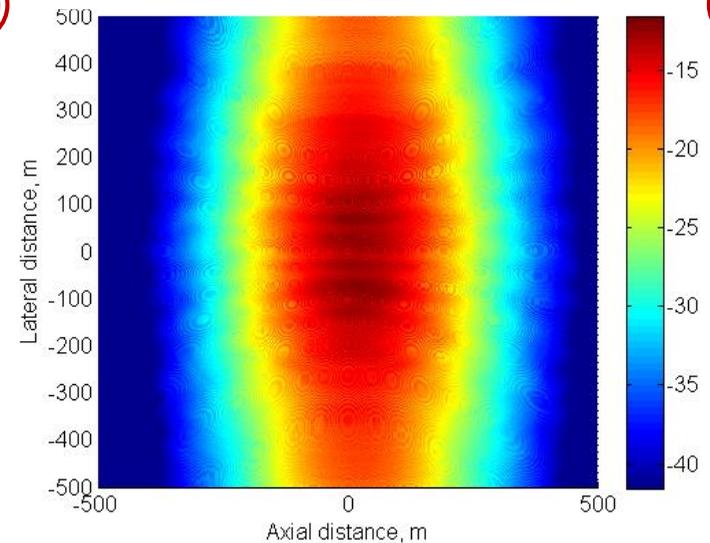
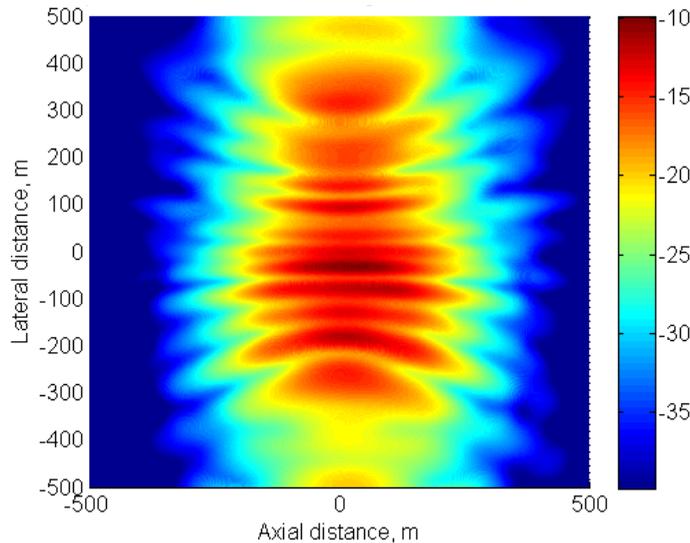


Spread Frequency (DF=1) - Unsteady Condition (Loose motor control: 1% Freq Error)

Steady



Unsteady



Minor changes in max level with unsteadiness

Some Example Design Choices (and their effect on auralized sound)



Spread Frequency (Steady)

Harmonic

BPF

$$\frac{\sin(2\pi n f_i t)}{r_i}$$

Distance

- Spread frequency $f_i \neq f_j$
- Props start at same angle and instantly attain their set RPM



Spread Frequency (Steady, Random Phase)

Initial prop phase ($0 < \theta < 2\pi/5$)

$$\frac{\sin(2\pi n f_i t + \theta_i)}{r_i}$$

- Initial random phase $\theta_i \neq \theta_j$
- Not symmetric port/starboard
- No phase control



Some Example Design Choices (and their effect on auralized sound)



Spread Frequency (Unsteady: Motor control error, No atmospheric turbulence)

Frequency offset Time varying phase

$$\frac{\sin(2\pi n(f_i + f_{e_i})t + \theta_i + \phi_i(t))}{r_i}$$

$$f_{e_i} \neq f_{e_j}$$

$$\phi_i \neq \phi_j$$

- **Loose** motor control: 1% pk-pk variation in frequency
- Tight motor control: 0.1% pk-pk variation in frequency



Spread Frequency (Unsteady: Perfect motor control, with atmospheric turbulence)

Amplitude Variance

Phase Variance

$$\frac{\alpha_i(t) \sin(2\pi n(f_i + \cancel{f_{e_i}})t + \cancel{\theta_i} + \psi_i(t) + \cancel{\phi_i(t)})}{r_i}$$



Some Example Design Choices (and their effect on auralized sound)



Spread Frequency (Unsteady: Motor control error, with atmospheric turbulence)

$$\frac{\alpha_i(t) \sin(2\pi n(f_i + f_{e_i})t + \theta_i + \psi_i(t) + \phi_i(t))}{r_i}$$

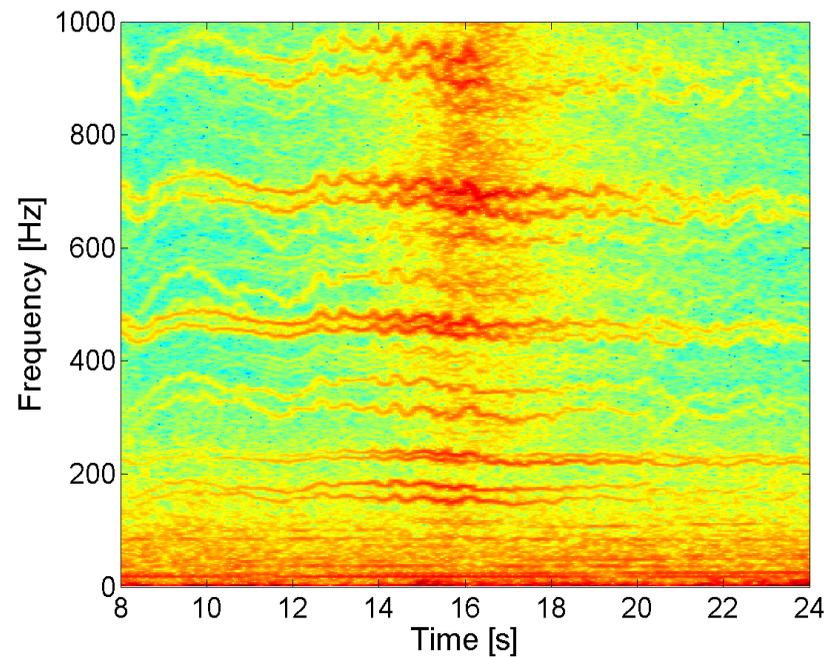


Spread Frequency (Steady)



September 2015 - Psychoacoustic tests to understand human response to distributed electric propulsor noise under steady and unsteady conditions.

DELIVER – Auralization of DJI Phantom 2 Quadcopter

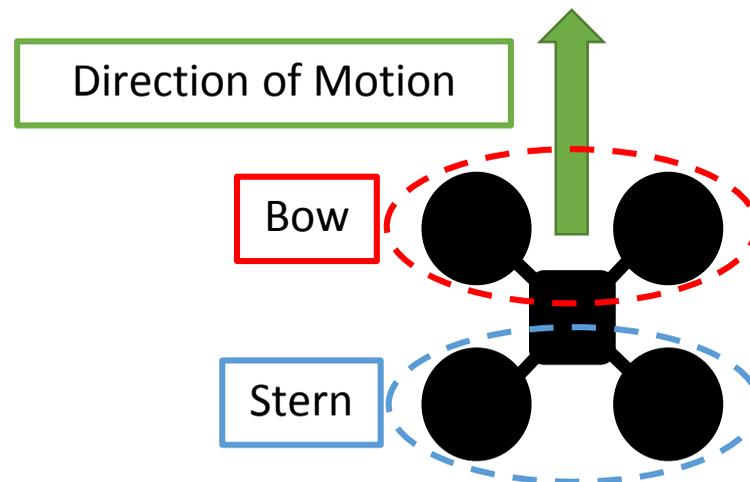
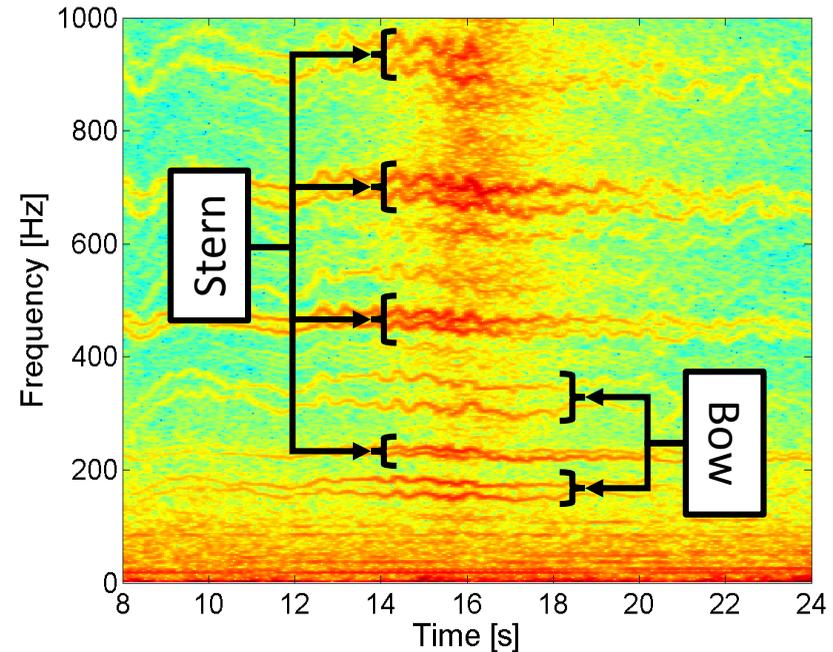


[“Acoustic Flight Testing of small Unmanned Aerial Systems (sUAS) at 42VA Virginia Beach Airport”, Grosveld, Cabell, McSwain, to appear]

Quadcopter Flyover – What's Going On

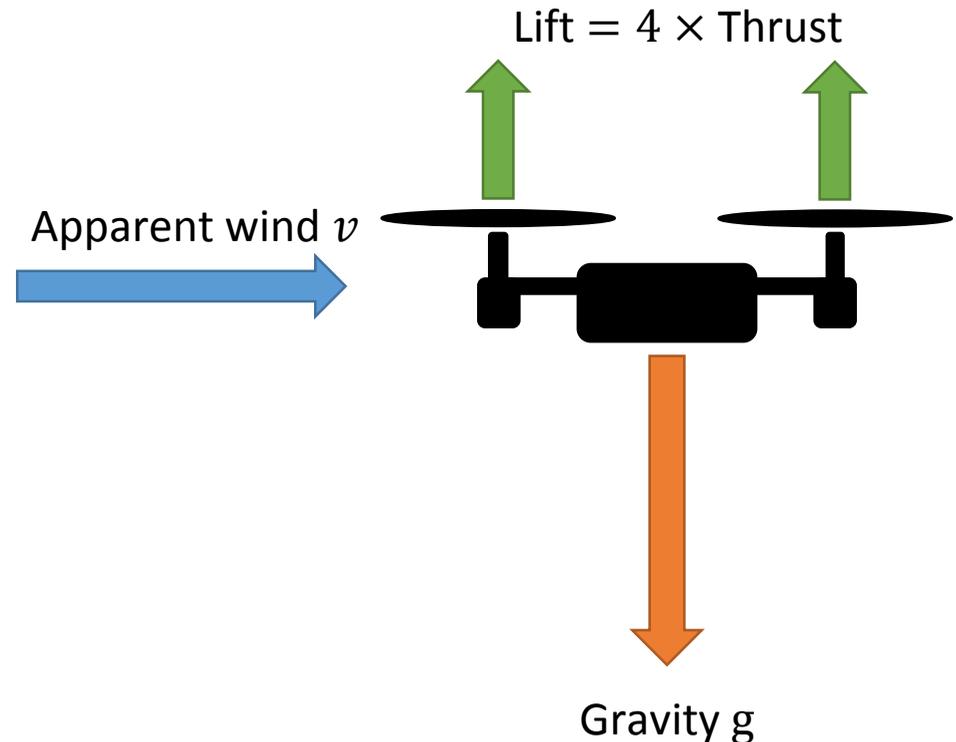
- The Phantom 2 has 4 rotors
- Each rotor produces a harmonic series starting at the blade passage frequency (BPF).
- These rotors work independently to maintain attitude based on an on-board closed-loop control system.
 - For instance a difference between the bow and stern pairs leads to pitch correction.

→ All of the system dynamics are coupled producing time-varying tones as the output!



Quadcopter Flyover – Simple Dynamics Model

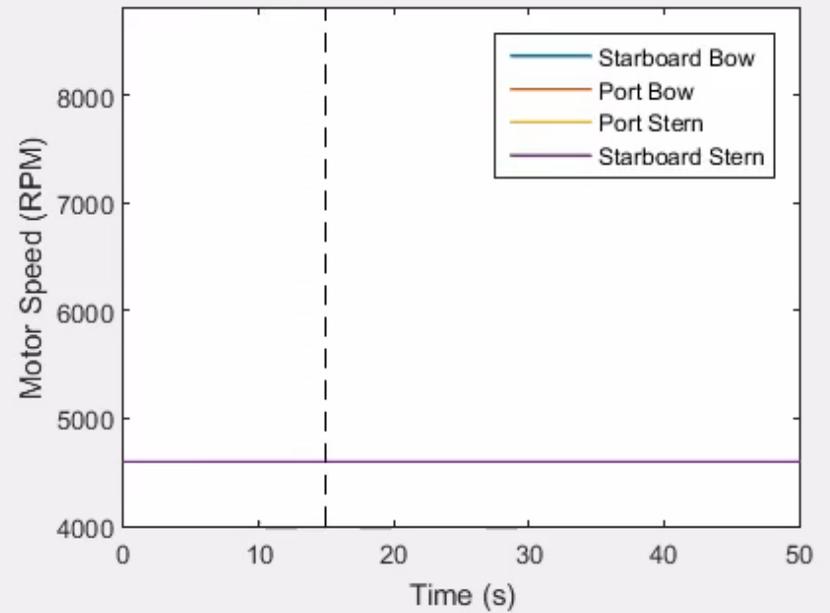
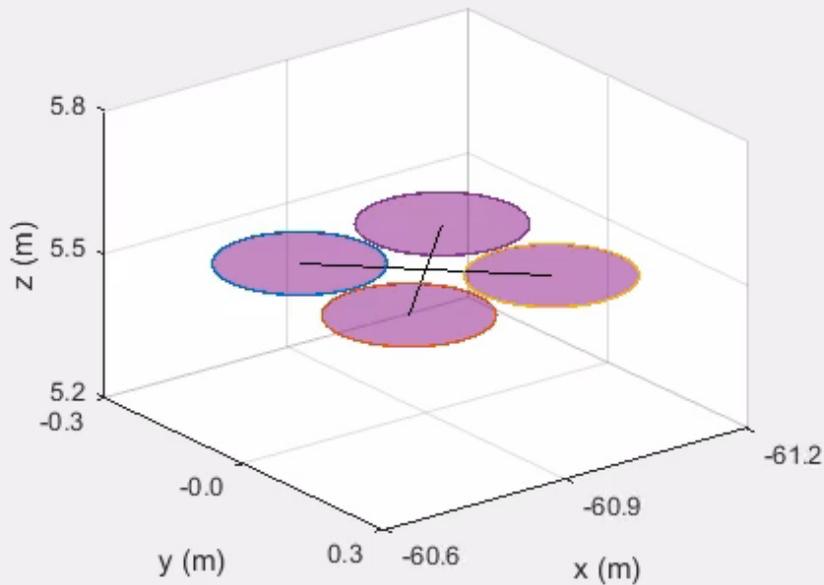
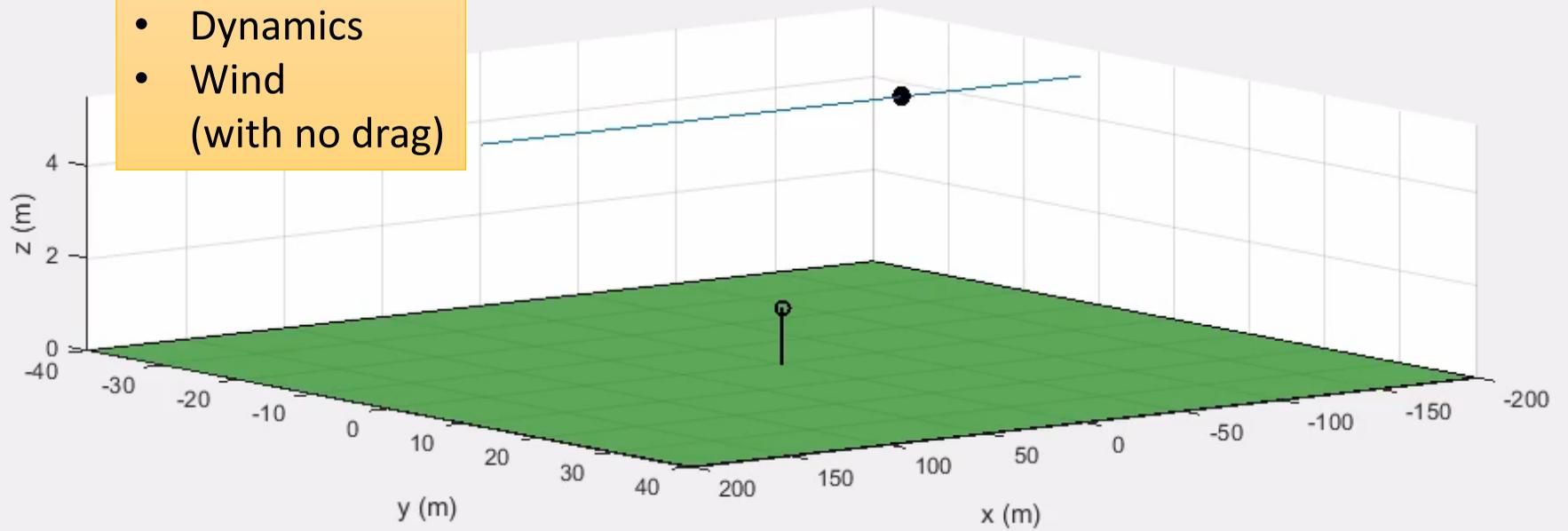
- **The simulations that follow use parameters meant to reflect the recorded flyover:**
 - 19.7 ft/s (6 m/s) nominal airspeed
 - 18 ft nominal altitude
 - DJI Phantom 2 specifications (weight, size, etc.)
 - Receiver (simulated microphone) at 4 ft
 - Included propagation effects:
 - Spherical spreading
 - Rigid ground reflection
 - Time dilation (Doppler shift)
- **This effort combines elements from across the DELIVER team :**
 - Measured blade parameters (e.g. thrust coefficient) by Nik Zawodny.
 - A hemispherical model of the tonal components of the rotor source noise. Based on CFD runs by Doug Boyd
 - Dynamics model programming by Joseph Lawrence.



- **The initial simulation includes a dynamics model and basic PID control system**
 - Adapted from open source SimULink model.
 - Custom ODE solver (entire code runs in vanilla MatLab)

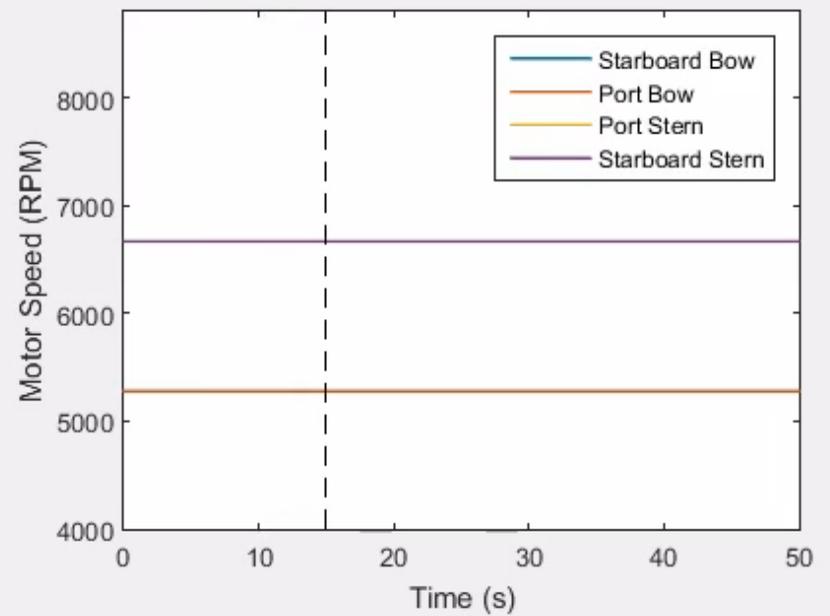
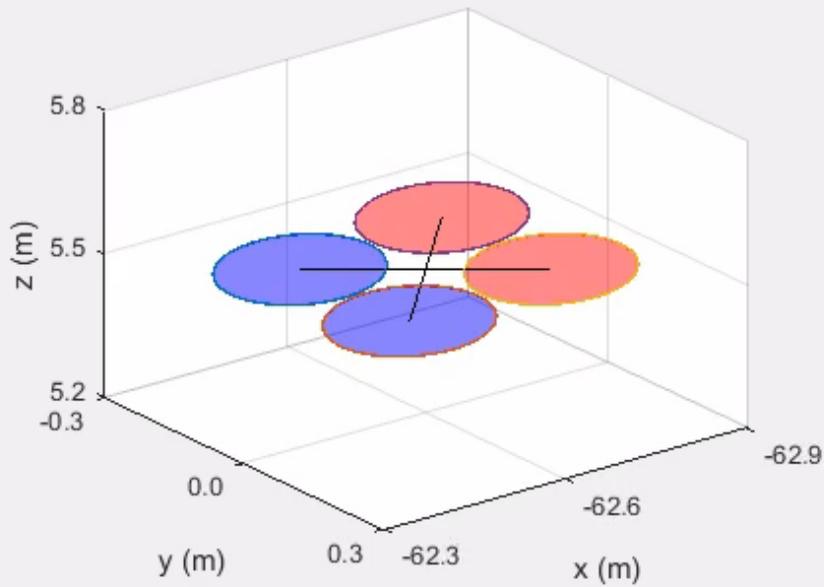
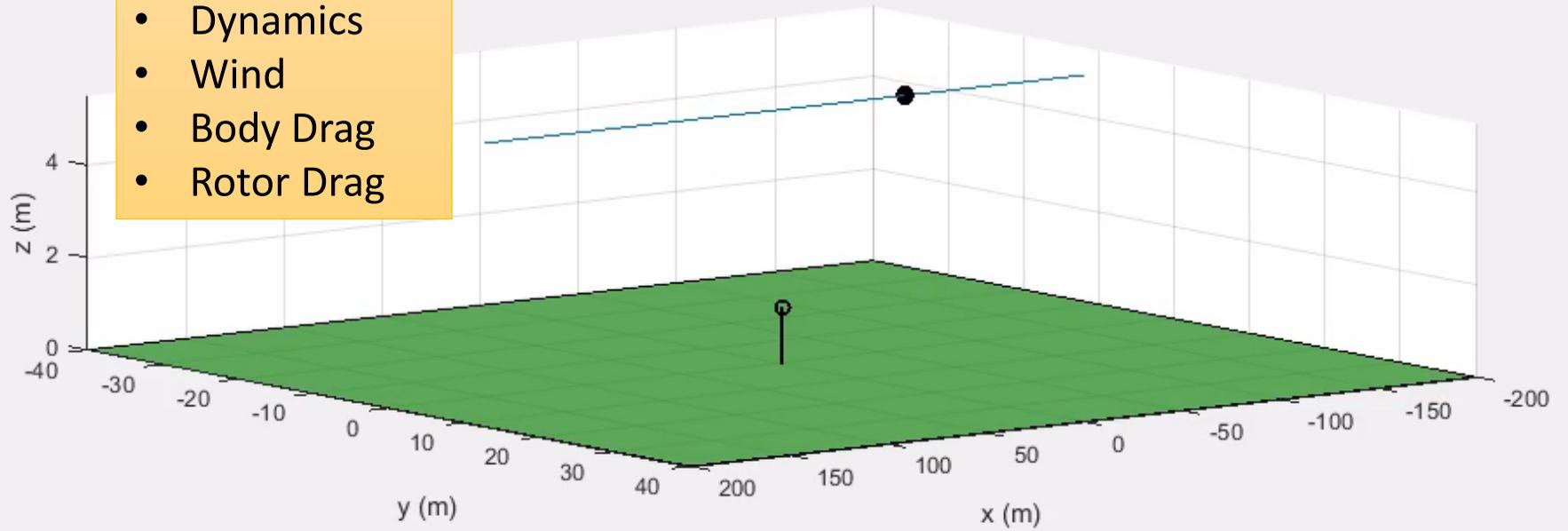
Included Effects:

- Dynamics
- Wind
(with no drag)



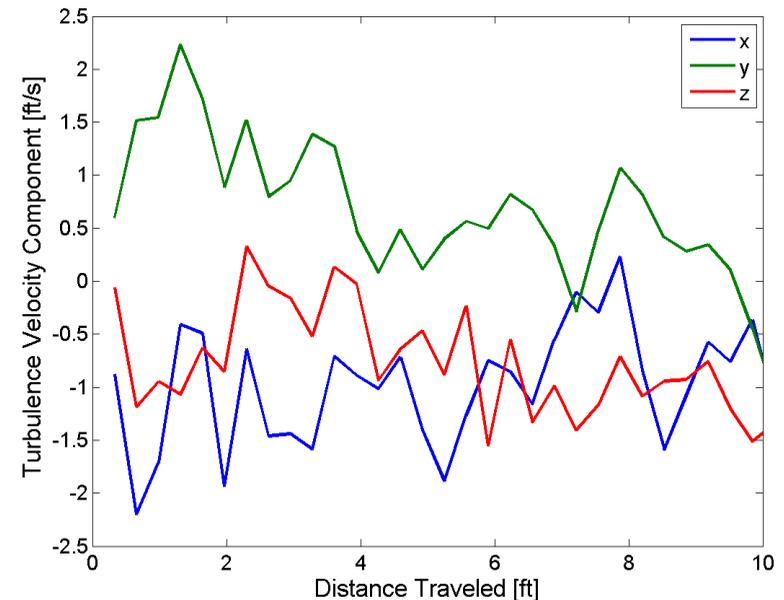
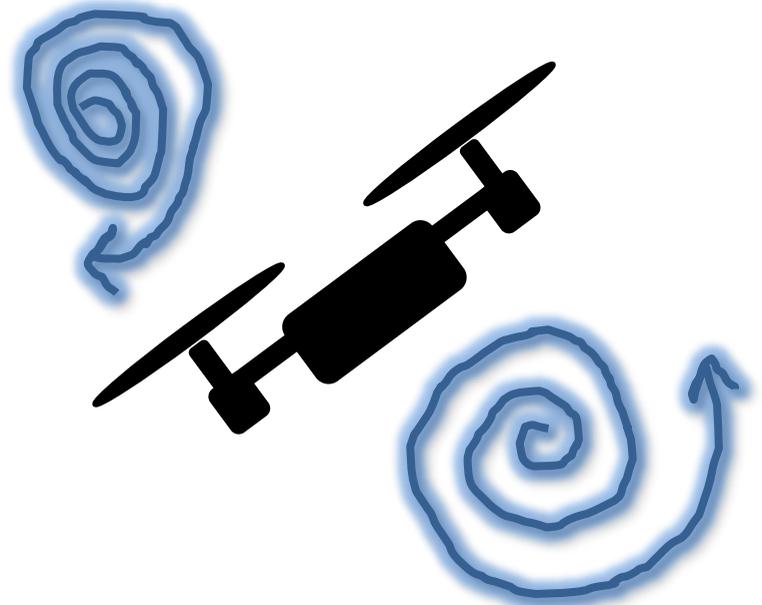
Included Effects:

- Dynamics
- Wind
- Body Drag
- Rotor Drag



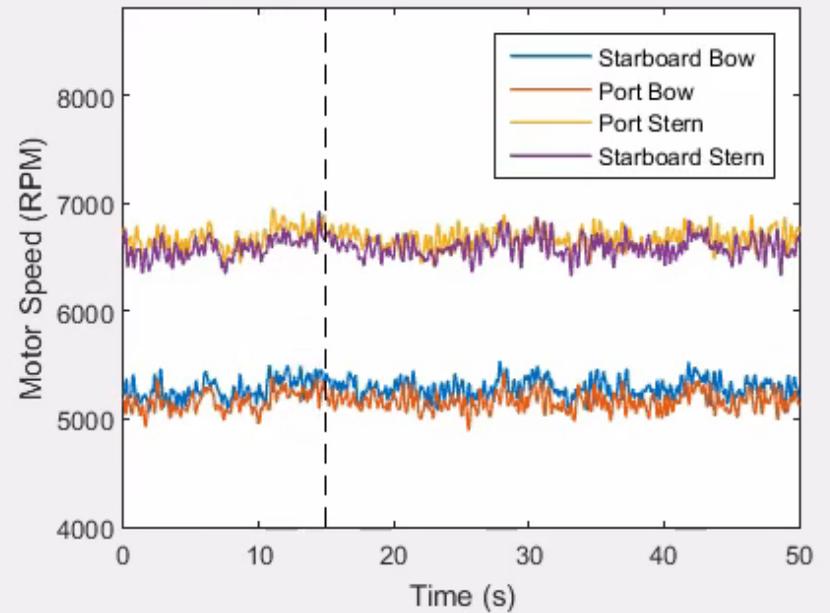
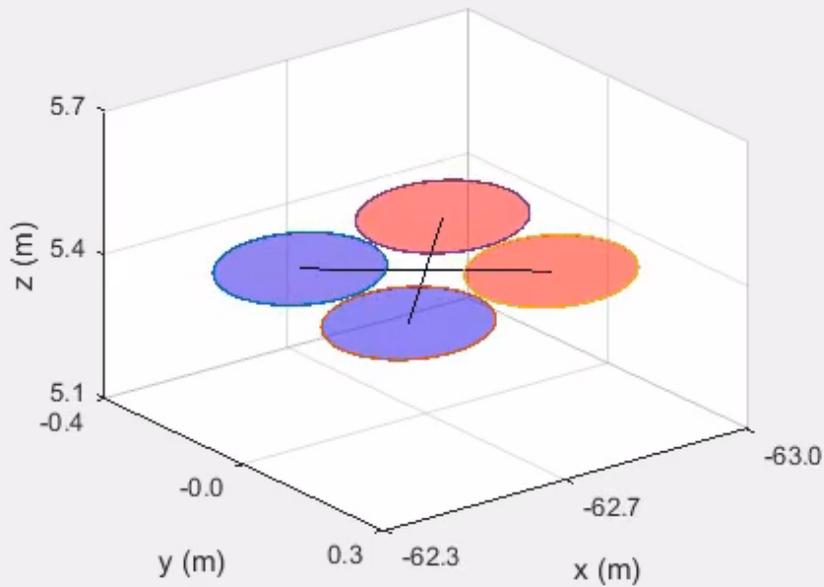
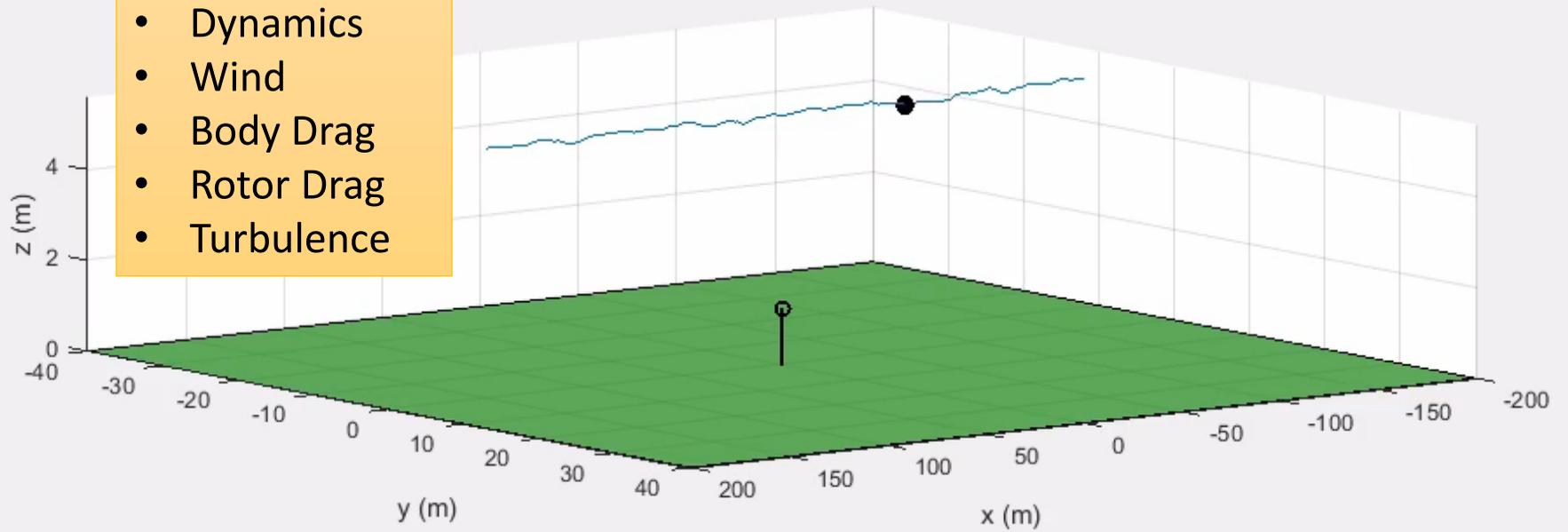
Quadcopter Flyover – Add Atmospheric Turbulence

- **Local variations in the wind can be caused by a number of effects:**
 - Convection effects in the presence of thermal gradients
 - Vortex shedding effects in the presence of the ground surface
 - Wake effects in the presence of buildings, trees, etc.
- **Turbulence adds a time-varying component to the apparent wind that affects the location and attitude of a quadcopter over time.**
- **Turbulence causes the quadcopter to have to constantly work in order to maintain its location (along a specified path in this case) and attitude (so that it does not slip and fall out of the sky).**



Included Effects:

- Dynamics
- Wind
- Body Drag
- Rotor Drag
- Turbulence





Quadcopter Flyover – Imbalance

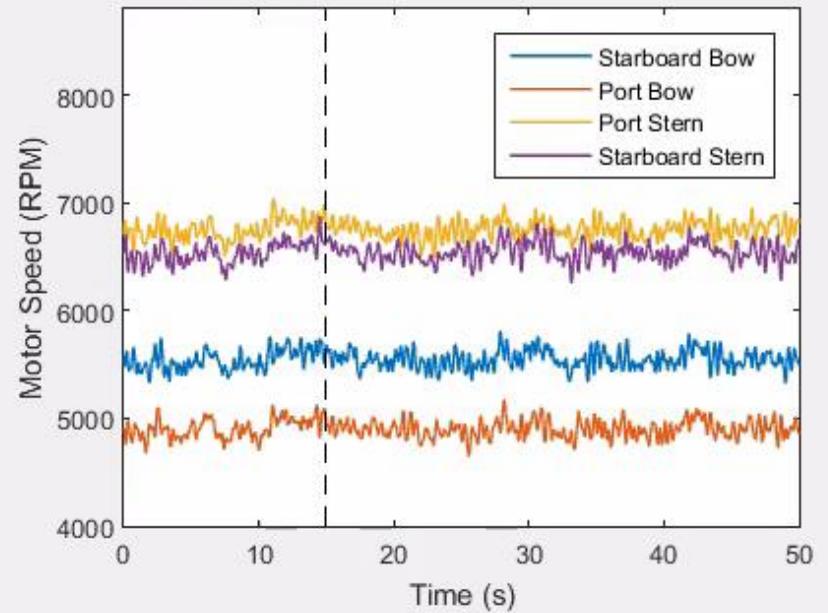
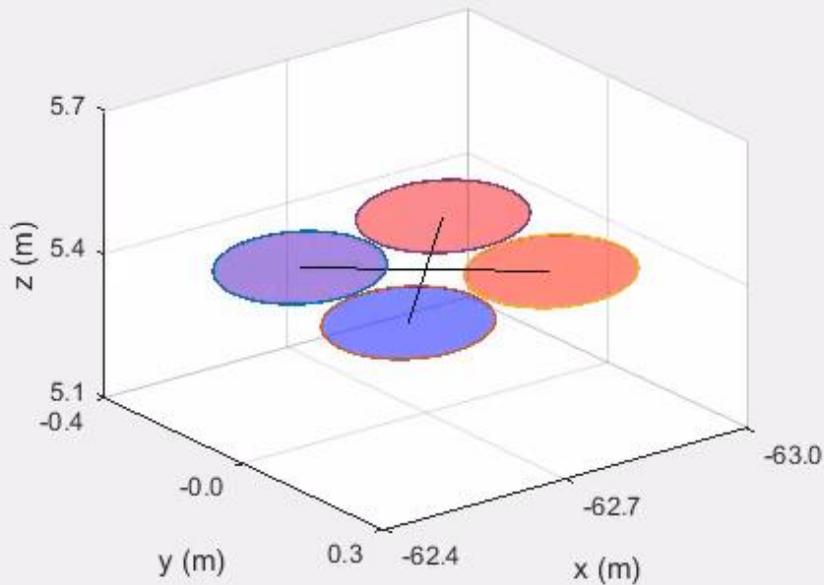
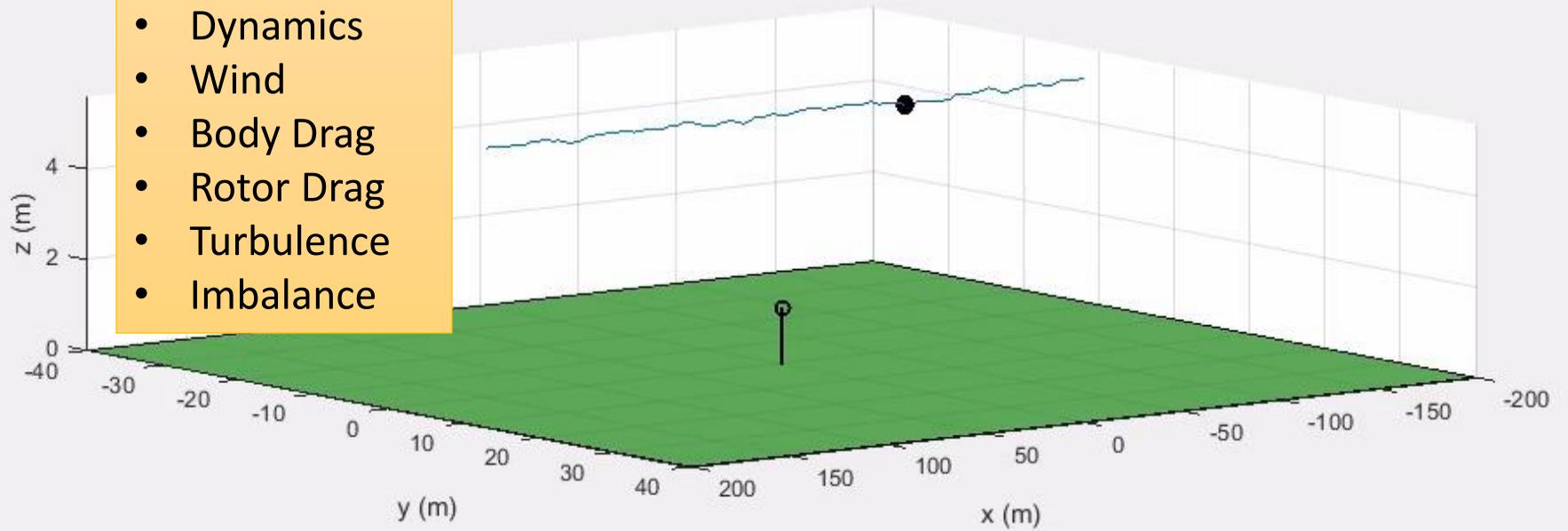


- **When setting up new quadcopter it is often necessary to ‘calibrate’ it so that there is a baseline setting in which the device knows that all of the rotors are producing equal thrust.**
 - This is not necessarily a place where all rotors are spinning at exactly the same RPM
 - This points to weight/operational imbalance in components of the system.
 - Systematic offsets between rotors have been observed in quadcopter recordings.
- **In this case, a random error of 5% (standard deviation) is added to the thrust coefficient of the rotors.**

- **The acoustic effect of error is to split the two pairs of RPMs into four independent traces (for instance, until now the bow motors had been running at the same nominal speed).**
- **It is important to note that this error splits the lower-RPM pair more than the higher one.**
 - This is due to the fact that thrust is related to RPM-squared.

Included Effects:

- Dynamics
- Wind
- Body Drag
- Rotor Drag
- Turbulence
- Imbalance





Simple models neglecting unsteadiness of the sources are not suitable for use in human annoyance studies that are intended to lead to low noise design strategies.

Thank You!