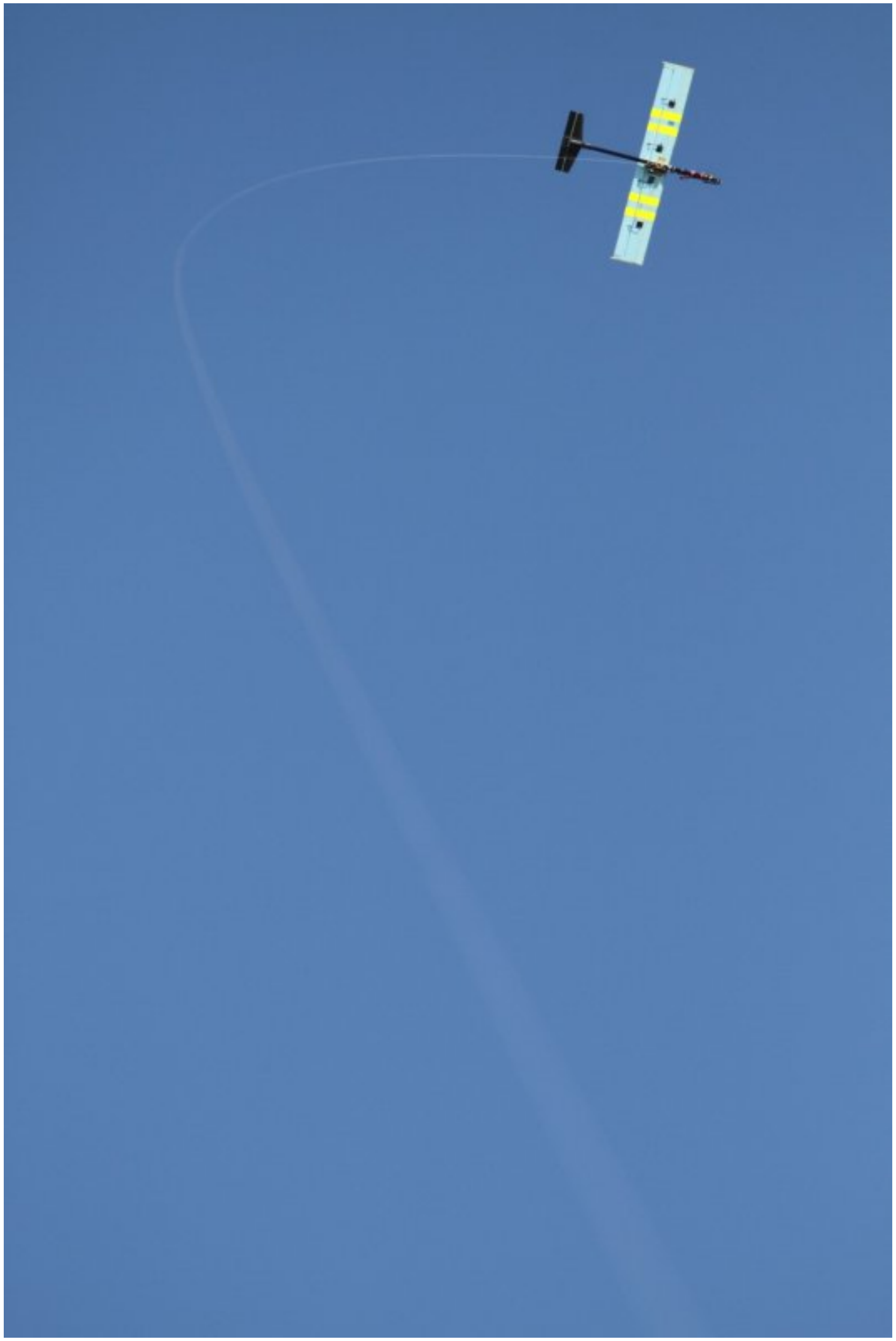
A longitudinal tethered aircraft dynamics model and its controls implications

Michael Sherback

Joby Energy

Outline:

- The Joby approach
- The controls challenges in steady operation
- What are the longitudinal dynamics?
- Why regulate angle of attack?
- Approaches with experimental results



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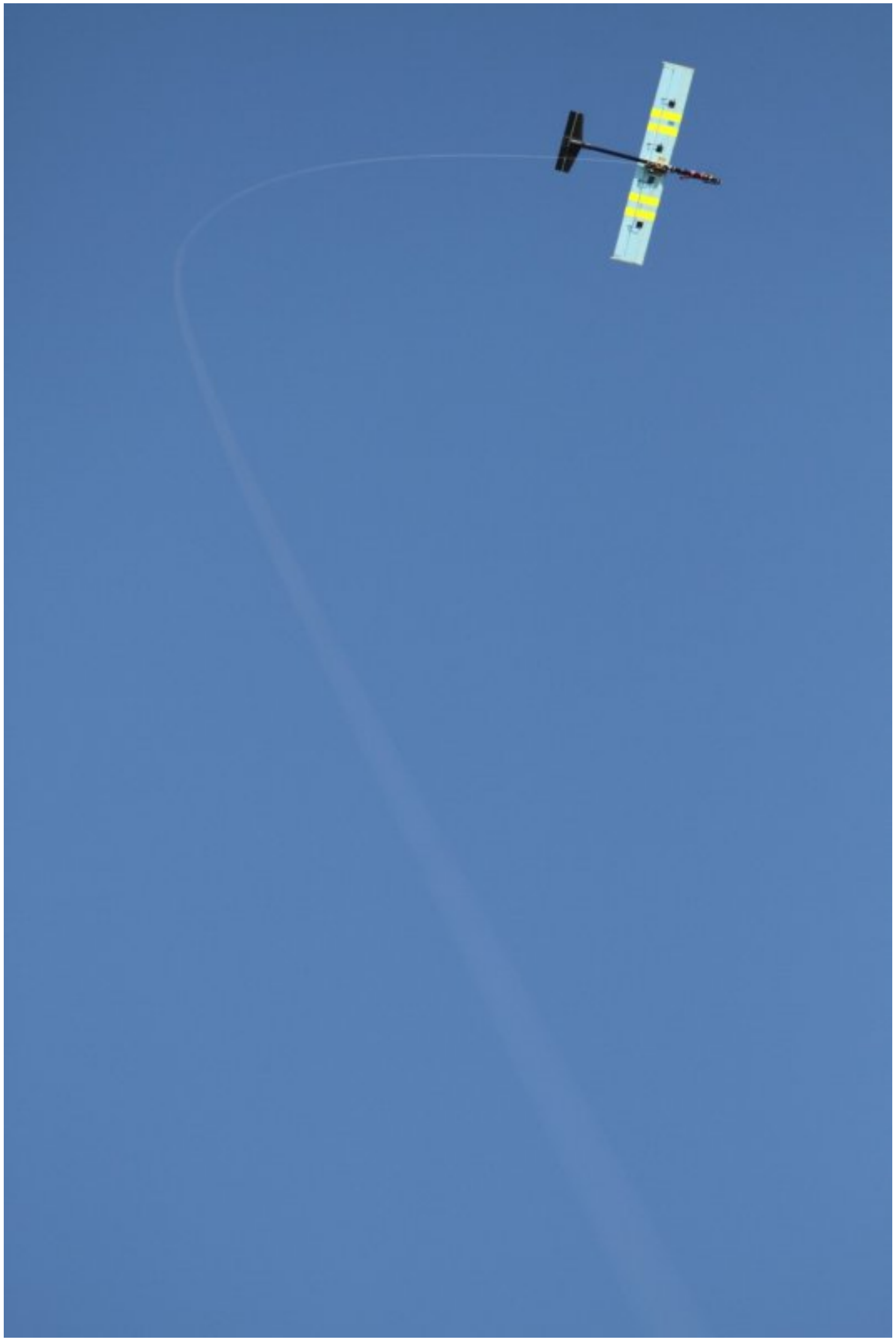


The Joby approach: background

- JoeBen already talked...
- drag mode
- conventional and VTOL rigid airframes

The Joby approach: sim and control

- Conventional 6-DOF aircraft sim plus a lumped tether model
- Simple contr
- GPS
- Controls tea

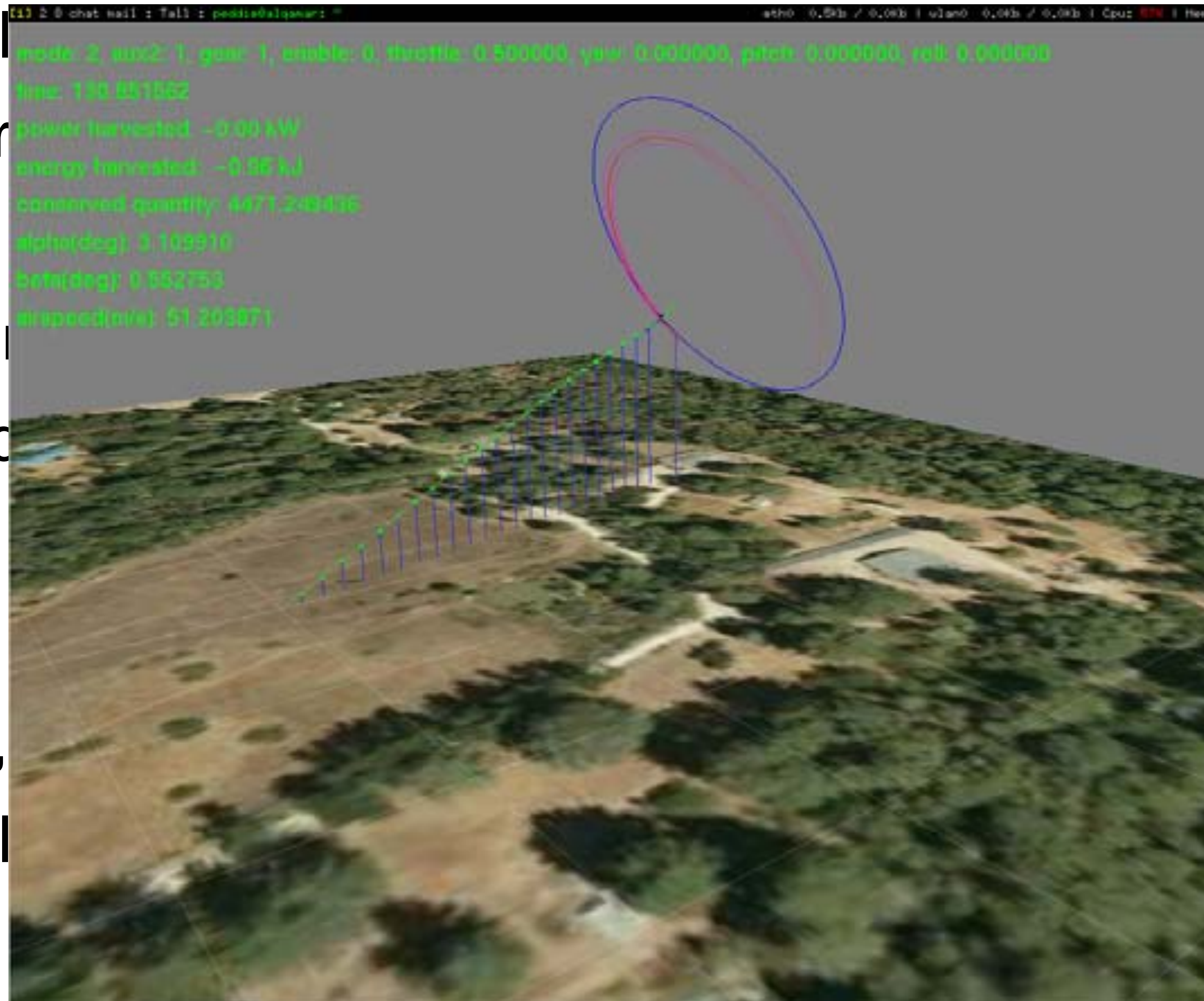
Me, Matt Pedd

Greg Horn,

Henry Hallam

Fergus Noble,

Fred Bourgaul



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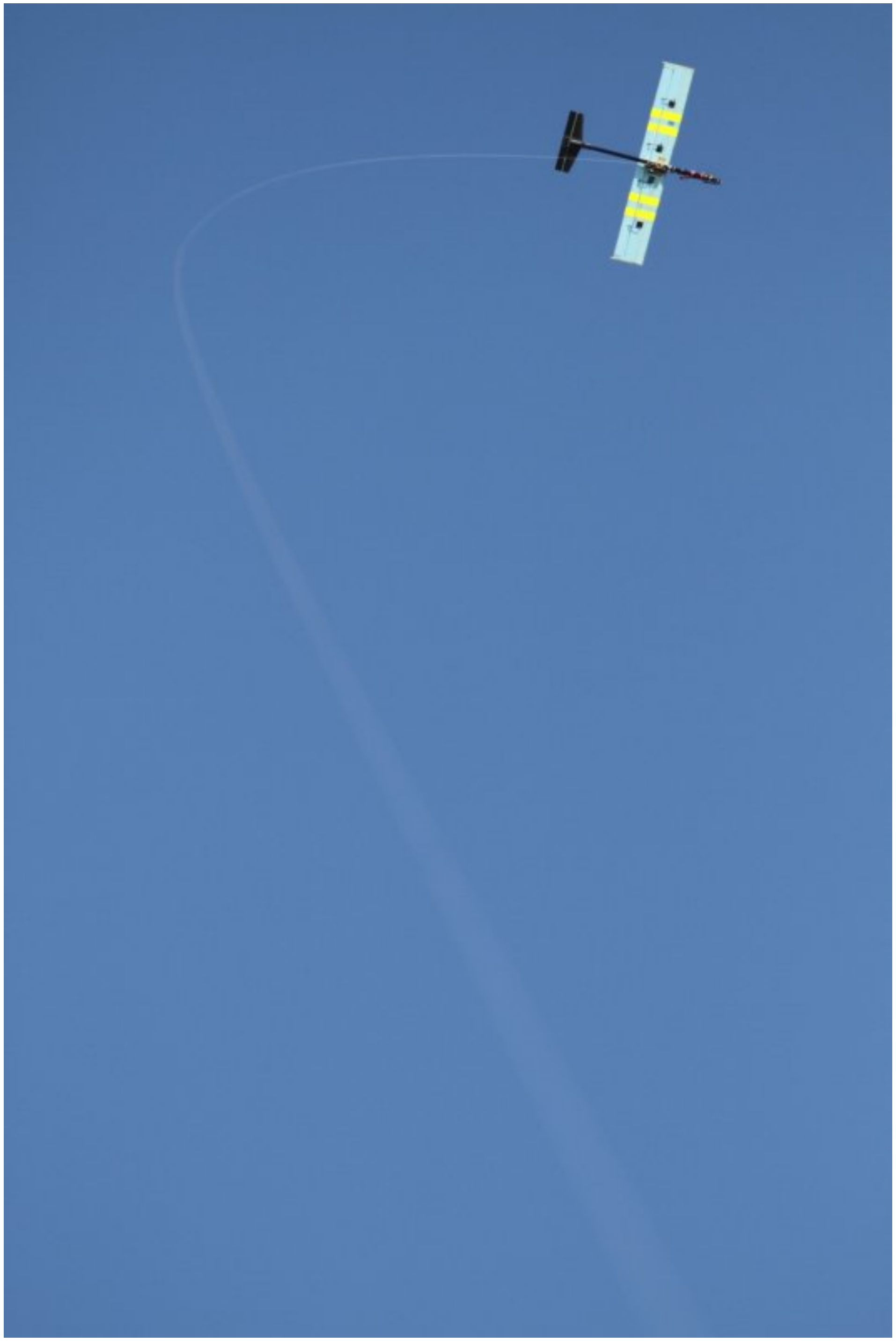
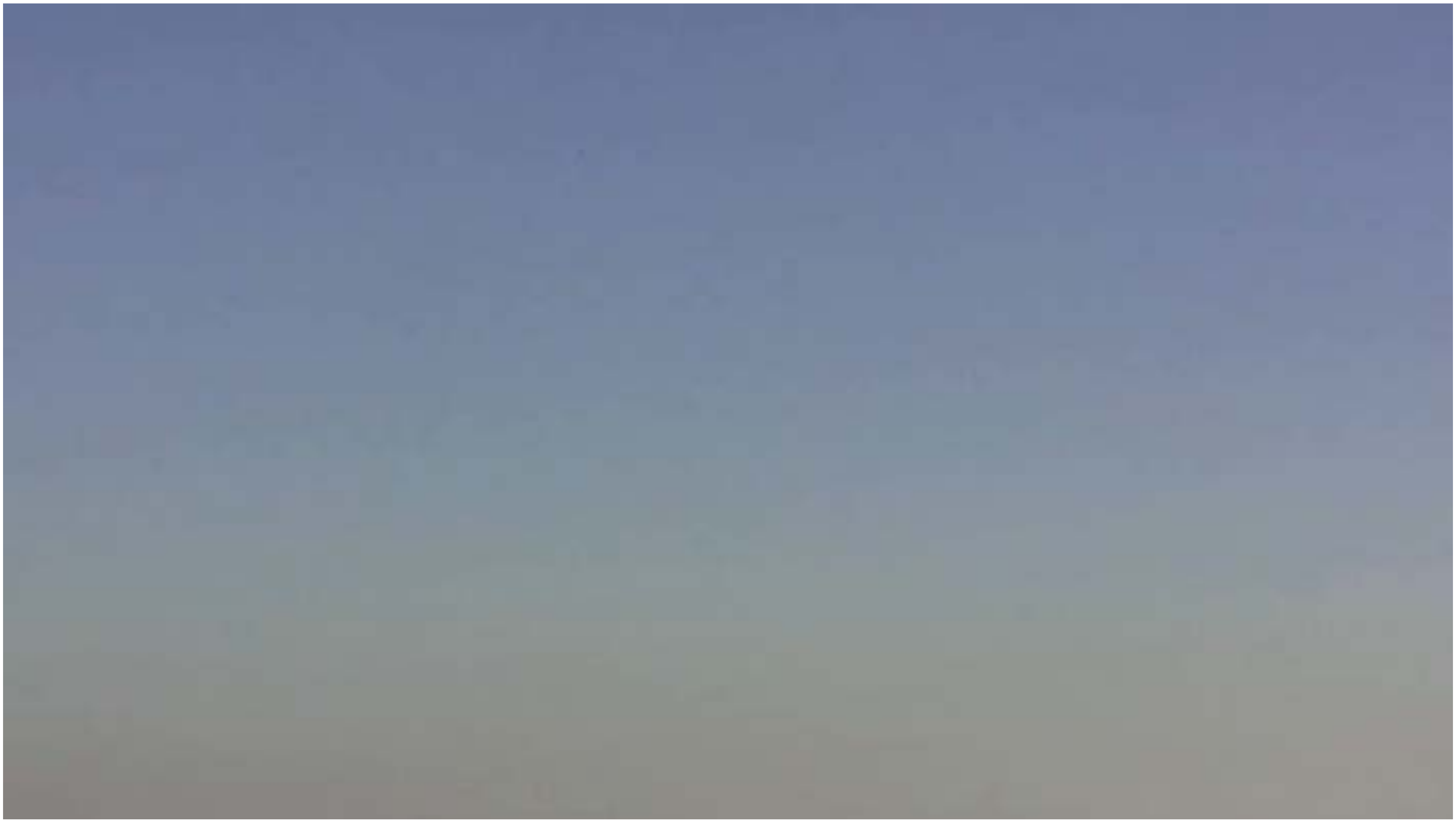


The most visible control challenge: steering

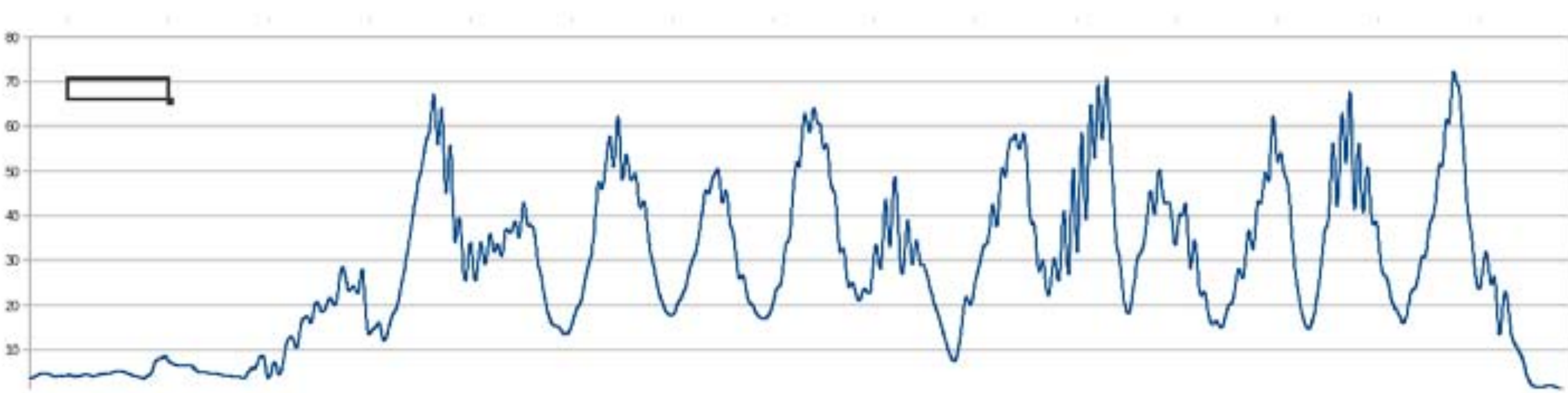
- relies on the interaction of lift, tether tension, gravity, and roll
- path curvature results from component of the sum perpendicular to the tether

Autonomous circles and 8s



Less visible but perhaps more critical: regulating lift and tether tension

- Changes in tether tension:
  - Cause airframe and tether fatigue or failure
  - Disturb the steering loop
  - Change the stiffness and damping of the tether in a quasi-steady model
  - Invalidate quasi-steady model
  - Drive attitude dynamics when bridled
- Data below was hand-flown to investigate these types of effects



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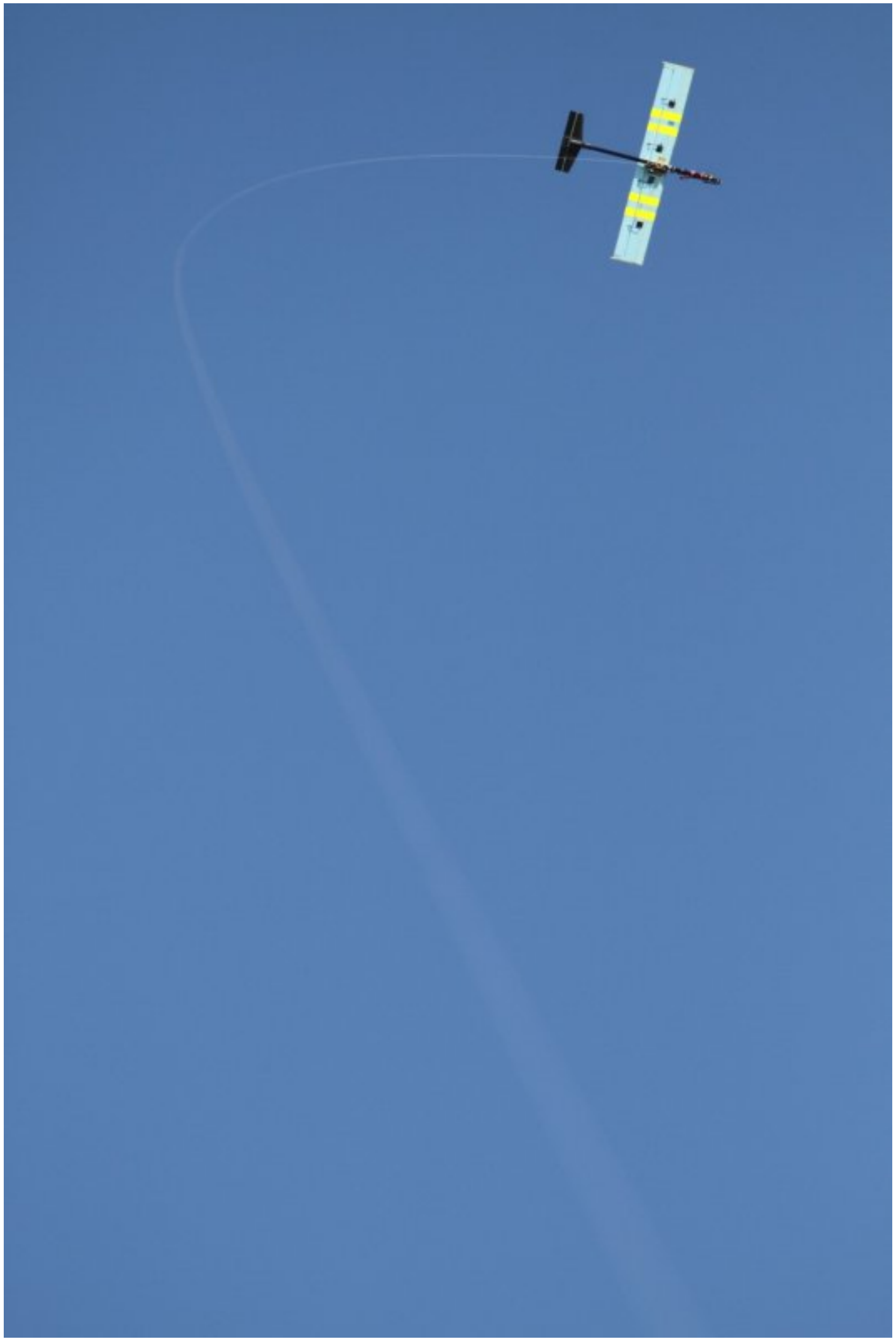
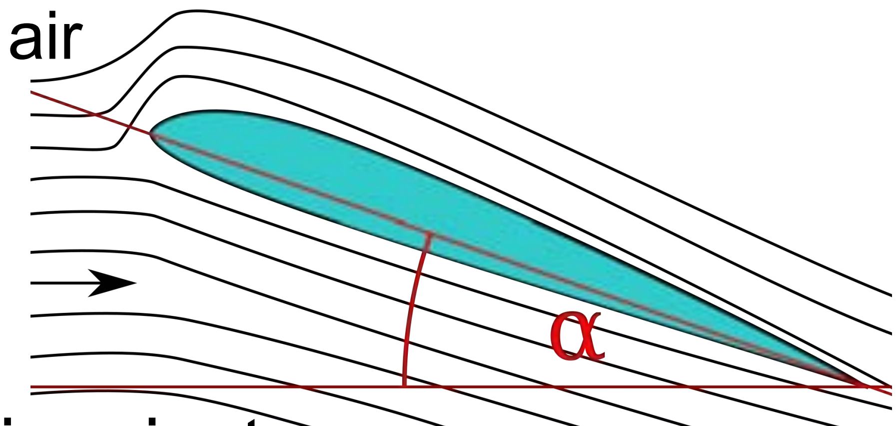


Untethered longitudinal dynamics

- The standard aircraft model has the states:
  - **Angle of attack** α rel. to air
  - Pitch θ rel. to ground
  - Pitch rate q
  - airspeed



- Short period approximation: just q, α
  - Neglects slow/regulated airspeed changes, gravity effects from pitch
  - $d\alpha/dt = q$ at high frequencies

Tethered angle of attack dynamics

- assume speed is tightly regulated by drag props (analogous to the short period approx.)

$$\omega_\alpha = \frac{-QSC_{L\alpha}}{mv}$$

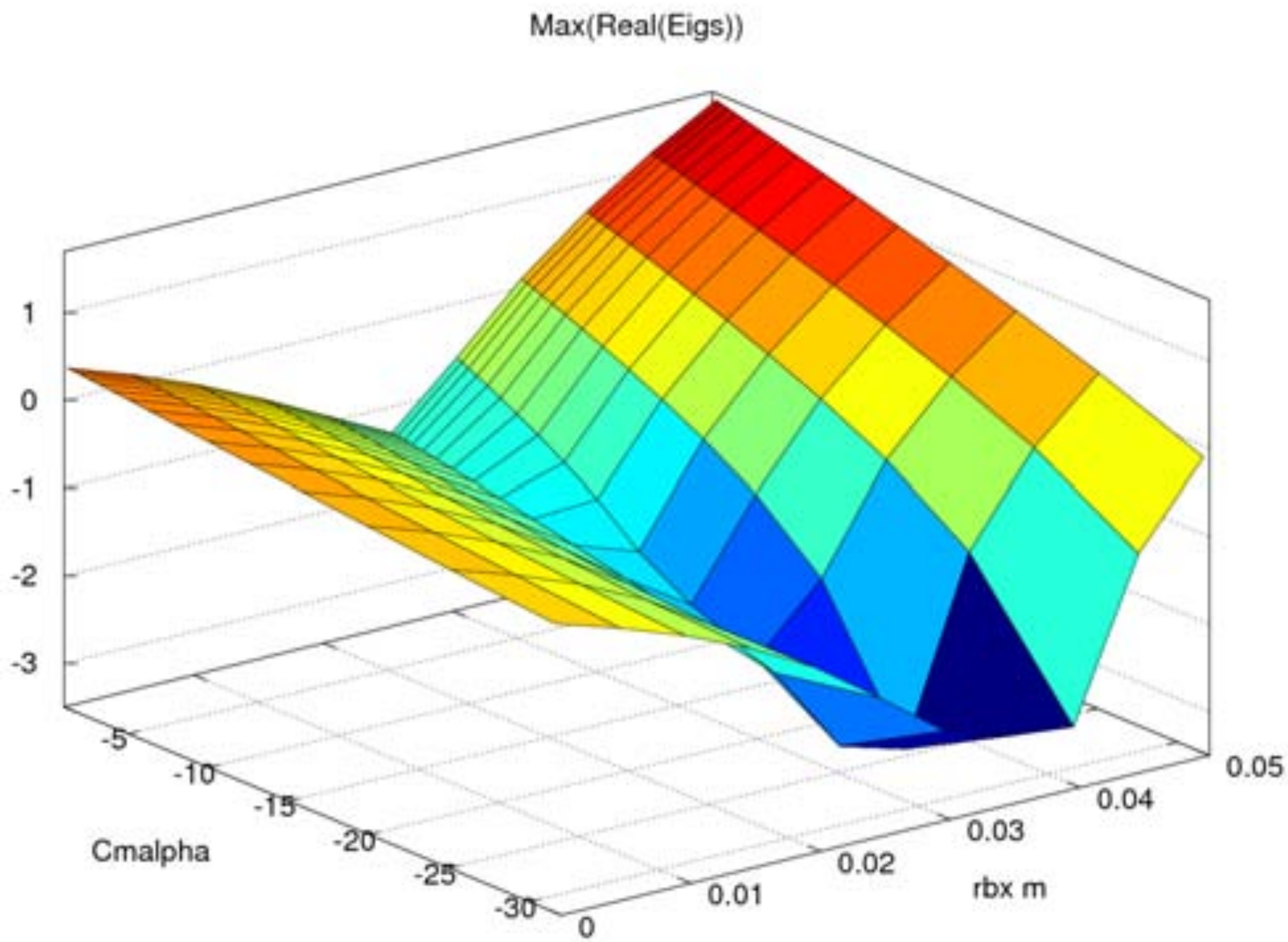
$$J\dot{q} = QScC_{mq}q \;+ QScC_{m\alpha}\alpha \;- r_{bx}k_\lambda\lambda \;- r_{bx}b_\lambda\dot{\lambda}$$

$$\dot{\alpha} = q \;+ \omega_\alpha\alpha \;+ \frac{k_\lambda}{mv}\lambda \;+ \frac{b_\lambda}{mv}\dot{\lambda}$$

$$m\ddot{\lambda} = mv\omega_\alpha\alpha \;- k_\lambda\lambda \;- b_\lambda\dot{\lambda}$$

$$\begin{pmatrix} \dot{q} \\ \dot{\alpha} \\ \dot{\lambda} \\ \ddot{\lambda} \end{pmatrix} = \begin{pmatrix} \frac{QScC_{mq}}{J} & \frac{QScC_{m\alpha}}{J} & \frac{-r_{bx}k_\lambda}{J} & \frac{-r_{bx}b_\lambda}{J} \\ 1 & \omega_\alpha & \frac{k_\lambda}{mv} & \frac{b_\lambda}{mv} \\ 0 & 0 & 0 & 1 \\ 0 & \omega_\alpha v & \frac{-k_\lambda}{m} & \frac{-b_\lambda}{m} \end{pmatrix} \begin{pmatrix} q \\ \alpha \\ \lambda \\ \dot{\lambda} \end{pmatrix}$$

Effects of fundamental design choices: C_m_alpha, bridling



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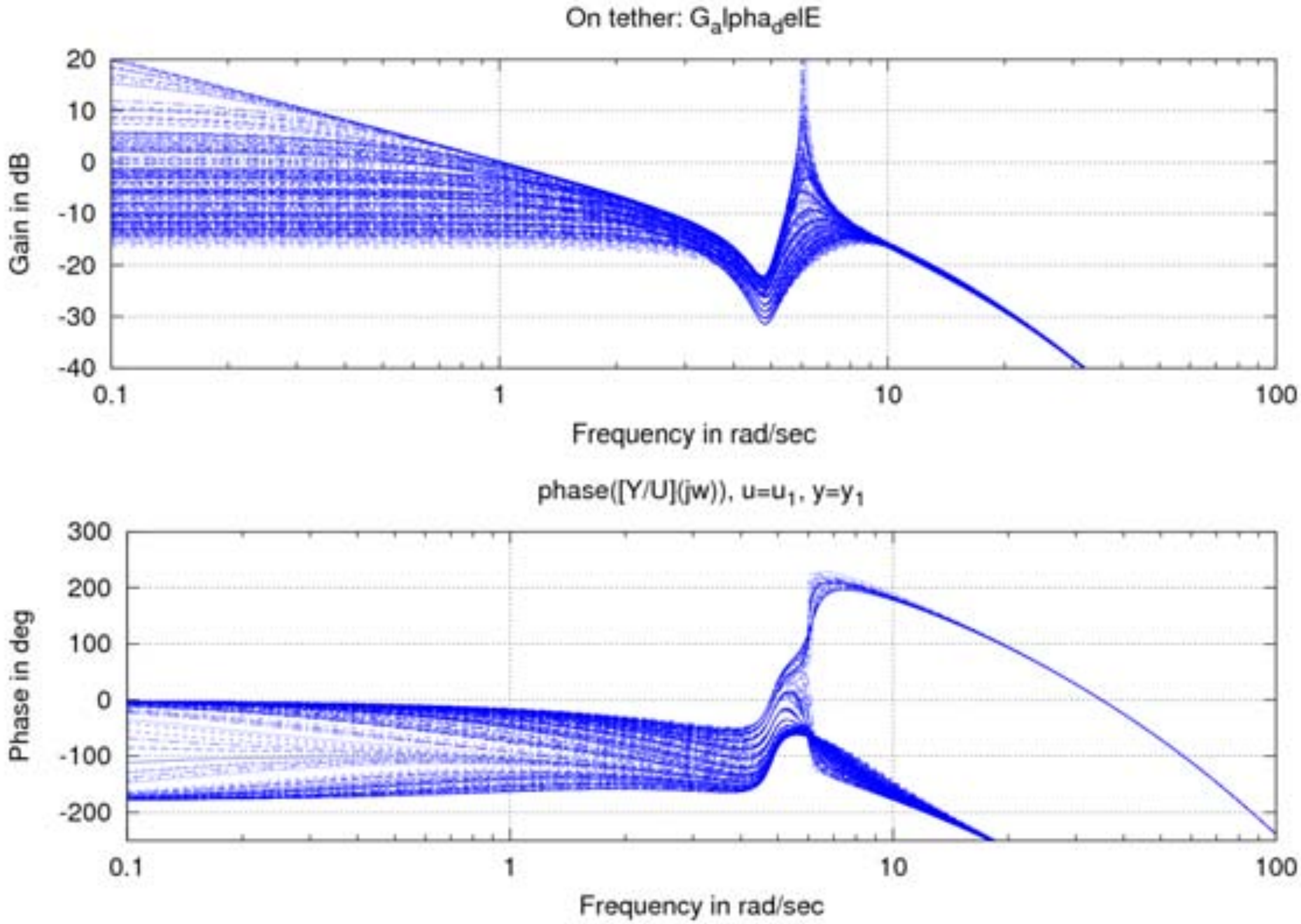
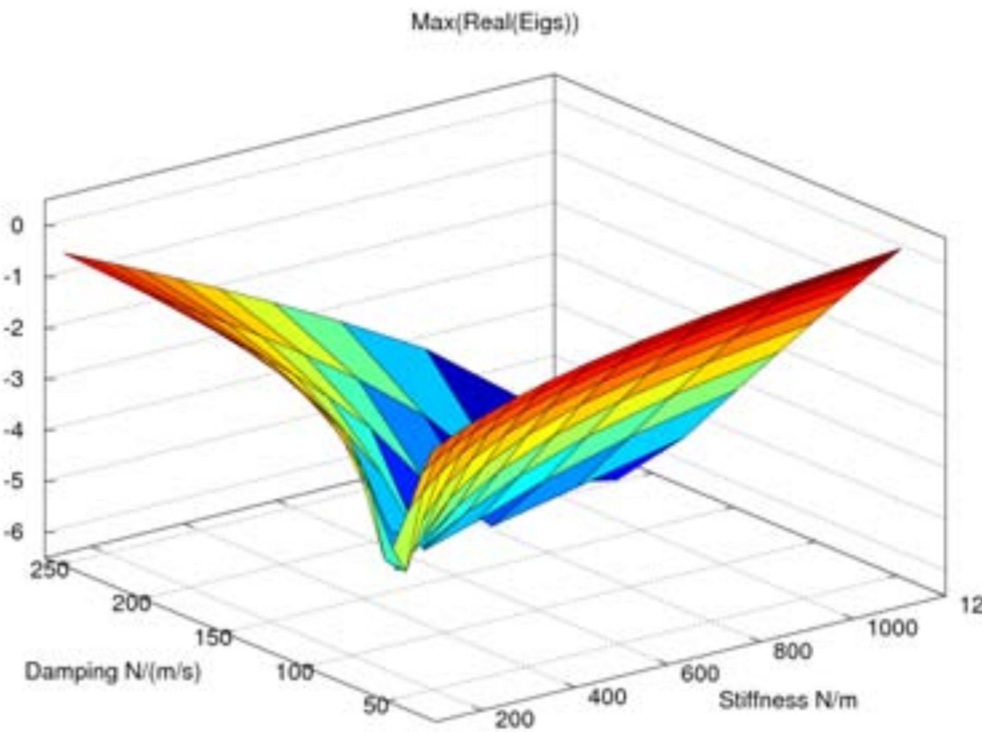
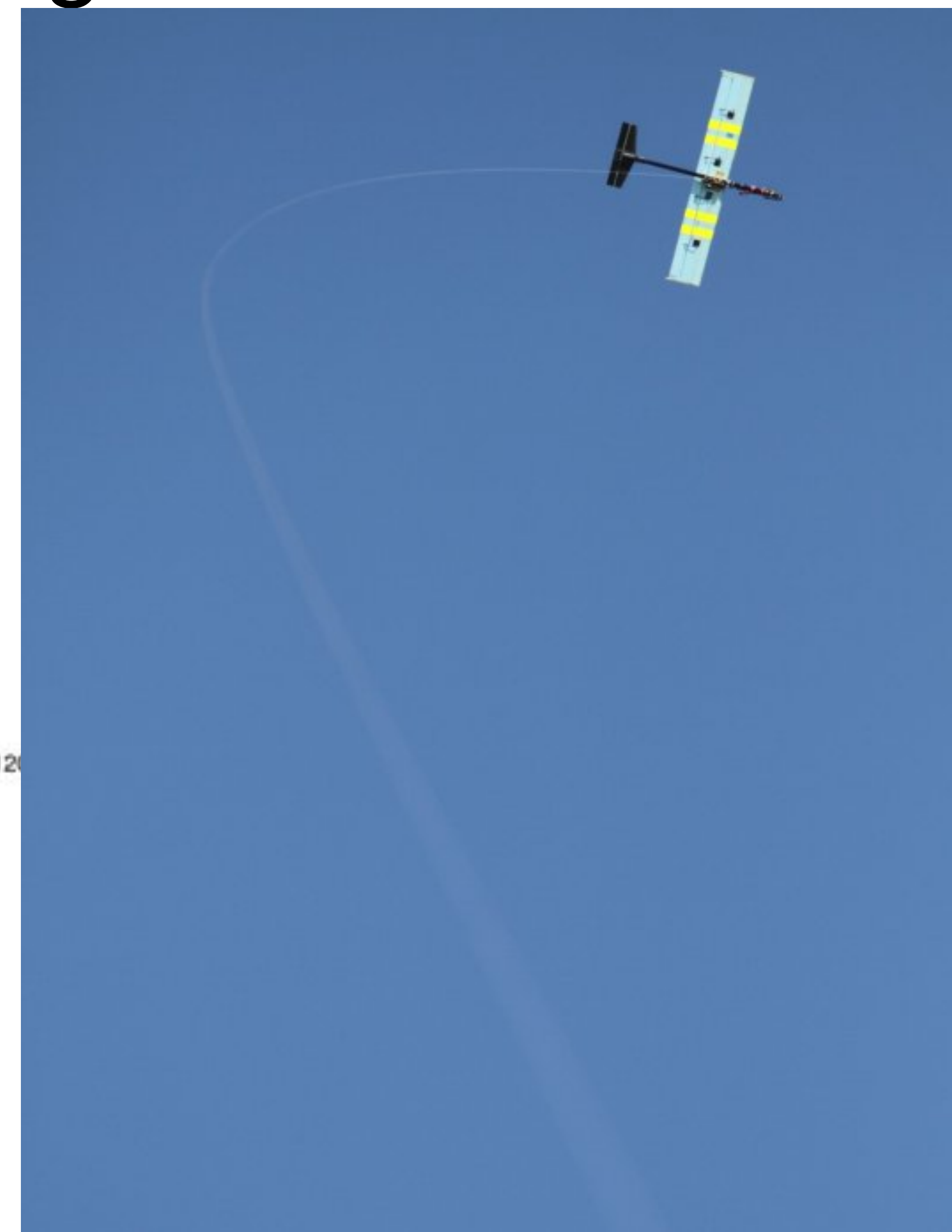


Effects of tether stiffness and damping





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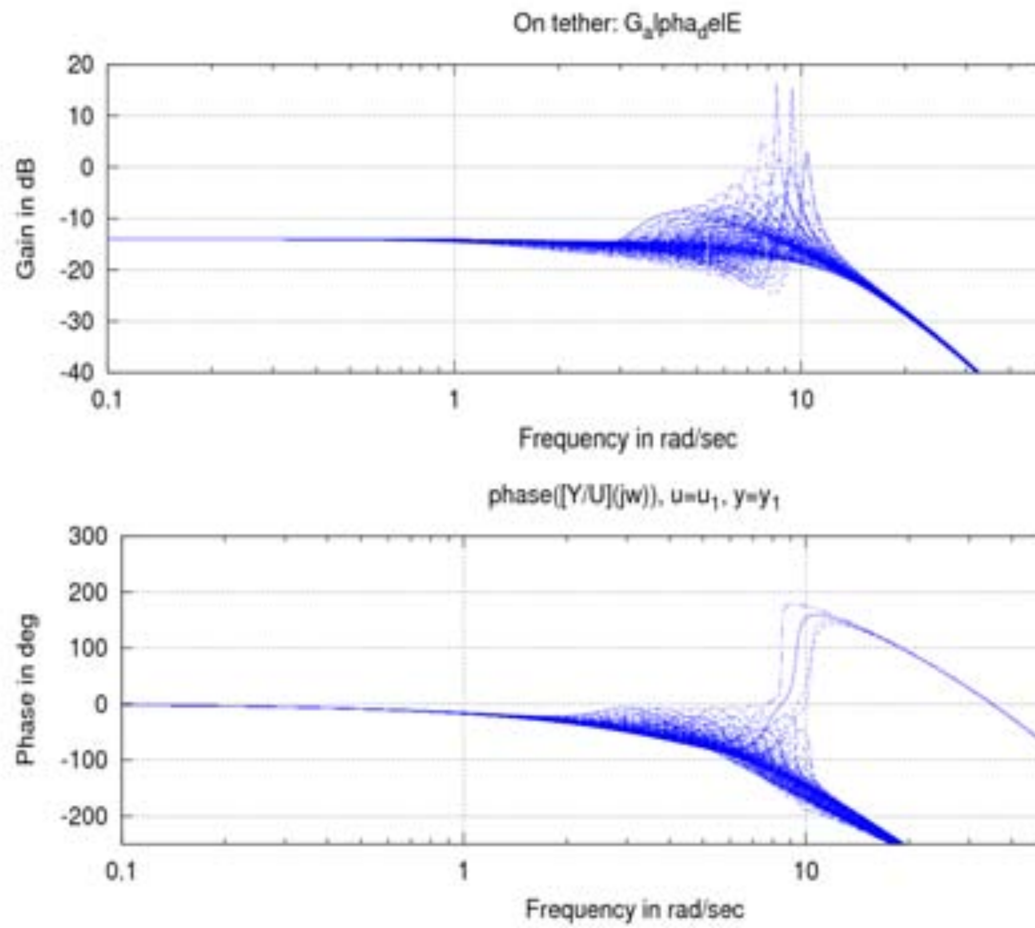

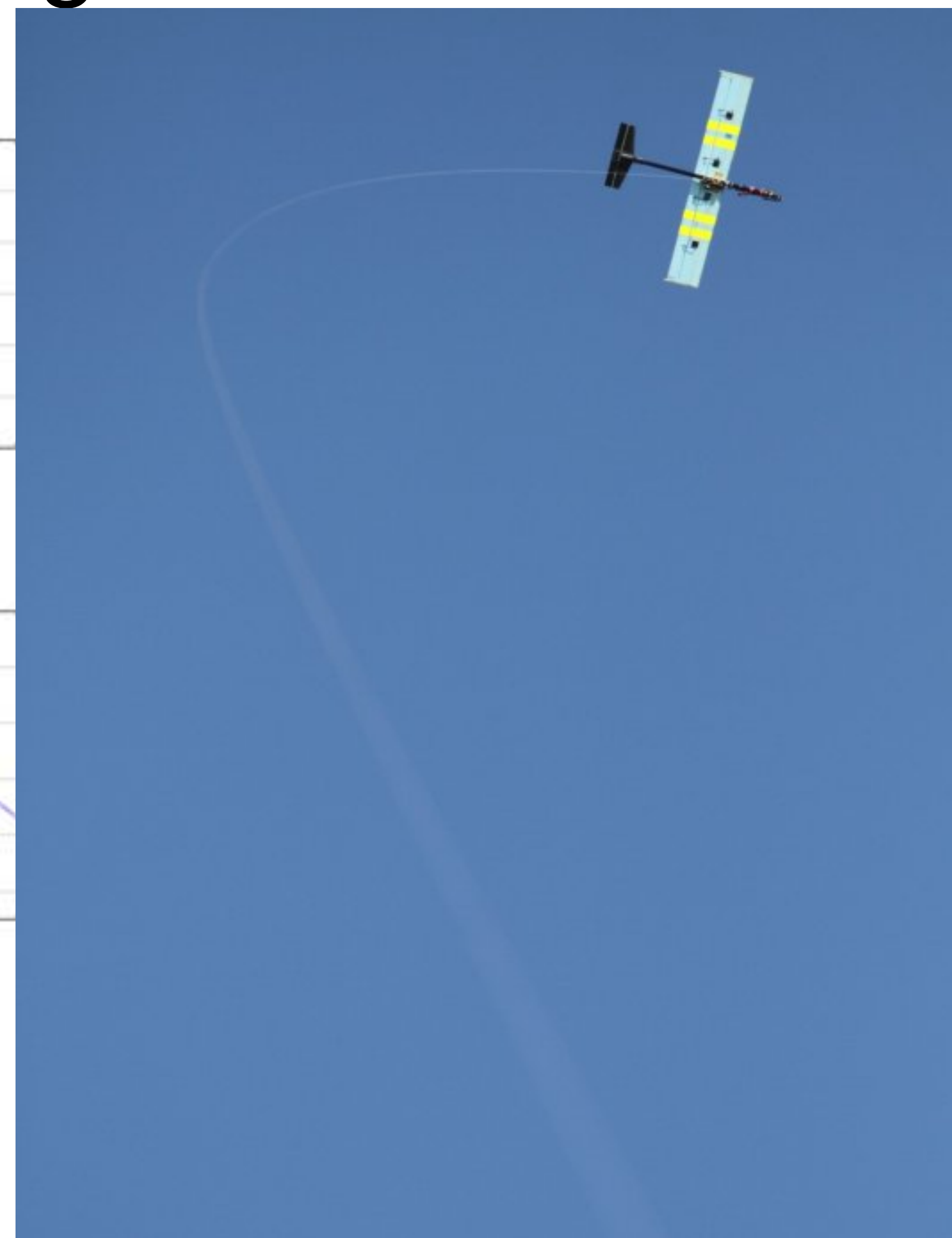

Exp. data: alpha oscillations detail

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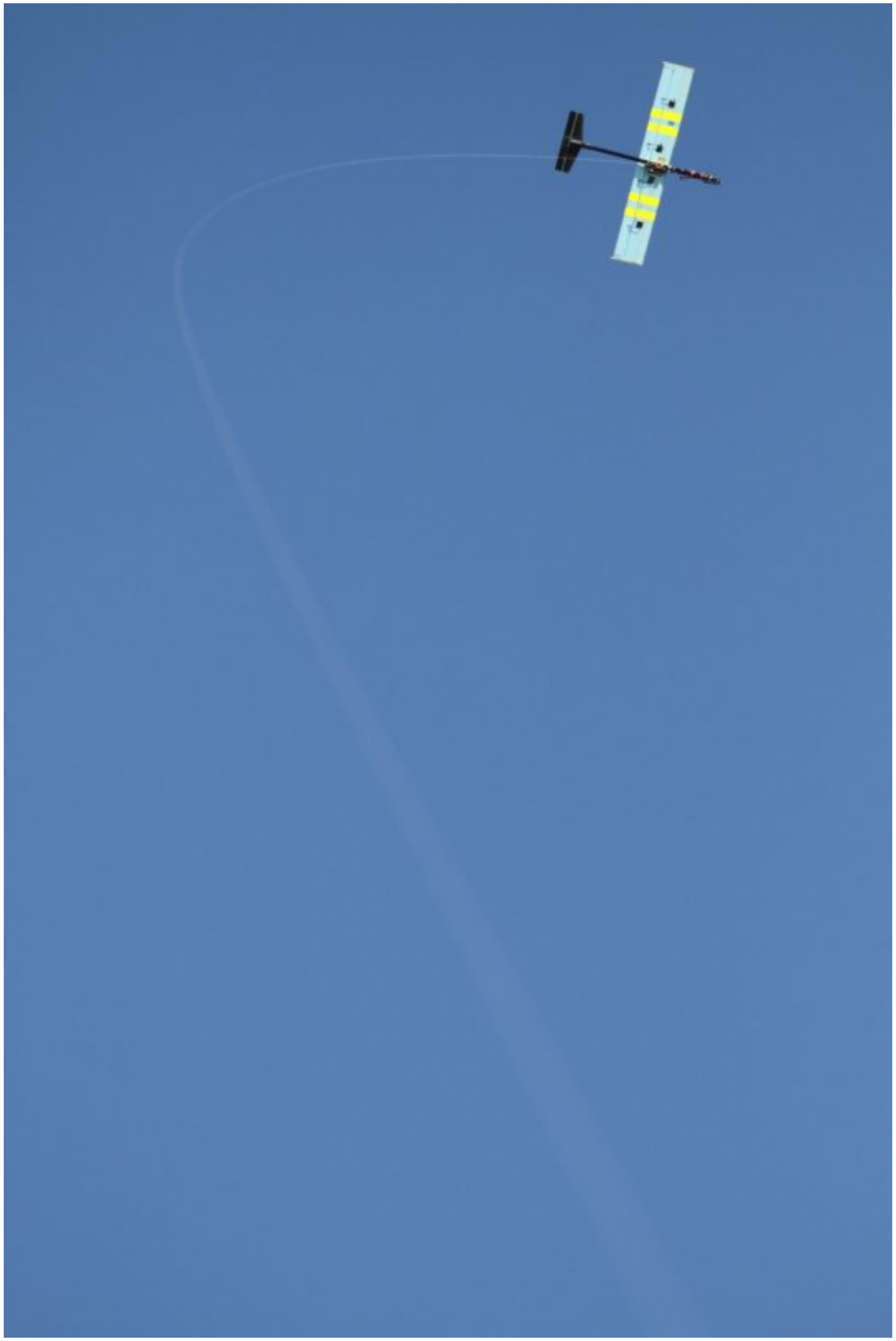


How to parametrize longitudinal control?

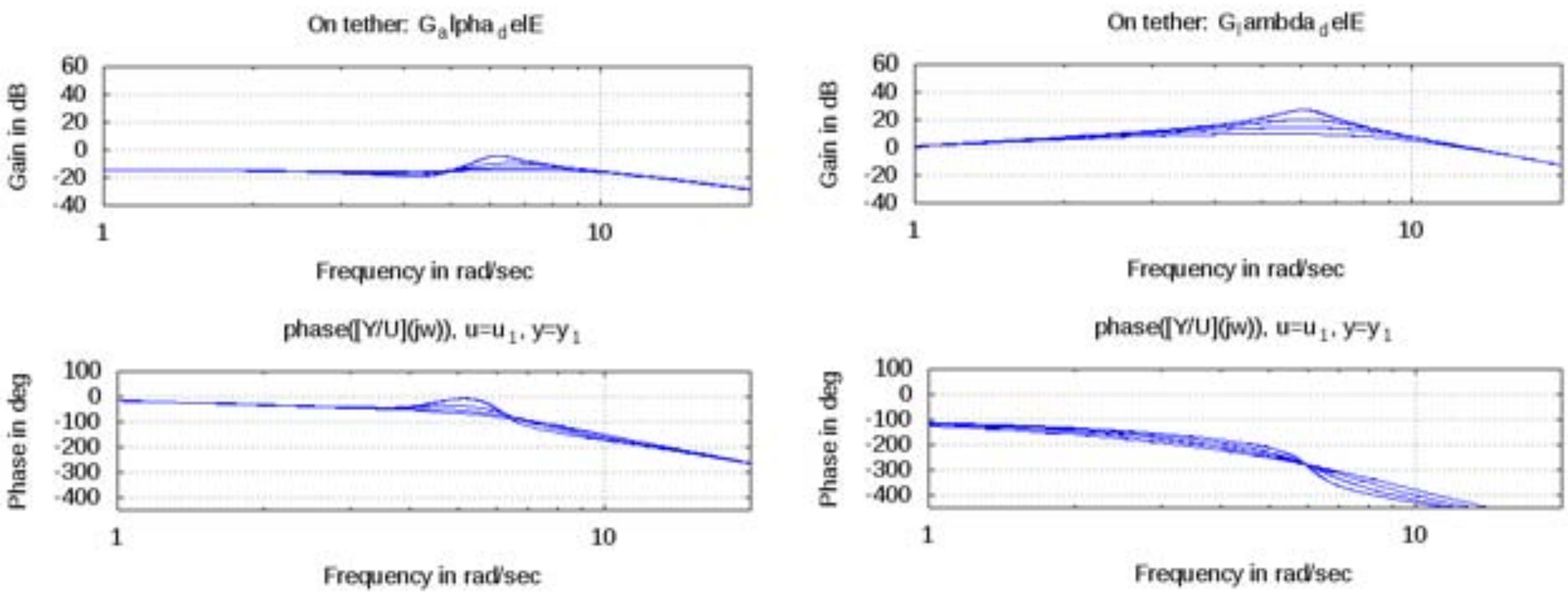
- Tension, lift, and alpha are tightly coupled
  - $L = .5\rho v^2 C_{L\alpha}\alpha$

Why regulate angle of attack α?

- advantages of feeding back in terms of alpha:
  - Alpha behavior is better understood than tether
  - Command sanity is easily determined without considering airspeed, etc.
  - Straightforward geometry/aero-101 maps a commanded steady tether tension to a target alpha
  - Experts have advocated treating alpha as the fundamental aircraft response variable (Rynaski)
- limiting factors on α regulation:
  - Actuator bandwidth
  - Estimate accuracy, especially vs. frequency
  - Tether dynamics still matter

Alpha response vs. tether response

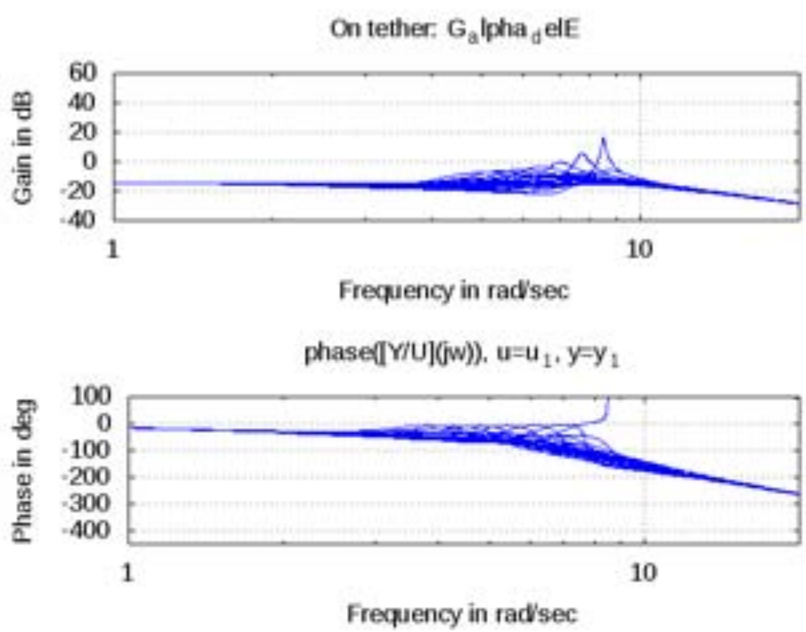
Stiffness 320 N/m, damping 20-100 N/m/s

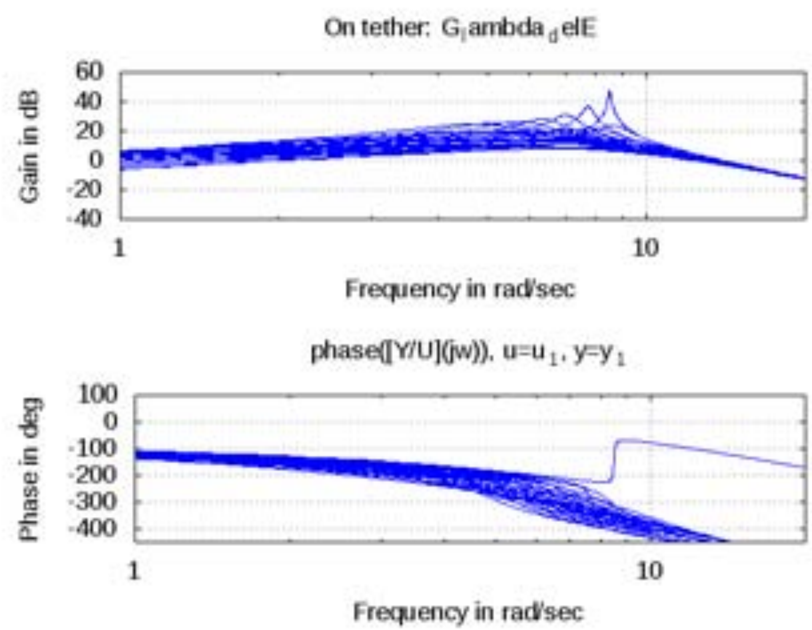


You can feedback off of either or both, but...

Alpha response vs. tether response

Stiffness 200-700 N/m, damping 20-100 N/m/s





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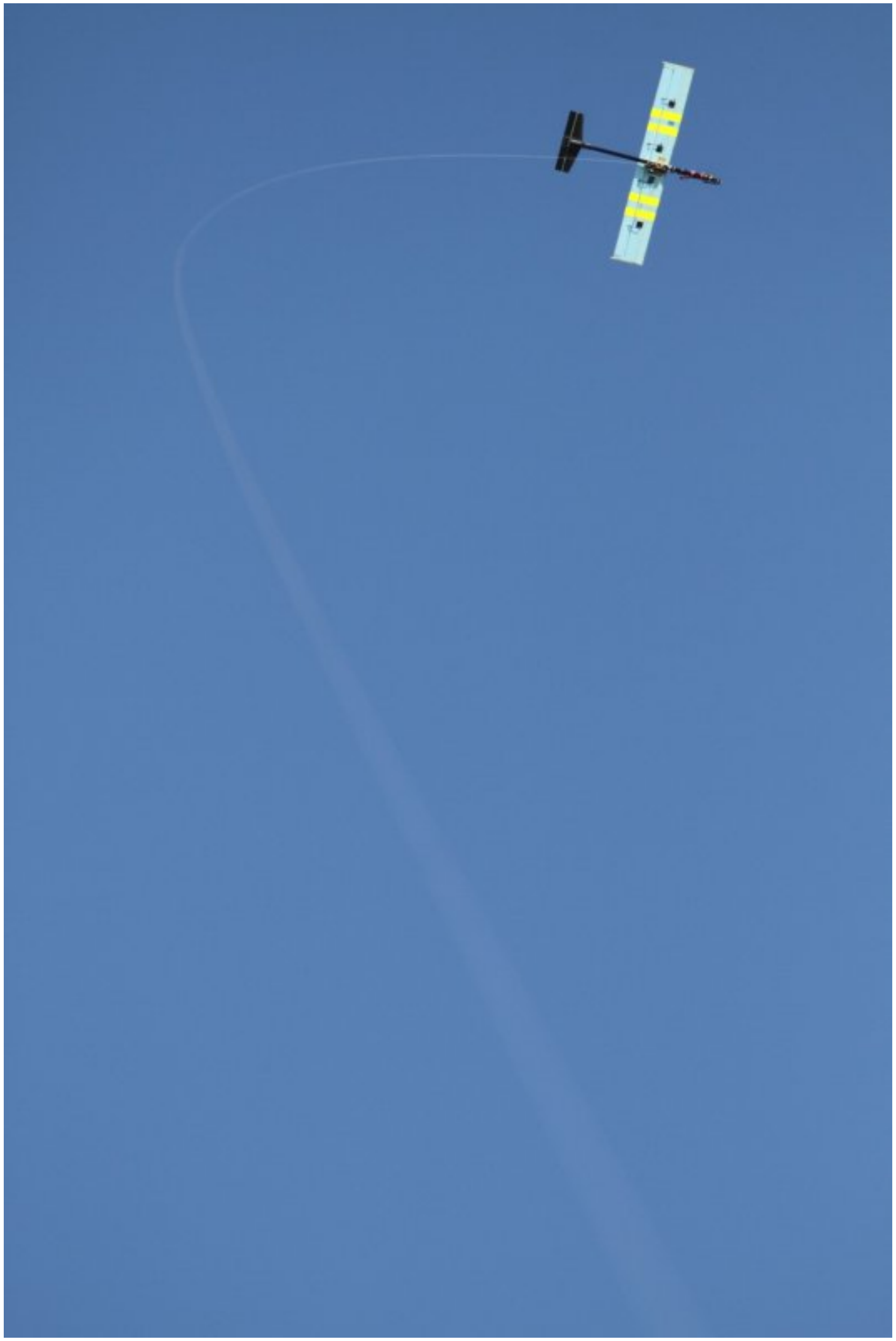
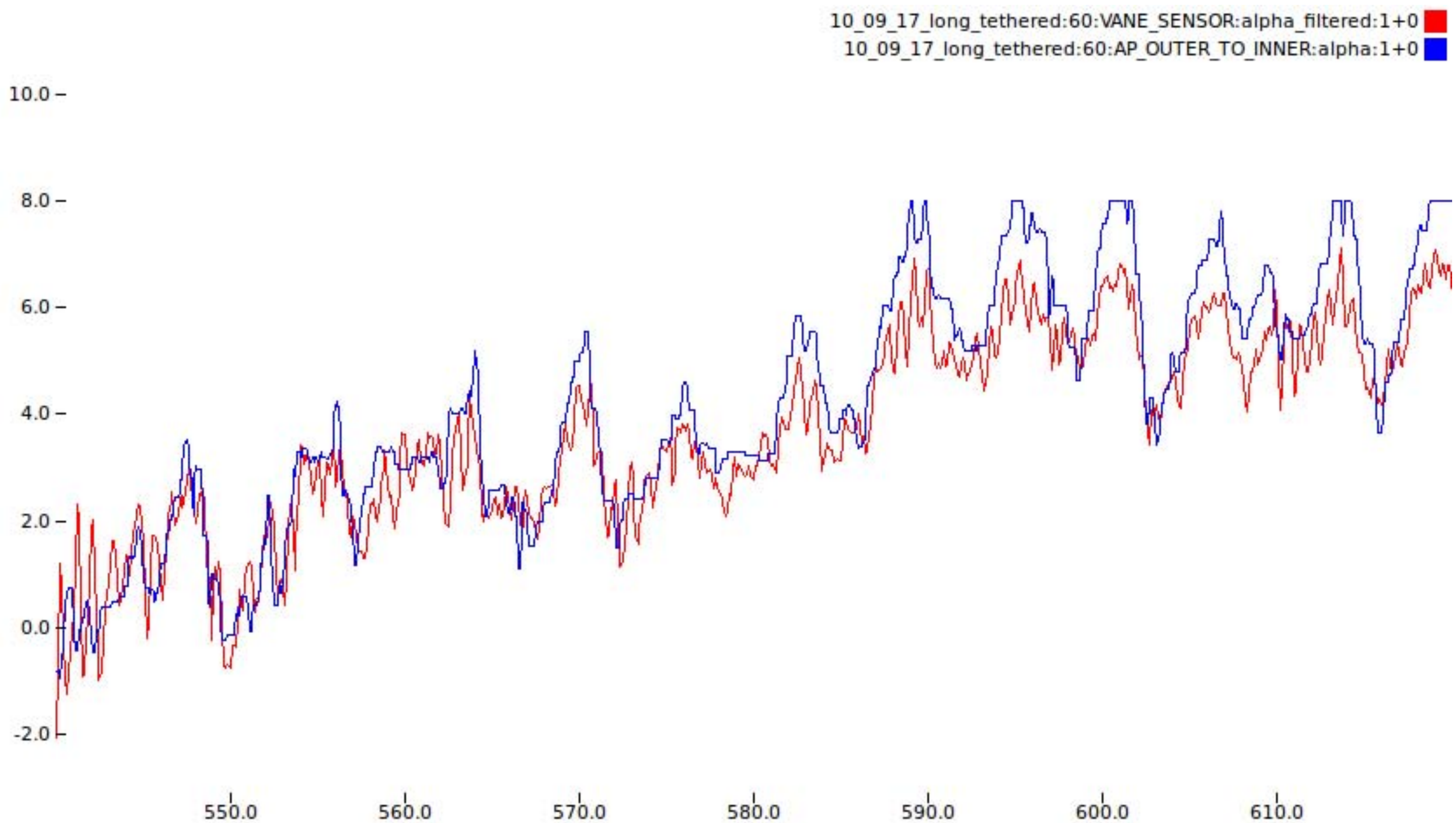


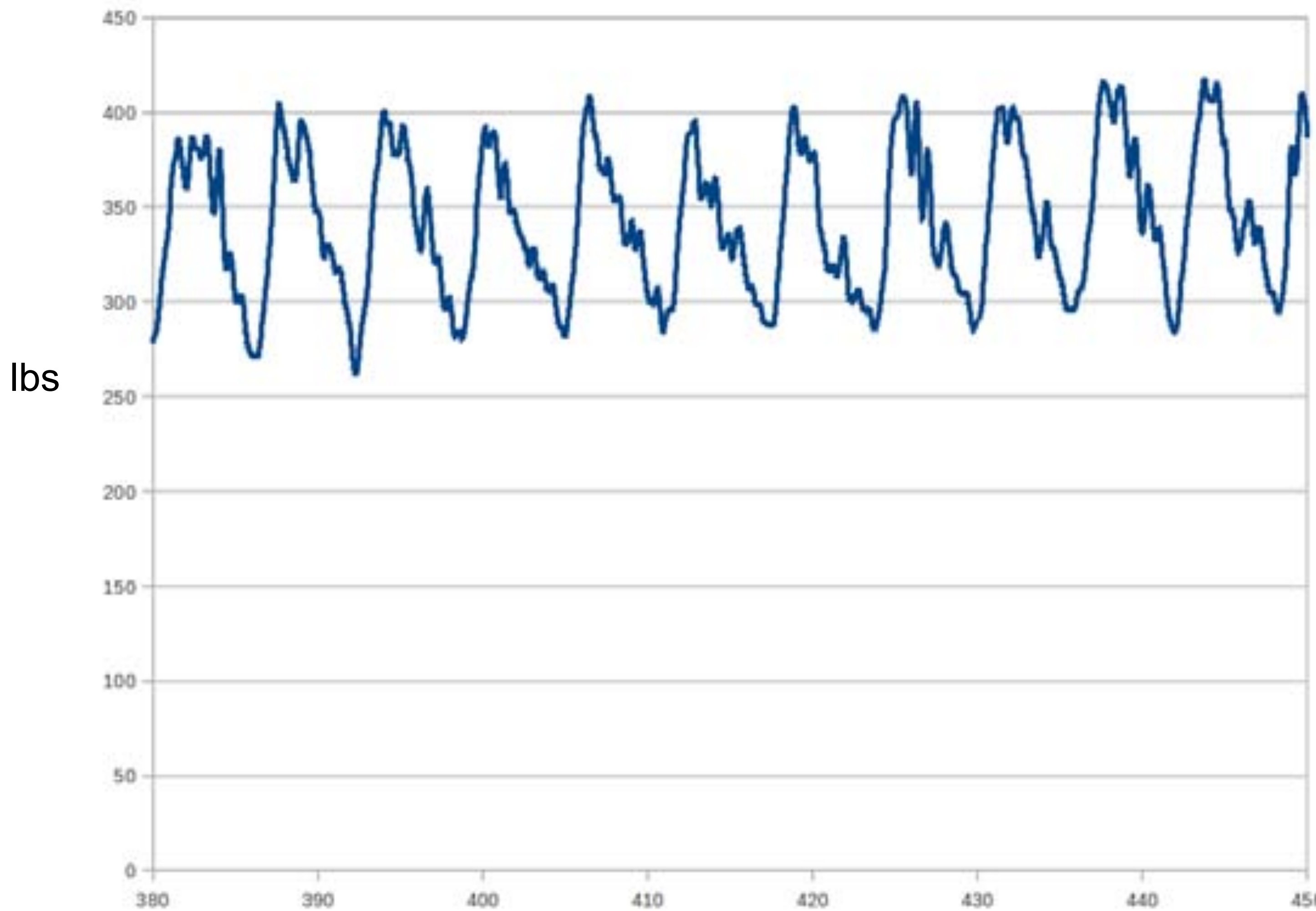
Regulating alpha: strongly stable aircraft

- Joby Arnold series
- Strong static response from elevator to alpha
- Feedforward is easy and successful, with **optional** PID cleanup

Alpha tracking: PD + Feedforward



Tension: pure feedforward for constant α

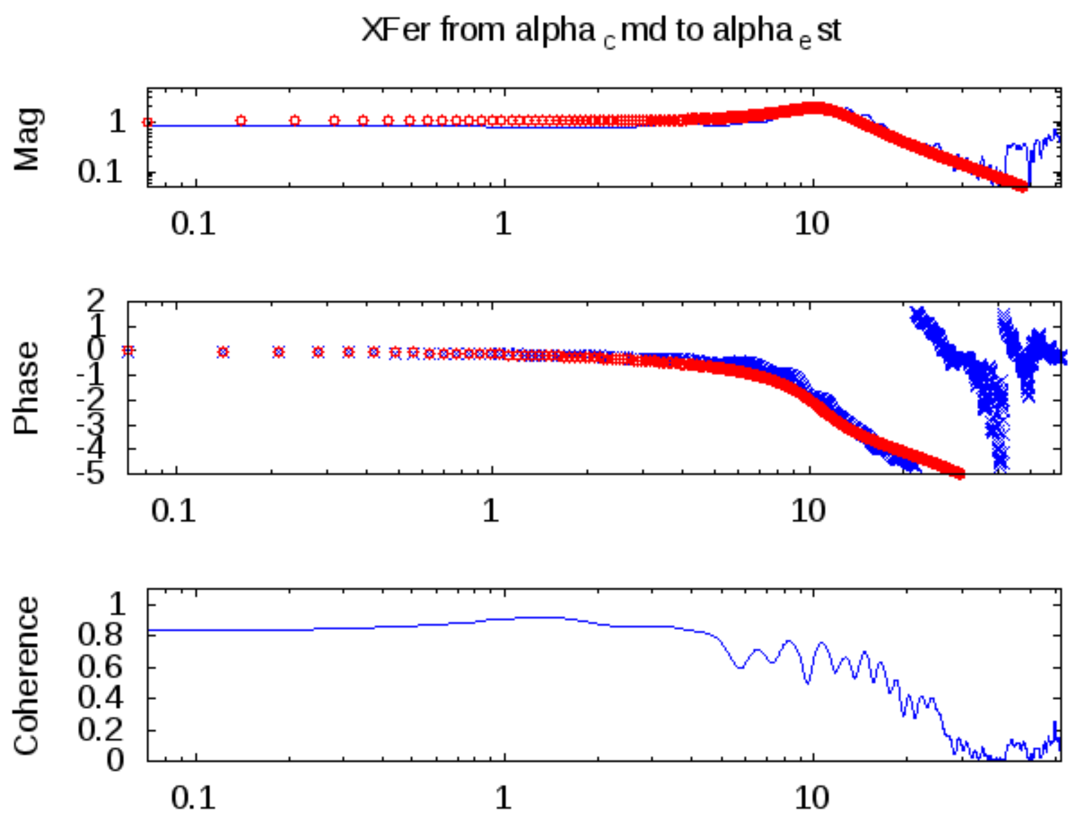


Regulating α: marginally stable aircraft

- Joby Mercury series
- Form an alpha estimate with vane data at low frequencies and gyro data at higher frequencies
  - Use of gyro data requires a short period model
  - Avoid high frequency vane dynamics, etc.
  - Tunable
- PID

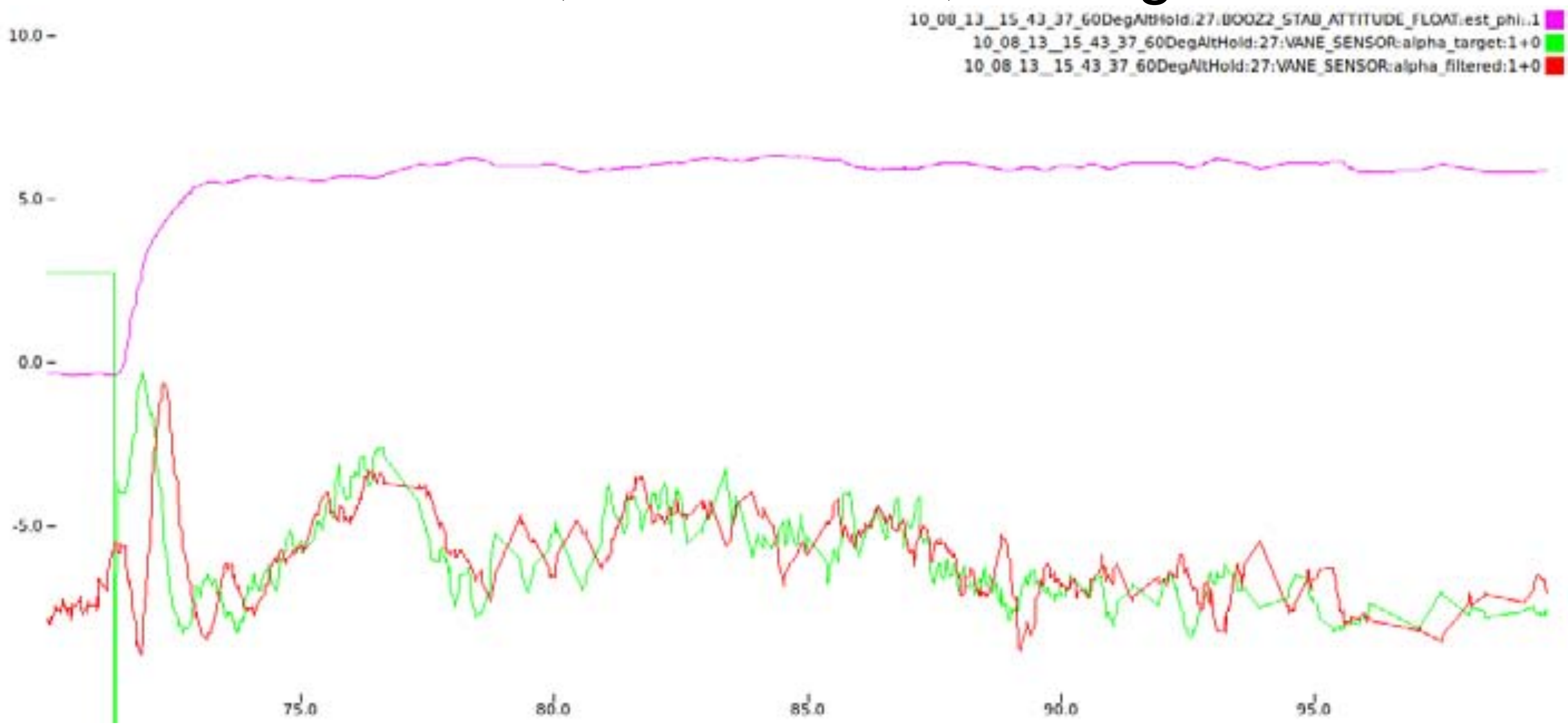
Regulating alpha: marginally stable aircraft

- Here: fixed canard, differential pitch thrust
- Red: fit with short period dynamics, motor lags



Regulating alpha: marginally stable, untethered

- Actuated canard, time domain, 60 deg. bank



The road not taken: elevator driven by tether tension sensor

- Simple, and it probably works at low bandwidth with a passively stable plant (we have not tried it)
- drawbacks: it is not robust to feed back on a plant with a variable resonance in the frequency range of that resonance, especially when lightly damped
  - Disturbances have significant power in this frequency range
- lack of explicit alpha control leaves open the possibility that the system is driven into stall / spin

Conclusions:

- **Longitudinal behavior must be well regulated** to avoid structural fatigue, overload, disruption of steering, or stall/spin
- A four-state short-period model (built upon the conventional two-state short period approximation) is consistent with data so far
- Closed-loop longitudinal behavior of Joby designs is good and getting better...

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Acknowledgements:

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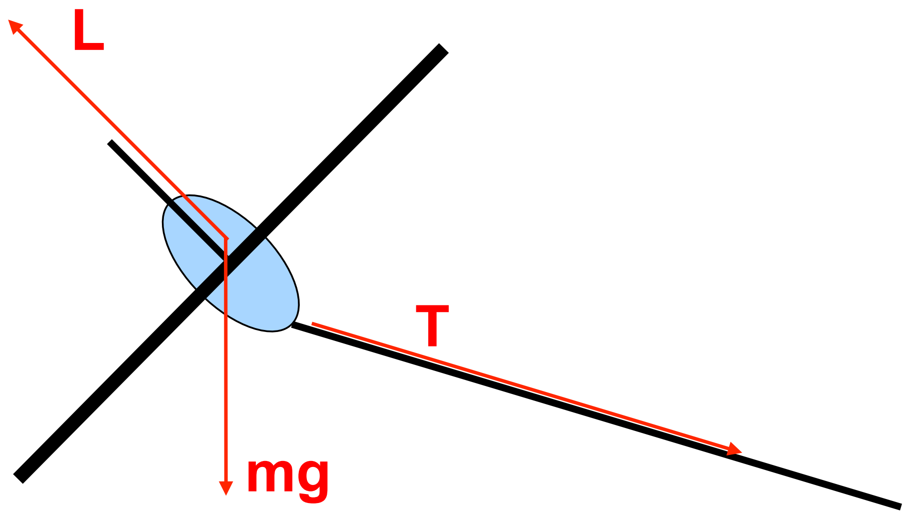
  - The controls team, especially Matt Peddie who set up a lot of alpha control
  - Allen Ibara (embedded systems and photography)
- alpha image courtesy Wikimedia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