Angle of Attack Specification

Project Redshift Internal Documentation

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1 Introduction

This paper presents documentation of the data and process used to define an initial specification for the maximum angle of attack rockets experience during flight.

Rockets experience a handful of forces, most of them along the rocket's axis and most of them very knowable. The forces off of the rocket's axis, however, are much more ambiguous. The simulations group is often asked the question of what aerodynamic forces and moments a rocket will feel perpendicular to it's axis. If known, those forces and moments could be applied to calculations on the strength of different structures of the rocket, in order to evaluate a factor of safety.

2 Background

Normal force can be nondimensionalized similar to drag force, with one modification. Since the normal force depends on the angle between the rocket and the free stream velocity, it is useful to talk about $C_{N\alpha}$, the derivative of normal force coefficient with respect to angle of attack. The equations for drag and normal force coefficients are given below.

$$F_D = \frac{1}{2} * \rho * A_{ref} * CD * v^2 \tag{1}$$

$$F_N = \frac{1}{2} * \rho * A_{ref} * C_{N\alpha} * \alpha * v^2 \tag{2}$$

Normal force scales linearly with angle of attack (at least for small angles) and quadratically with velocity. This is incrediby problematic, because it means that using conservative estimates for angle of attack and velocity can give forces that are orders of magnitude too high. Thus, knowing a reasonable estimate for this input pair is crucial in defining a specification that factors of safety could be based off of.

3 Angular rate data processing

3.1 FCB Gyro scaling

There was a bug in the offload script to take data off of FCB's, this was figured out in March 2022. Thus all FCB angular rate data offloaded prior to then was scaled (divided) by a factor of 4. This is why we test things.

3.2 FCB sensor coordinates

The FCB is the main board whose data is shown below, and it's coordinate axes are not entirely straightforward. The axes of different sensors are shown in the figure below. For the Inertial Measurement Unit (IMU) and gyroscope, the y-axis is to the right in the figure. This corresponds with vertical during flight, as the FCB is mounted antenna up.

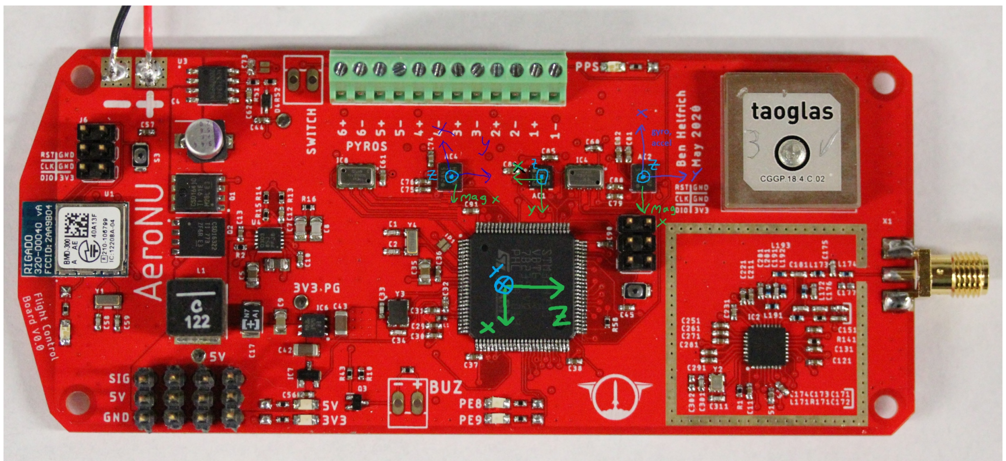

Figure 1: FCB Axes

3.3 Data offset and zero

Micro electro-mechanical (MEMs) gyroscopes tend to suffer from zero drift over time. To combat this issue, an offset was applied to each axis of a flight's data, such that the average value over the initial data points (while on the launch rod) was zero. For the purpose of integrating, the initial orientation of the rocket was set as [0, 1, 0], ie. vertical, with the y axis being up.

3.4 Angular math

The bulk of the math for this is the method used to integrate the gyroscope rates - to go from angular velocity to angular position. This math is handled by the ahrs library for python, linked here: https://ahrs.readthedocs.io/en/latest/filters/angular.html. The reason this math is more complicated than simply numerically integrating is that the rotation in all three axes is coupled. The function ahrs.filters.AngularRate takes in angular rate data in three axes and returns angular position over time in quaternion format. Quaternions are a mathematically convenient way of representing angles, but are not physically interpretable. It is easiest to interpret the angular position data if it is converted into angles off of an axis. The function ahrs.common.orientation.q2R inputs a quaternion and outputs a rotation matrix. That rotation matrix can be multiplied by a unit vector of the rocket's initial position (recall, [0, 1, 0]) to obtain that vector's components along each axis. From there, the angle off of vertical can be computed using trigonometry (acos(y component)). This angle will be called the pitch angle - the difference in orientation from the rocket's starting angle. It isn't necessarily equal to the angle of attack, as the rocket could (and likely is) moving partially sideways instead of straight up. For the purposes of this analysis, the two are assumed almost equivalent, with some exceptions.

3.5 For posterity

This data processing was run on May 9th 2022, and may be subject to change based on future analysis. All the code and input files used for this analysis are in the AeroNU gitlab, specifically located here: https://gitlab.com/aeronu/dollar-per-foot/python-avionics/-/tree/bjorn-flight-processing. The data, code, and images were committed and pushed as seen in this report to commit 99bdd304cc708c3f43498cfc9a9005c9a9395054.

4 FCB Data Review

This club was busy in 2021 and that is evident here. There were 7 total successful flights of FCB data, all of which collected angular rate data. 5 flights were on Travel Request Denied (TRD), one was on SuperGuppy, and one was on Carby. A goose was flown once on TRD in November, among other times. The data from this is questionable as it doesn't align very well with the FCB's data. This could be due to an incorrect sampling time.

4.1 FCB 3-20-21 TRD

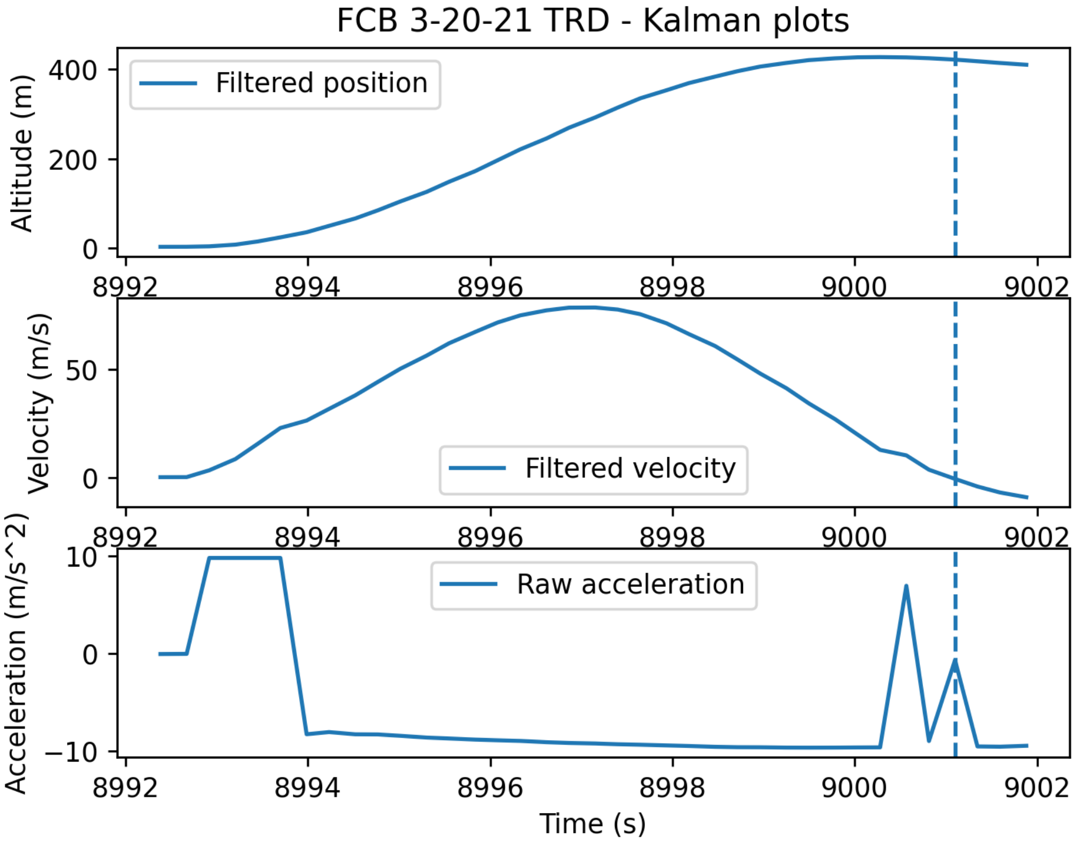

Figure 2: FCB 3-20-21 TRD - Kalman plots

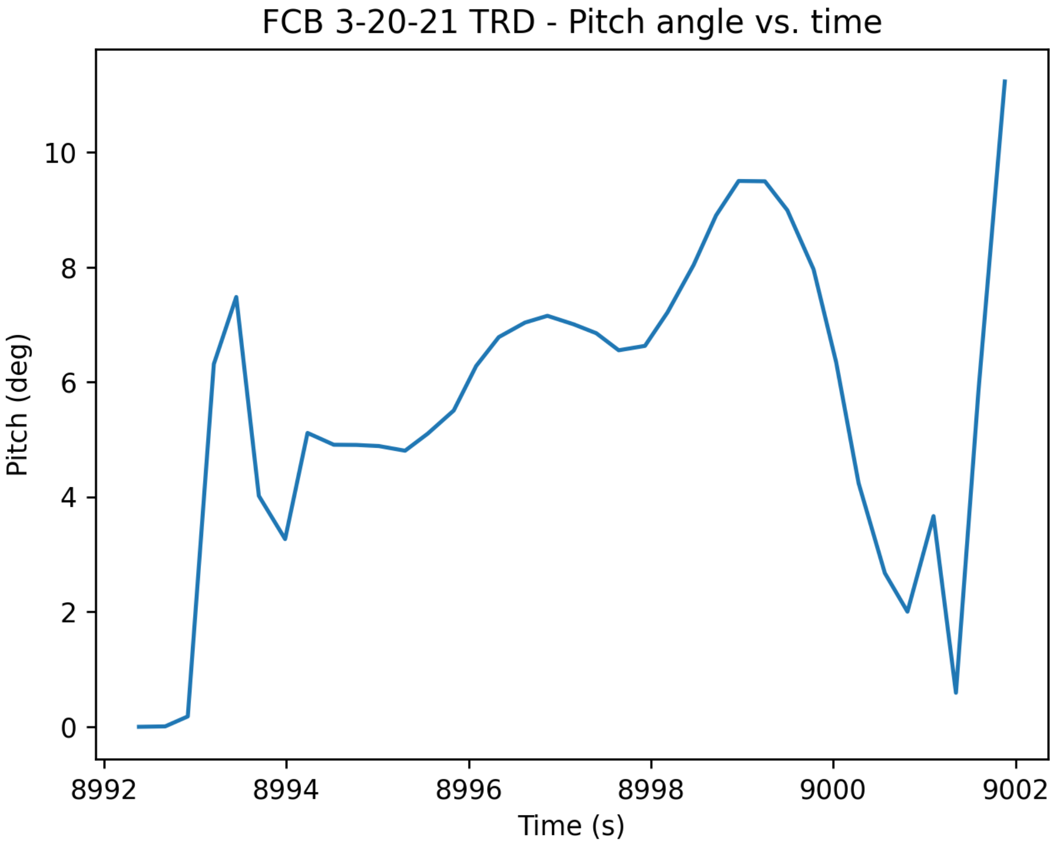

Figure 3: FCB 3-20-21 TRD - Pitch angle vs. time

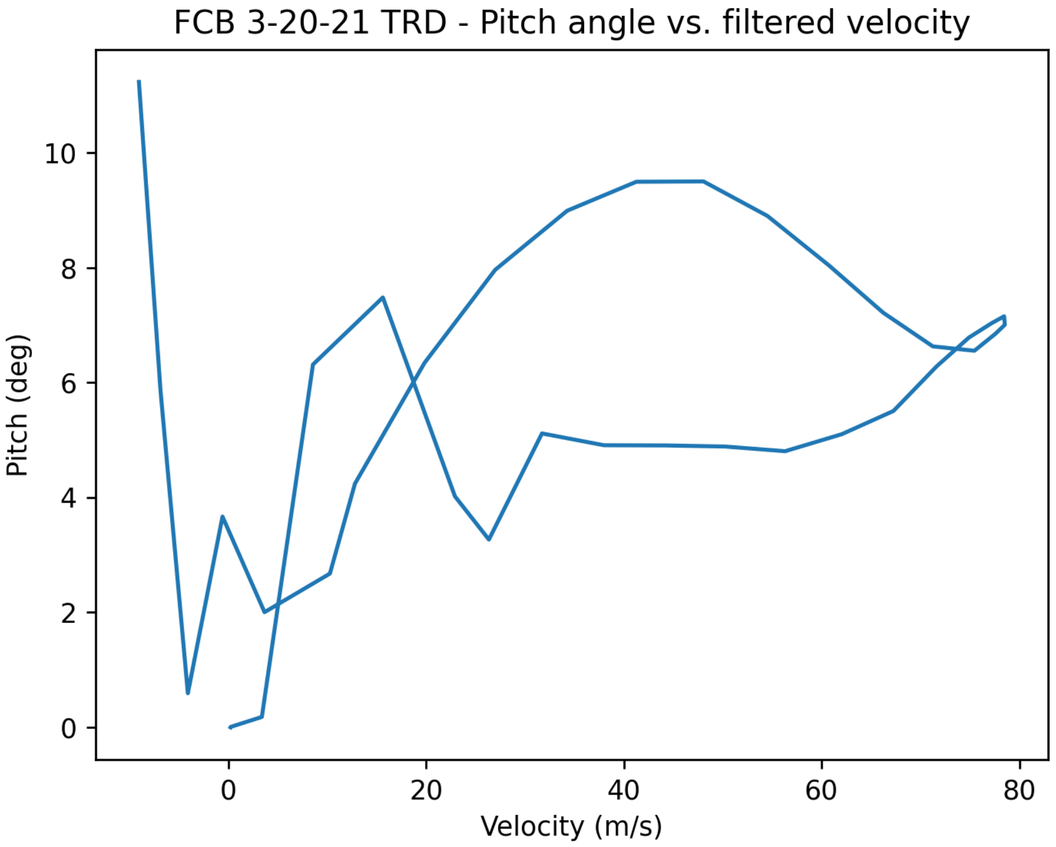

Figure 4: FCB 3-20-21 TRD - Pitch angle vs. filtered velocity

4.2 FCB 5-15-21 TRD

Figure 5: FCB 5-15-21 TRD - Kalman plots

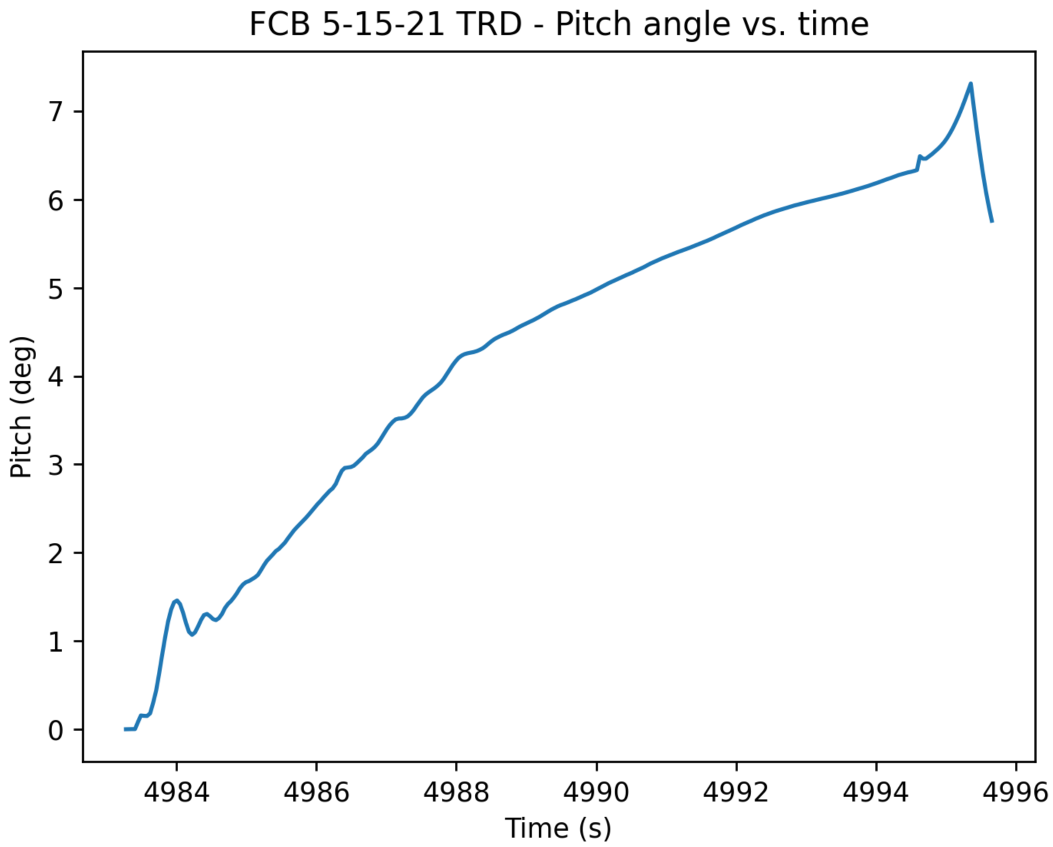

Figure 6: FCB 5-15-21 TRD - Pitch angle vs. time

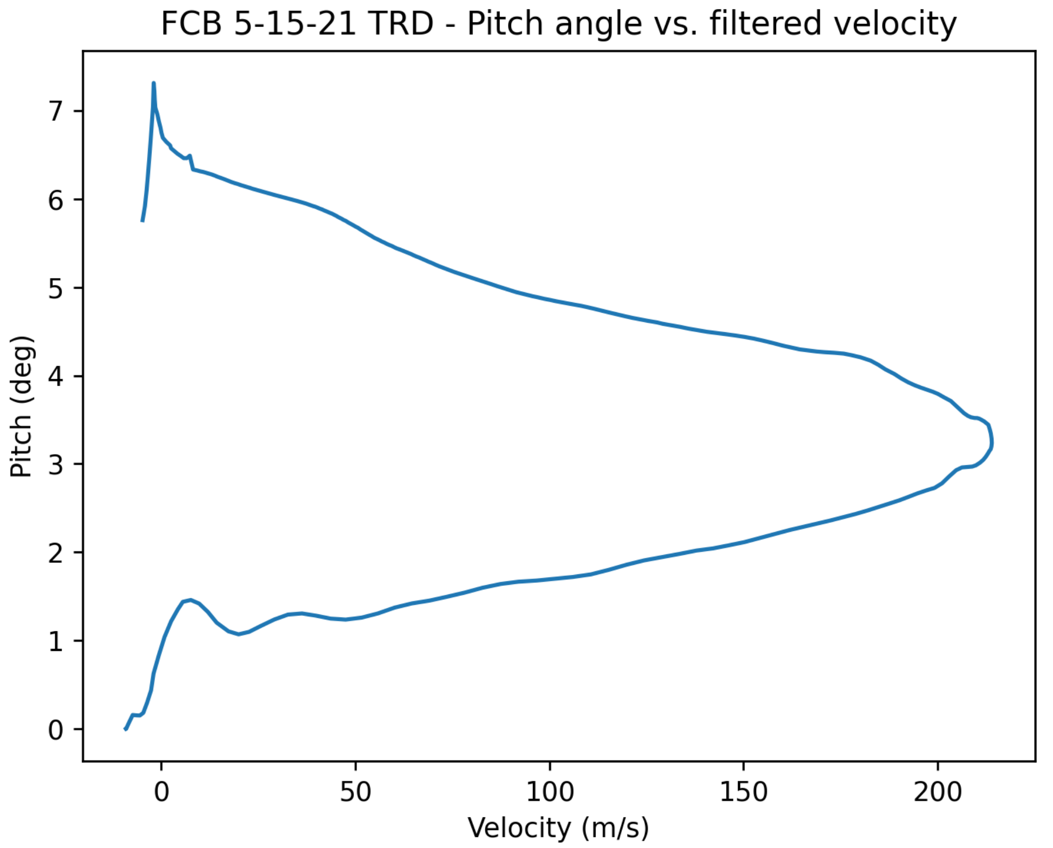

Figure 7: FCB 5-15-21 TRD - Pitch angle vs. filtered velocity

4.3 FCB 6-20-21 TRD

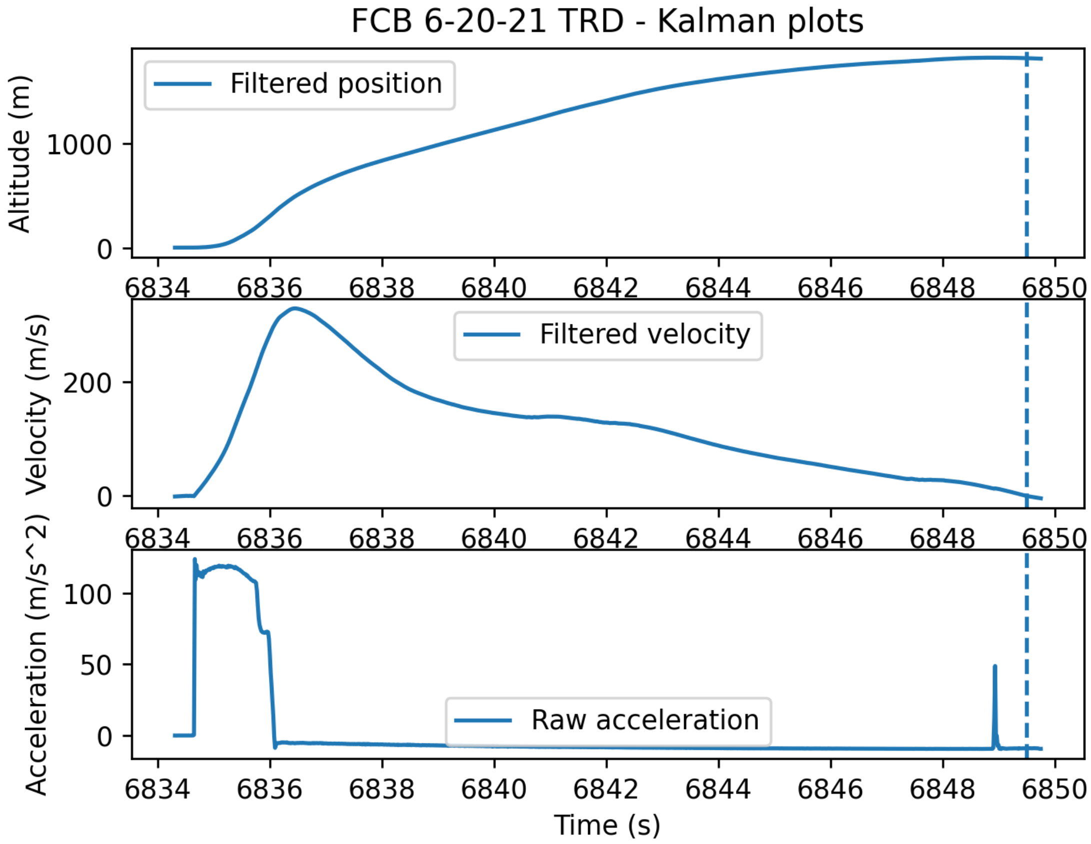

Figure 8: FCB 6-20-21 TRD - Kalman plots

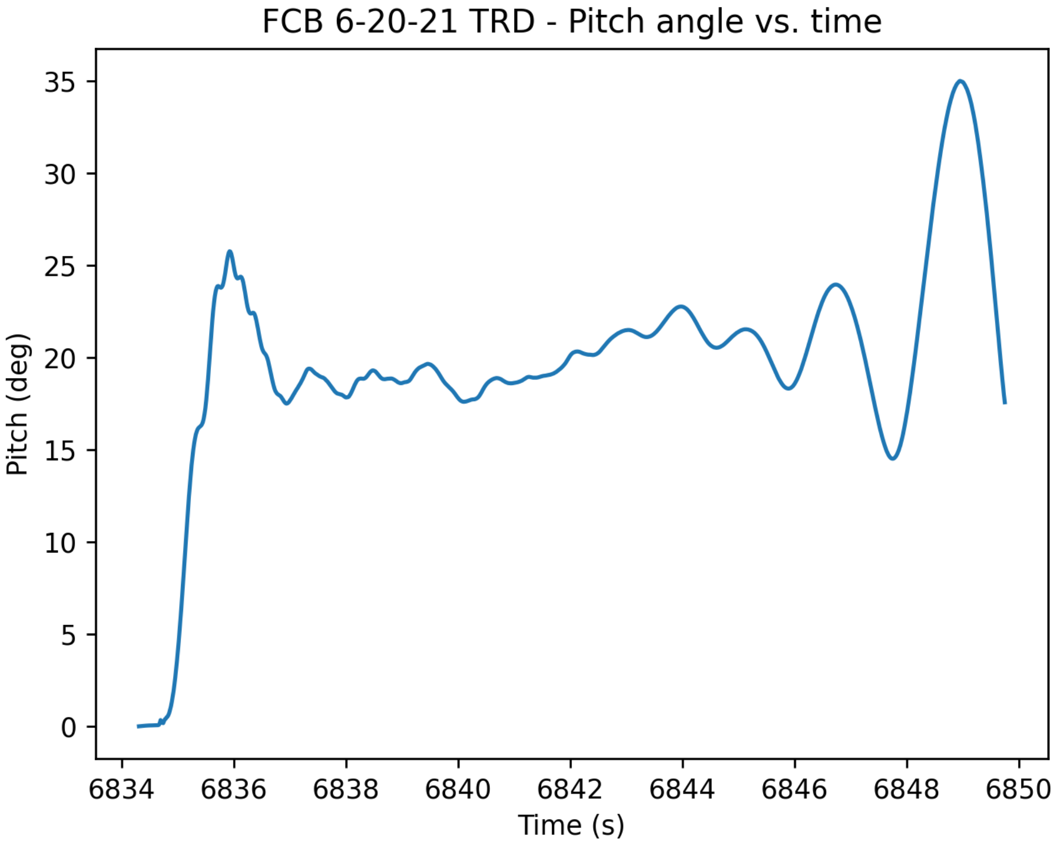

Figure 9: FCB 6-20-21 TRD - Pitch angle vs. time

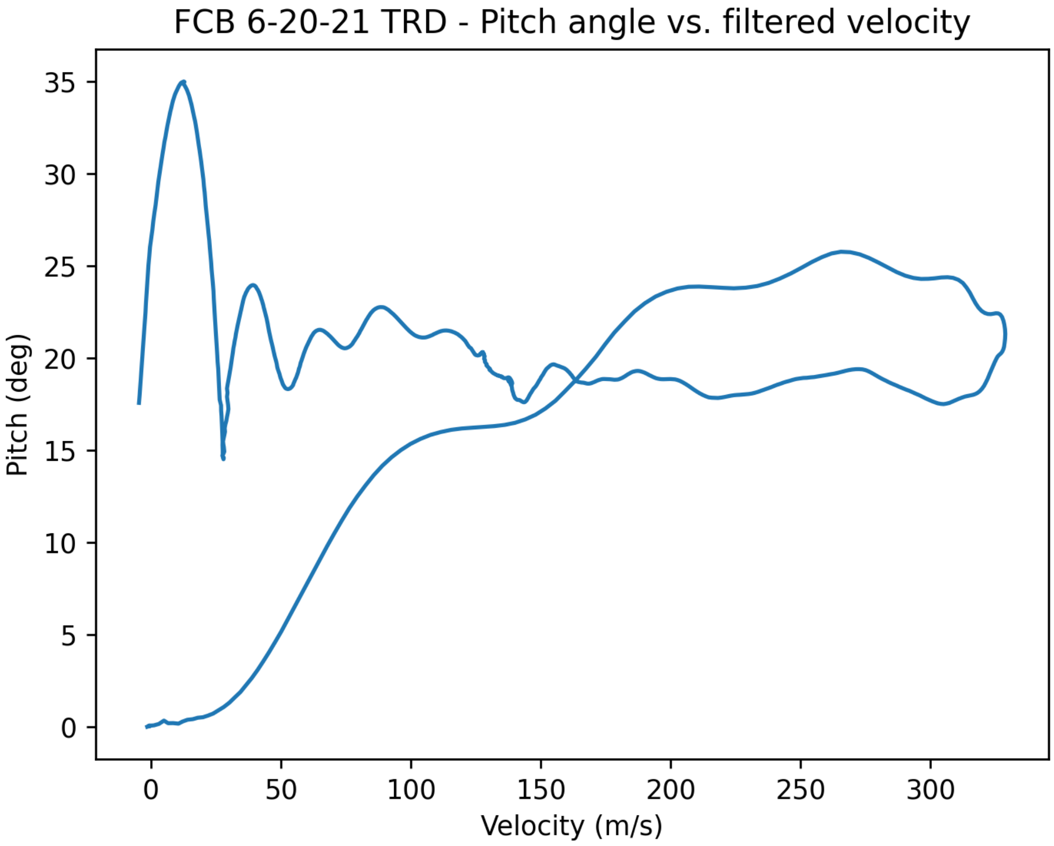

Figure 10: FCB 6-20-21 TRD - Pitch angle vs. filtered velocity

4.4 FCB 11-14-21 SuperGuppy

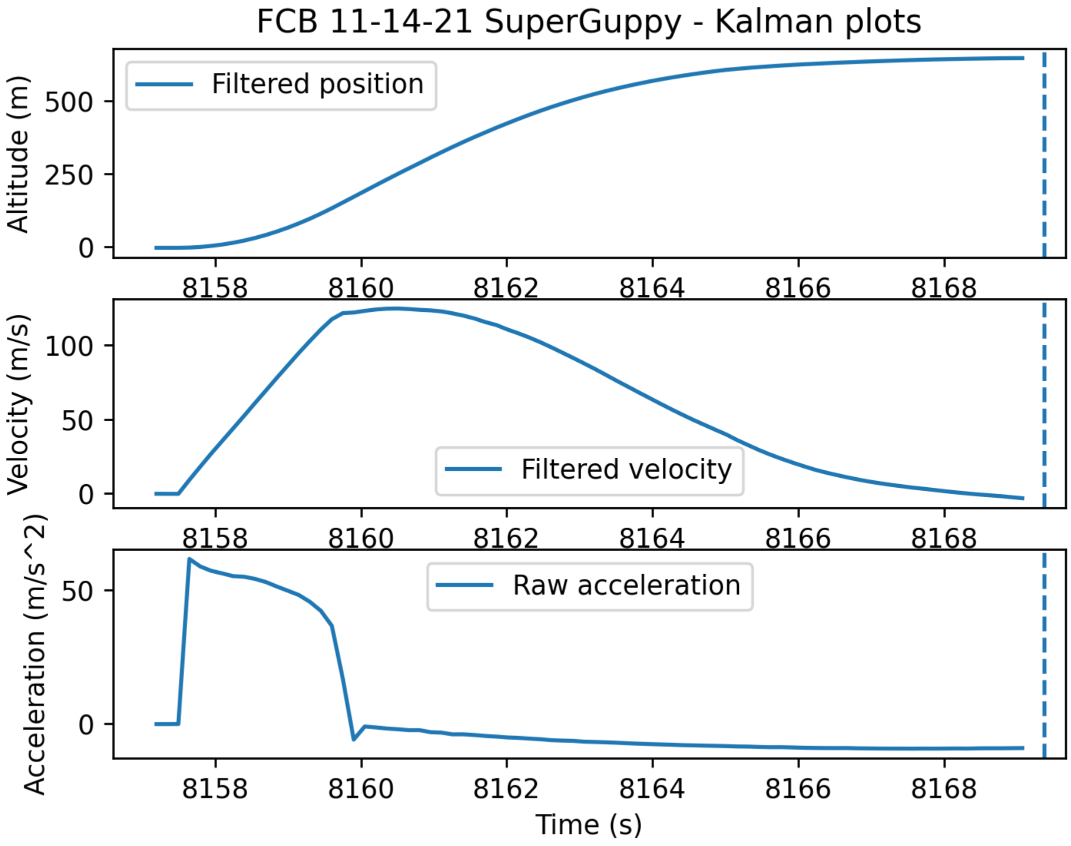

Figure 11: FCB 11-14-21 SuperGuppy - Kalman plots

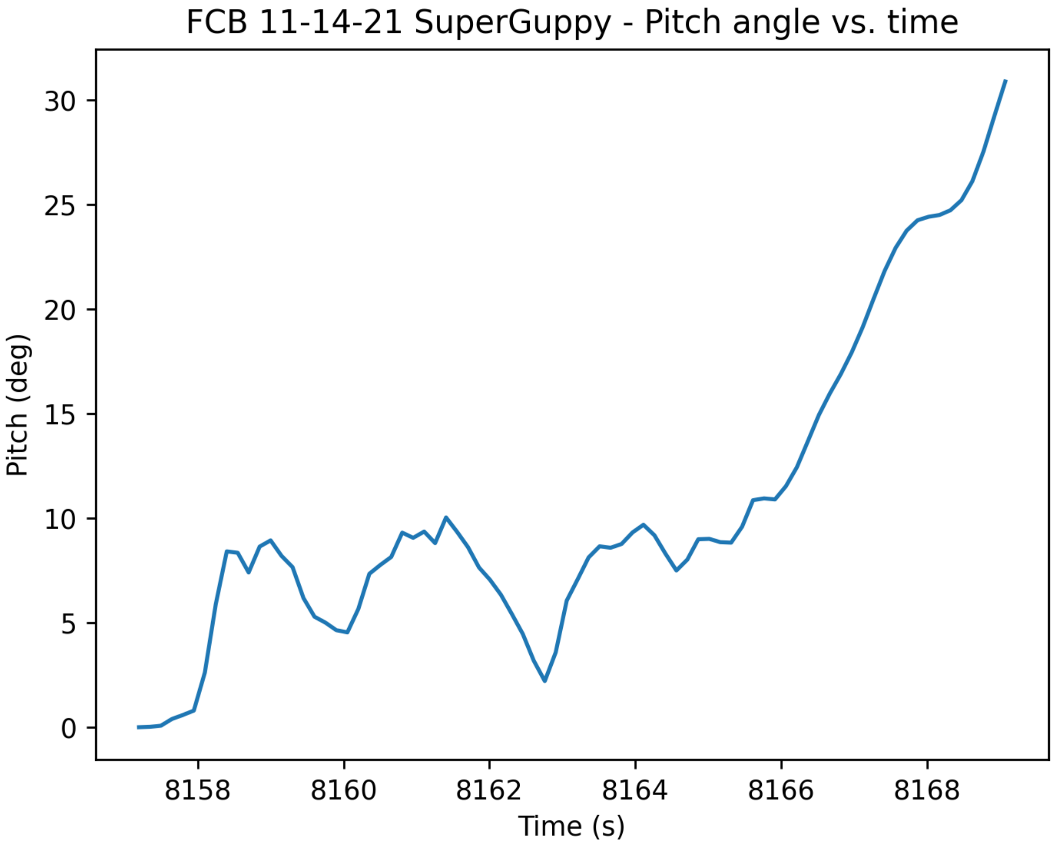

Figure 12: FCB 11-14-21 SuperGuppy - Pitch angle vs. time

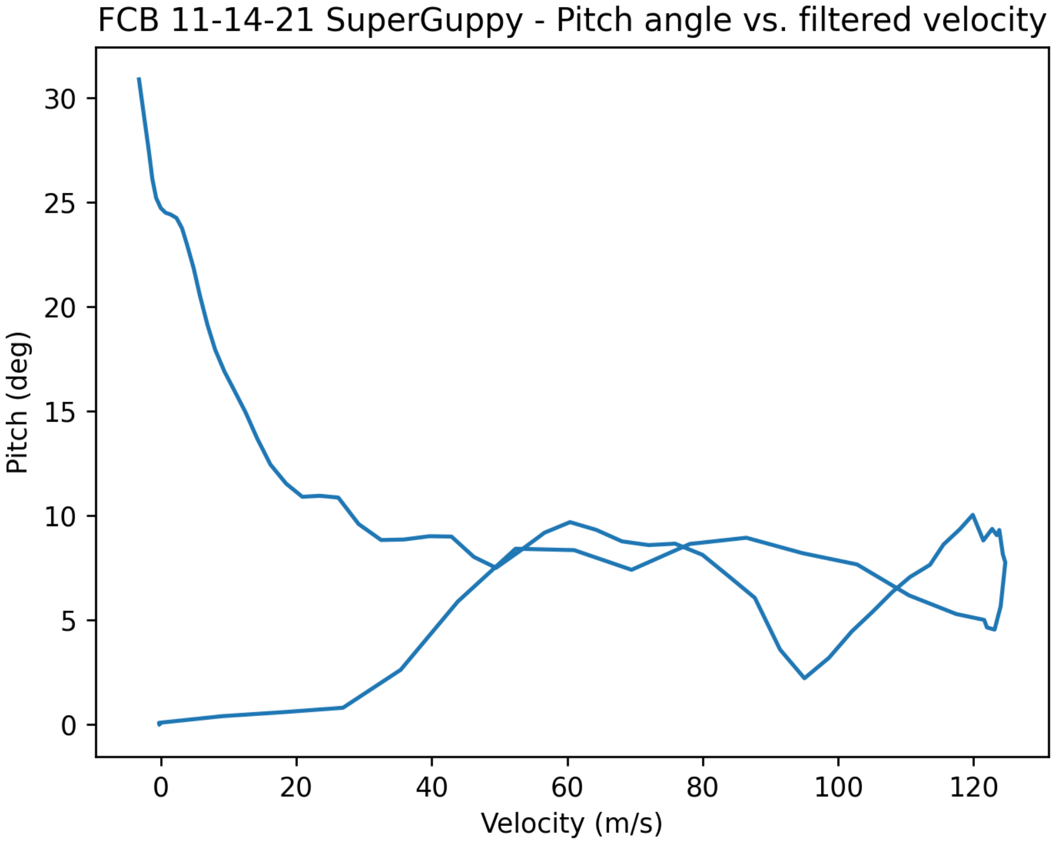

Figure 13: FCB 11-14-21 SuperGuppy - Pitch angle vs. filtered velocity

4.5 FCB 11-14-21 TRD

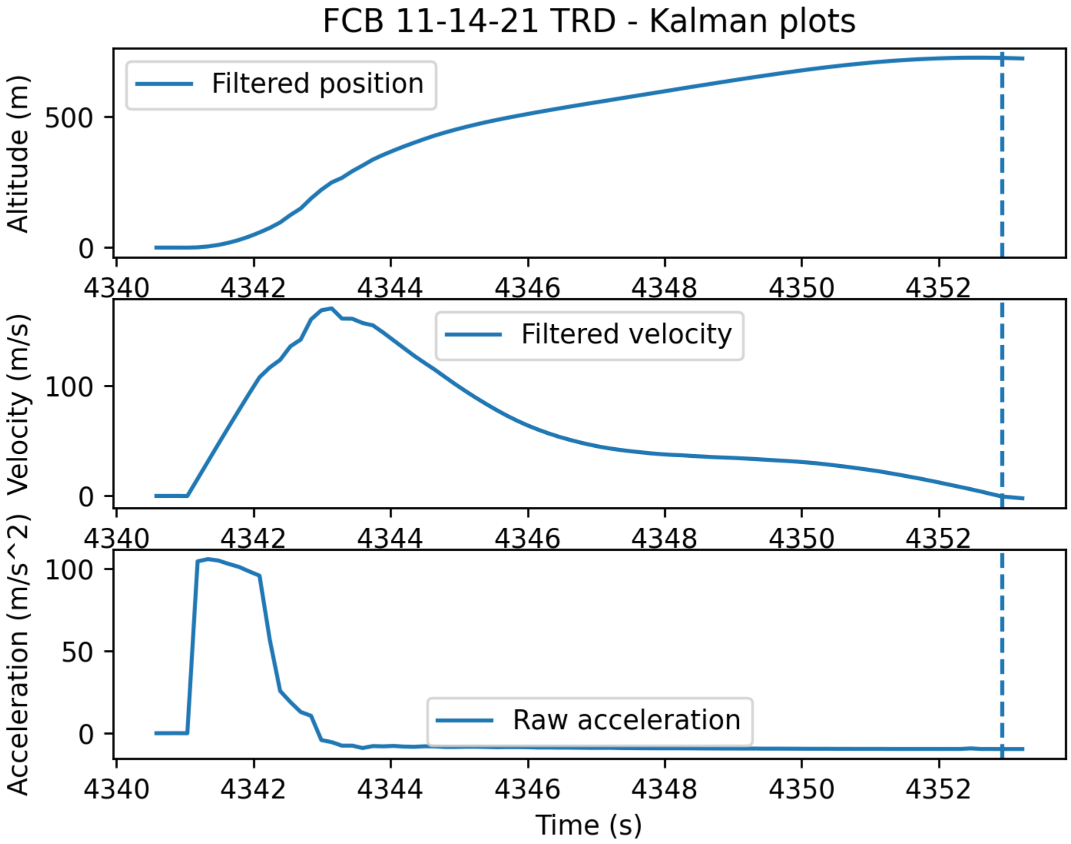

Figure 14: FCB 11-14-21 TRD - Kalman plots

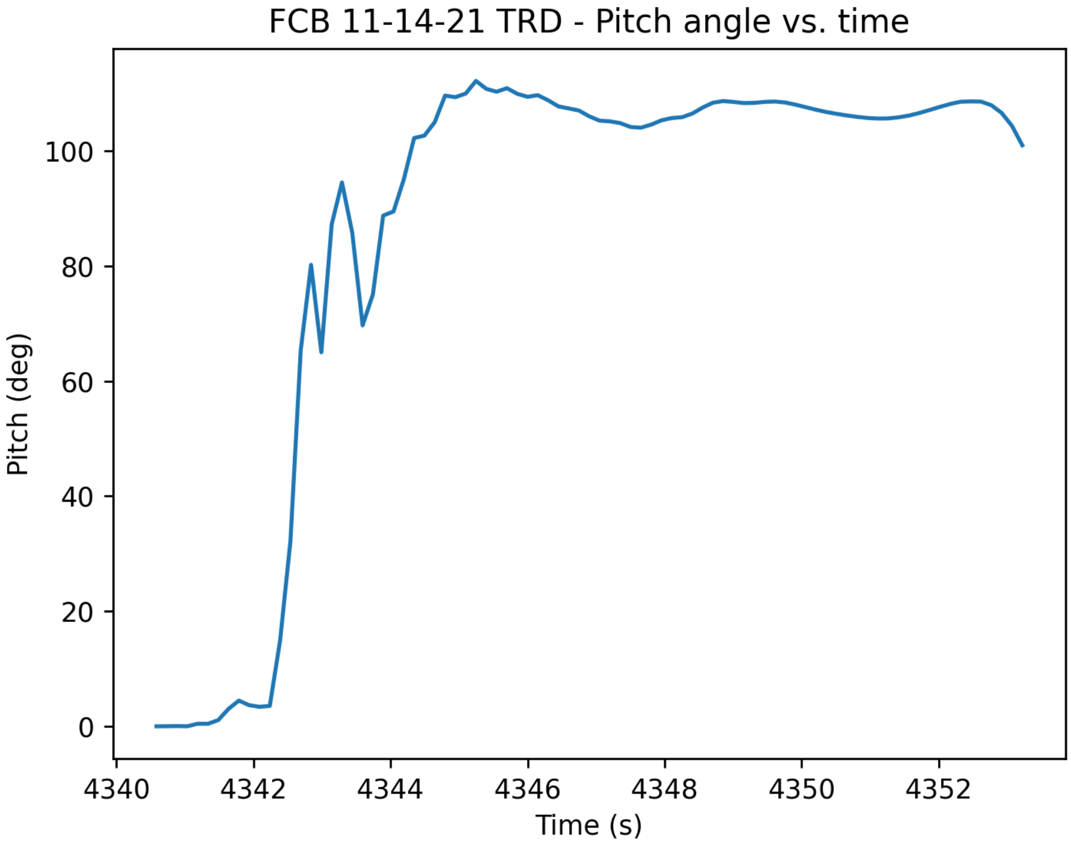

Figure 15: FCB 11-14-21 TRD - Pitch angle vs. time

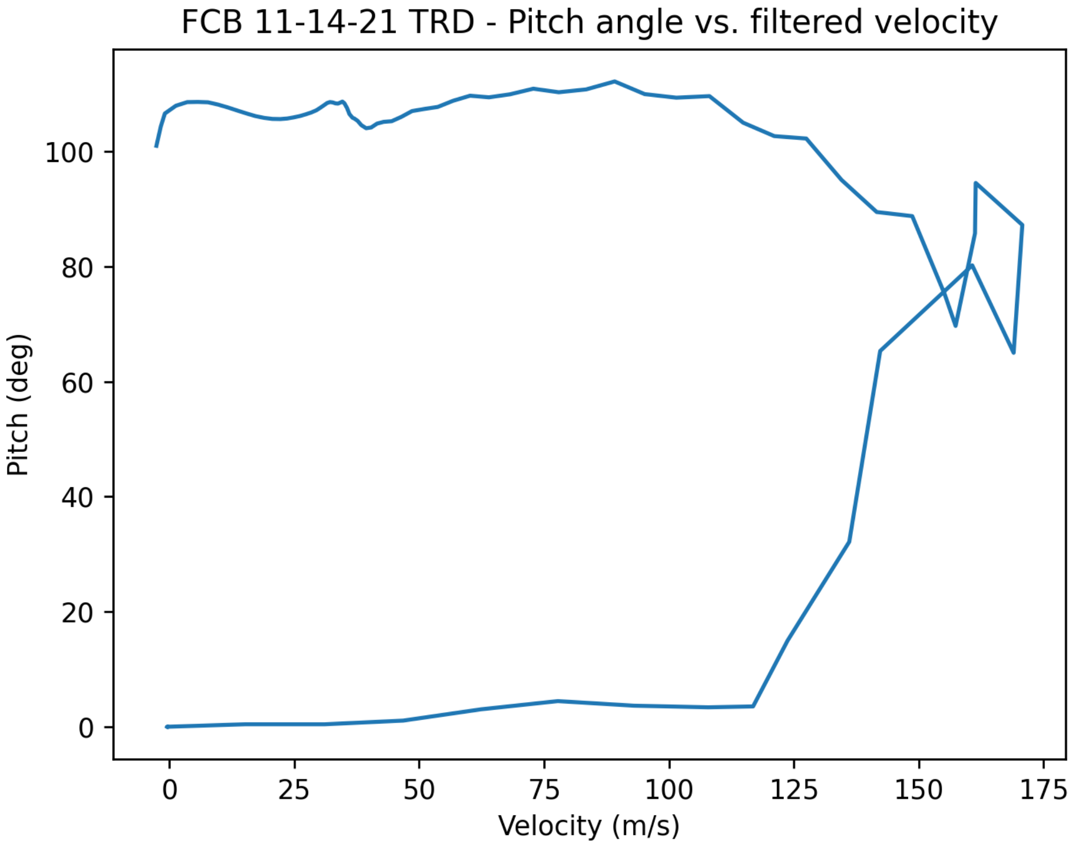

Figure 16: FCB 11-14-21 TRD - Pitch angle vs. filtered velocity

4.6 Goose 11-14-21 TRD

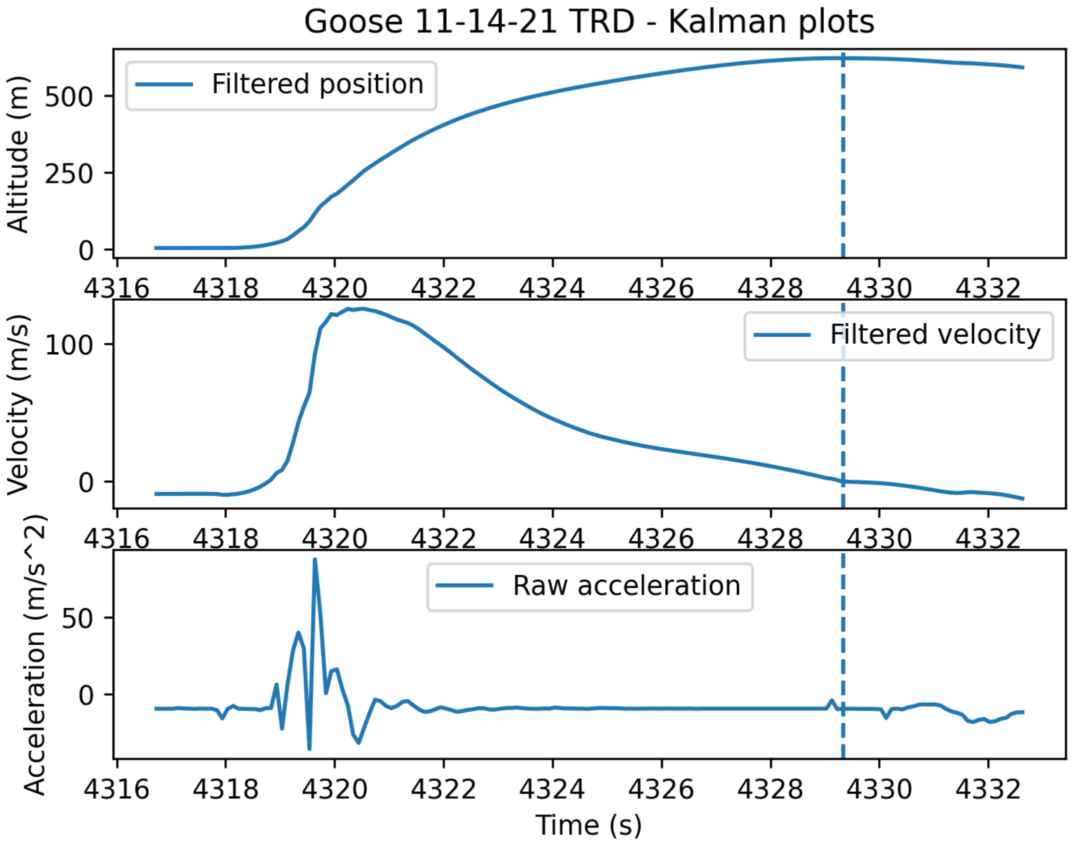

Figure 17: Goose 11-14-21 TRD - Kalman plots

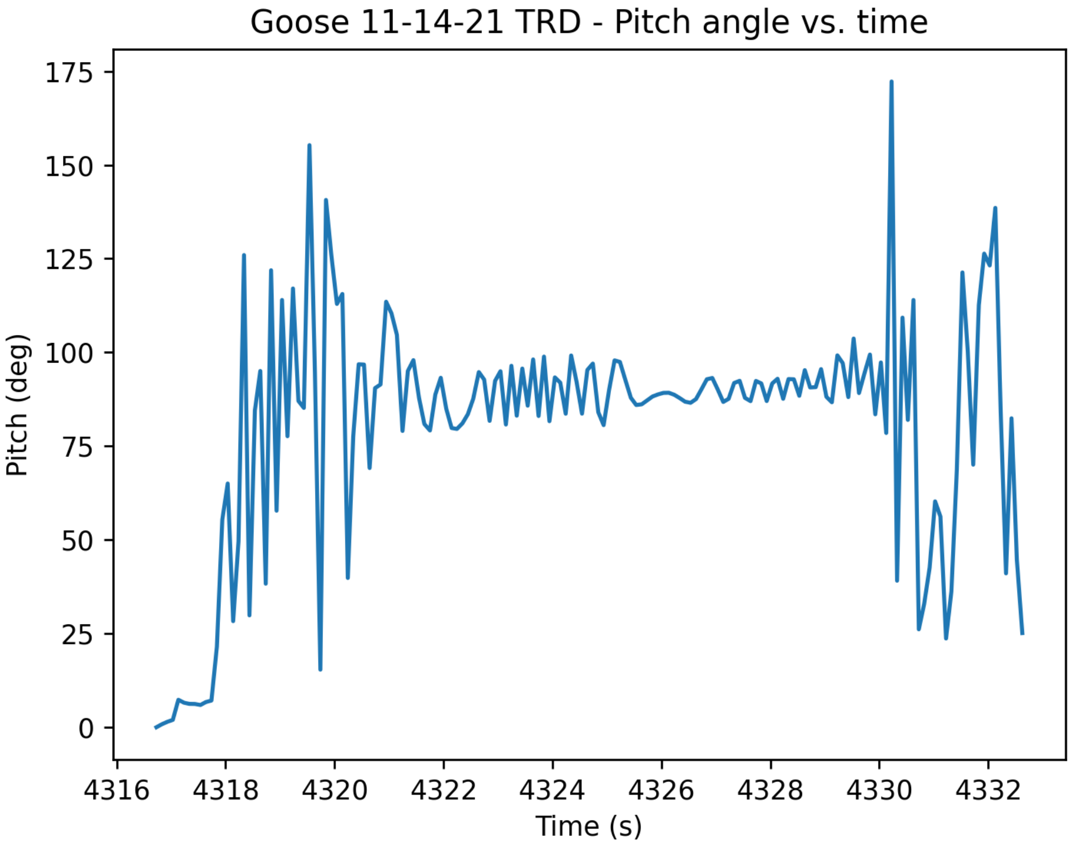

Figure 18: Goose 11-14-21 TRD - Pitch angle vs. time

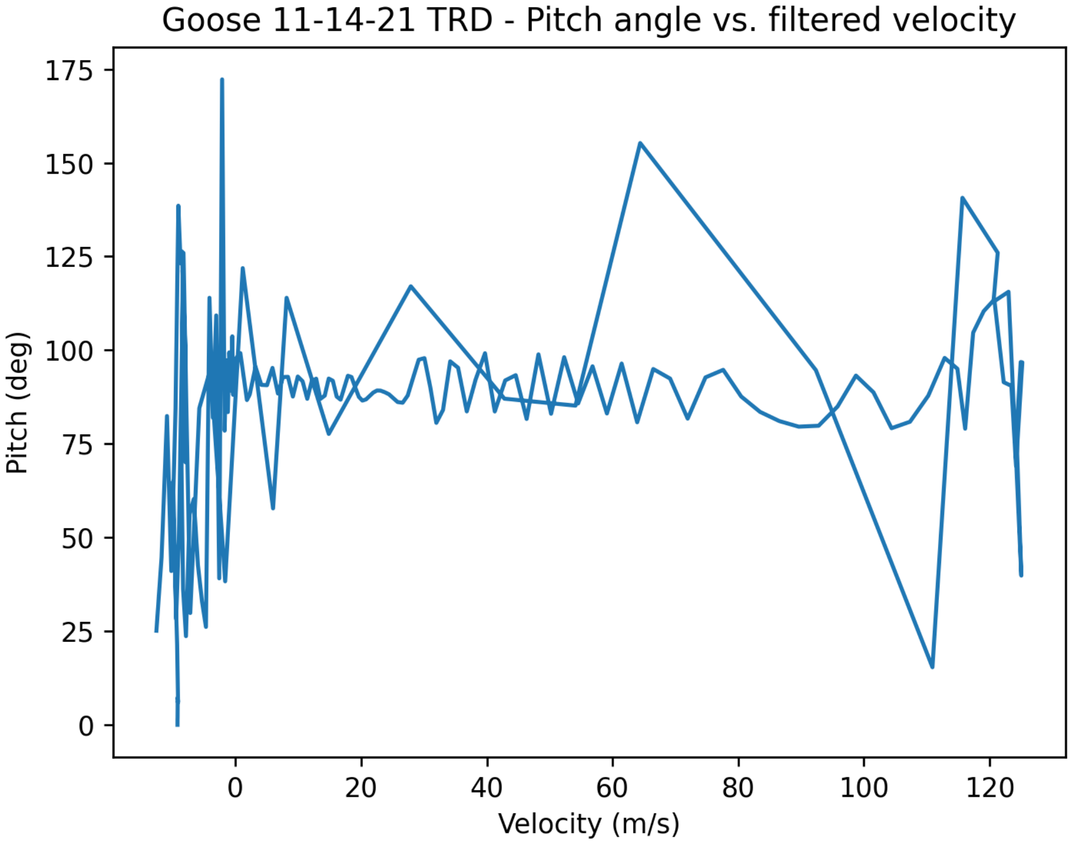

Figure 19: Goose 11-14-21 TRD - Pitch angle vs. filtered velocity

4.7 FCB 11-20-21 Carby

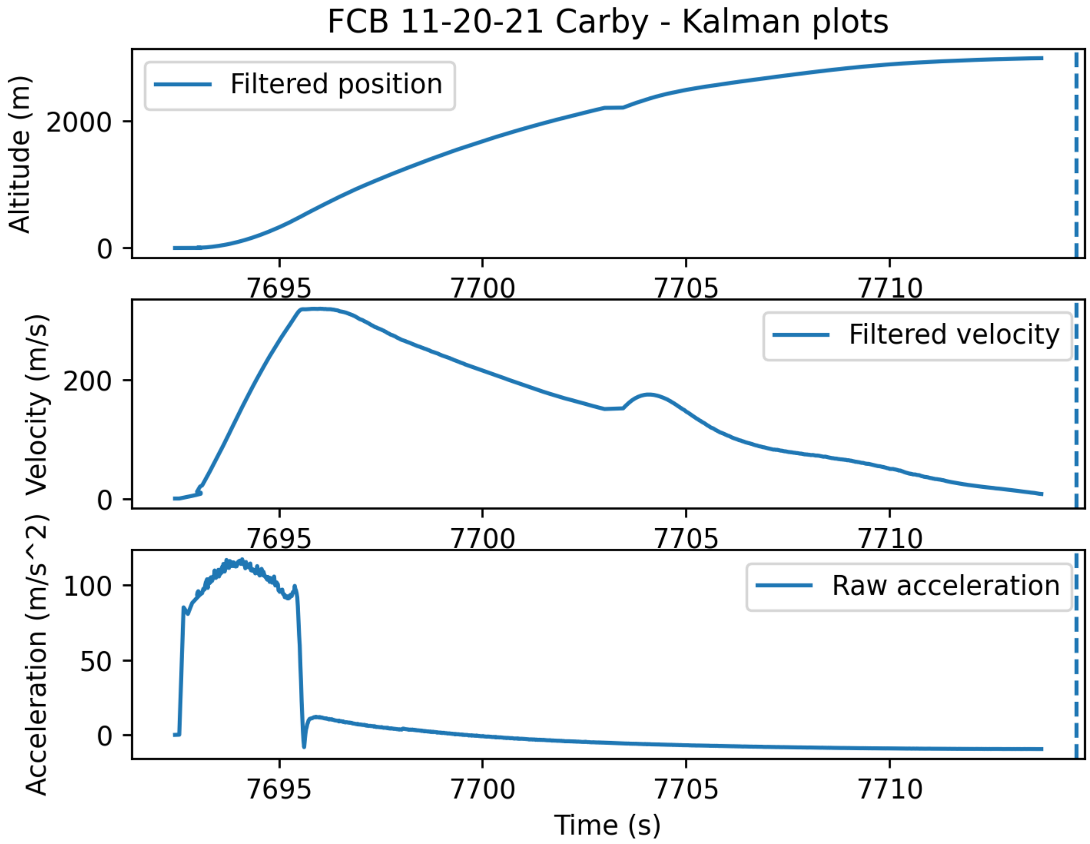

Figure 20: FCB 11-20-21 Carby - Kalman plots

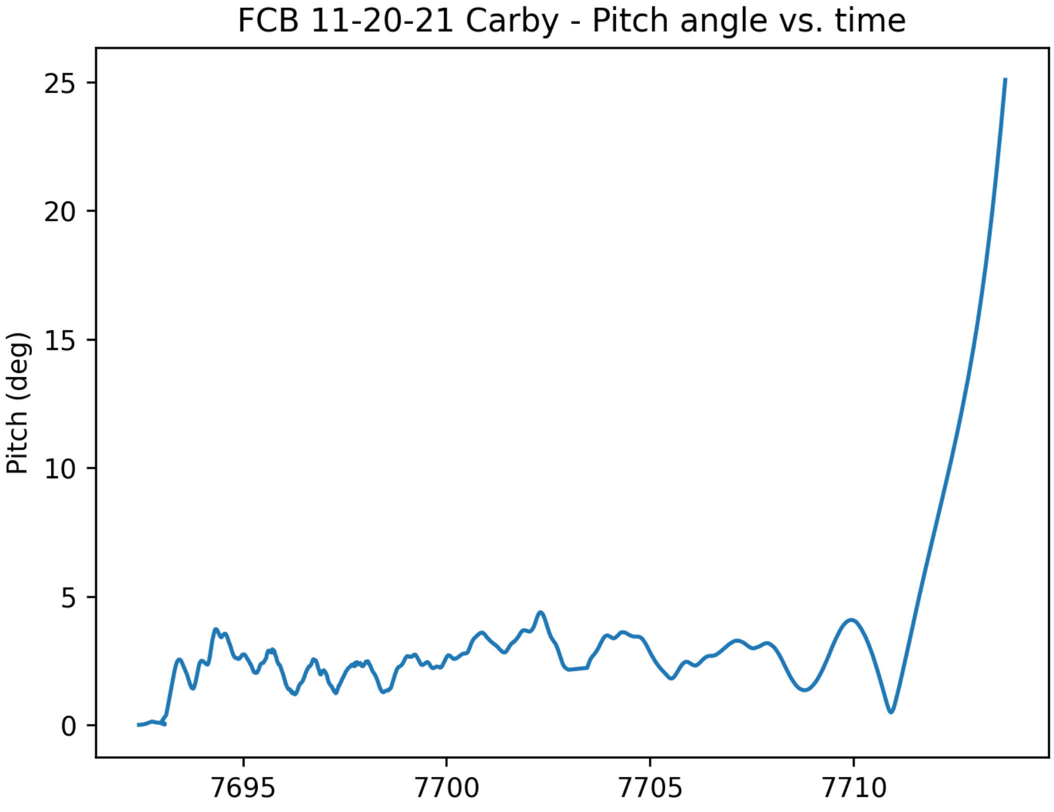

Figure 21: FCB 11-20-21 Carby - Pitch angle vs. time

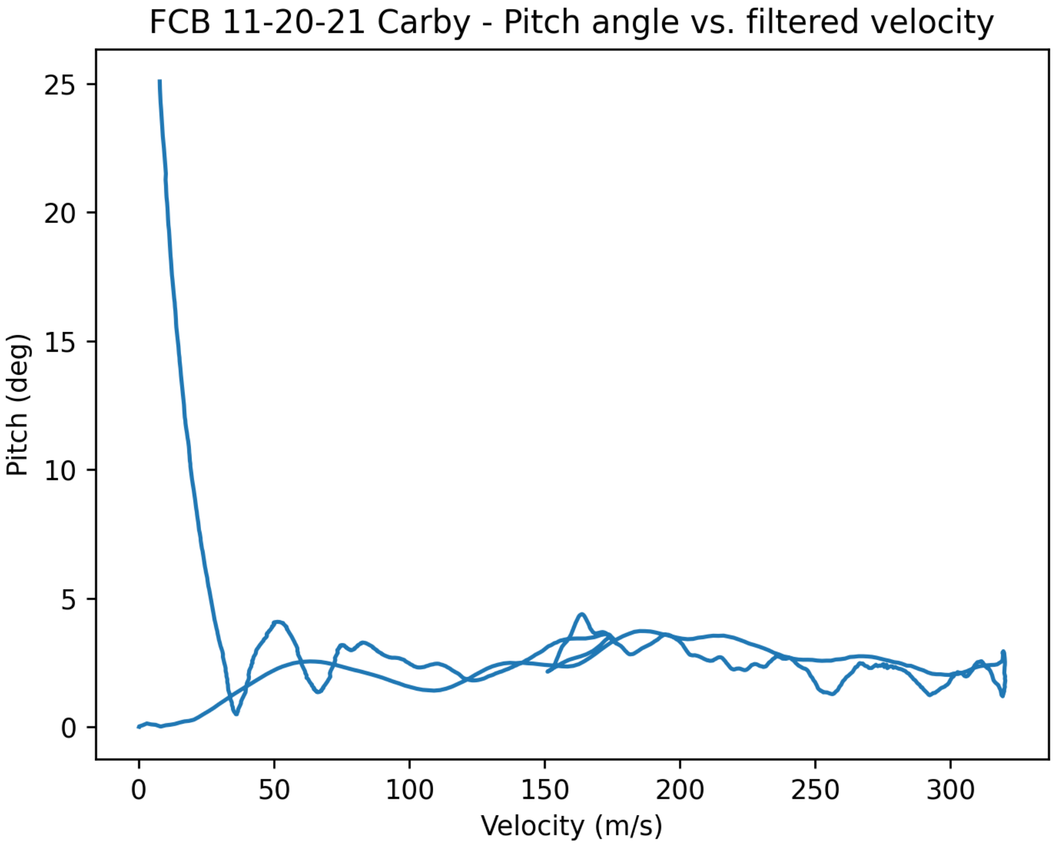

Figure 22: FCB 11-20-21 Carby - Pitch angle vs. filtered velocity

4.8 FCB 12-19-21 TRD

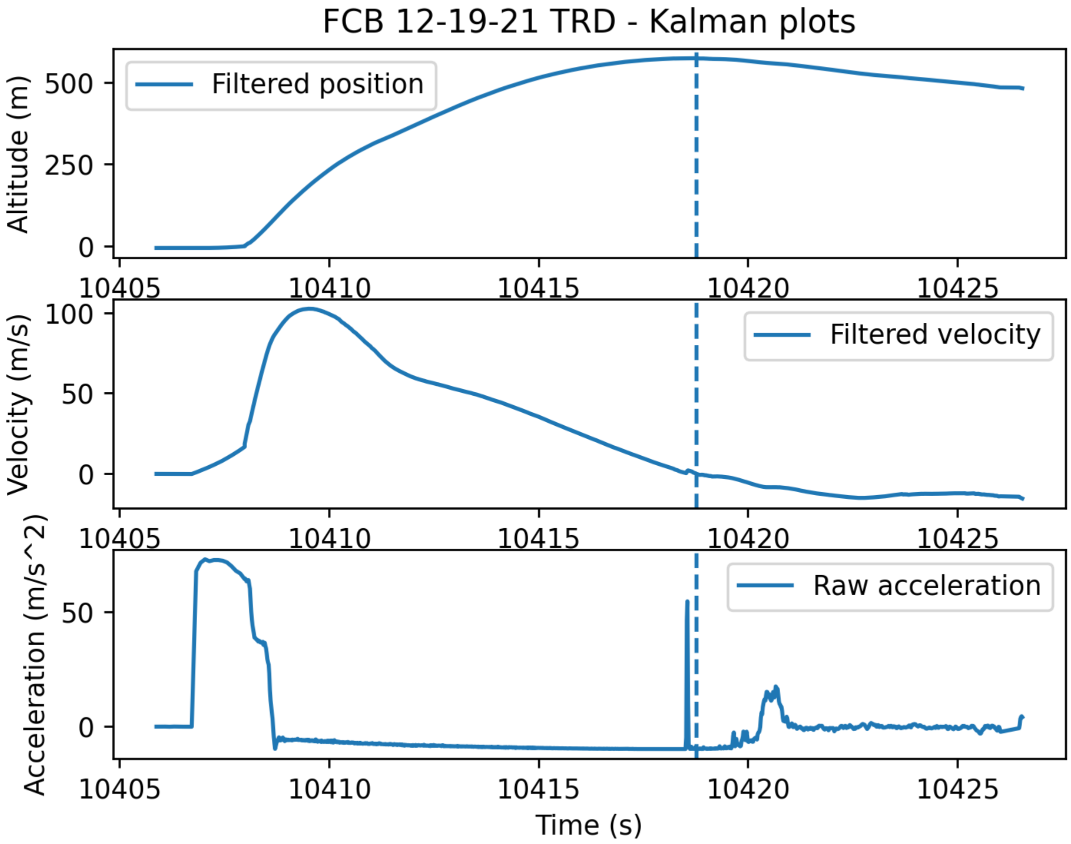

Figure 23: FCB 12-19-21 TRD - Kalman plots

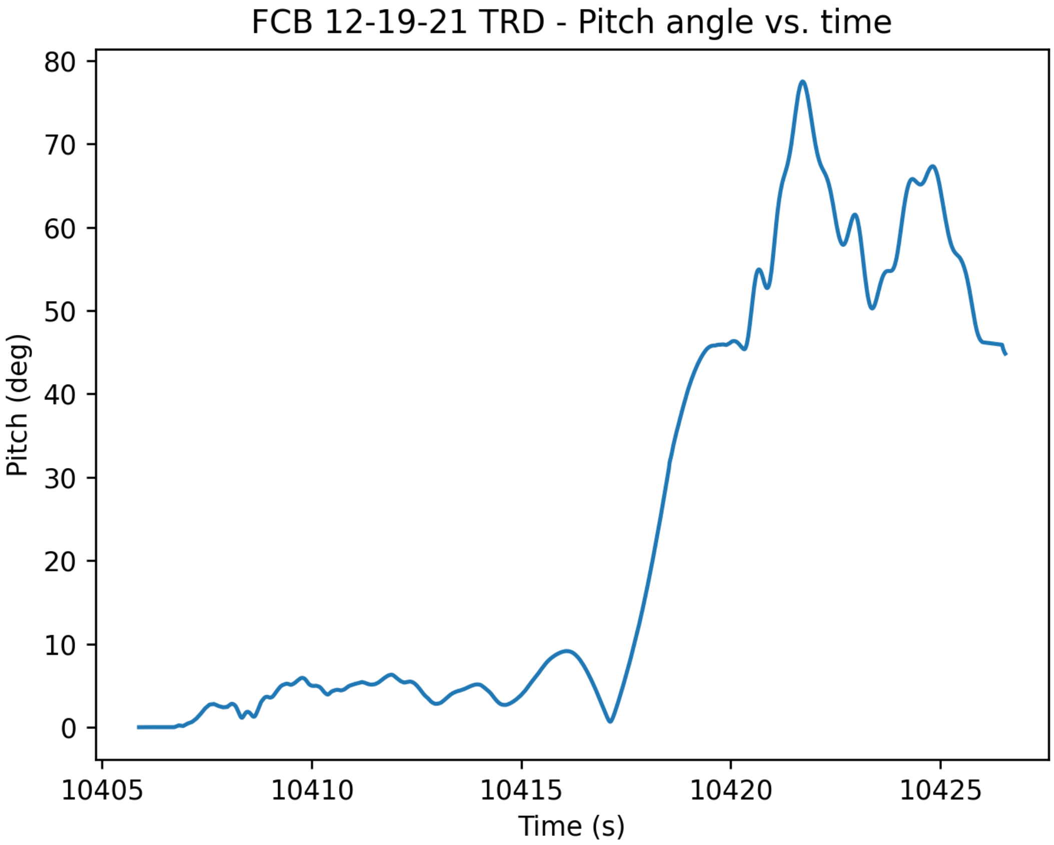

Figure 24: FCB 12-19-21 TRD - Pitch angle vs. time

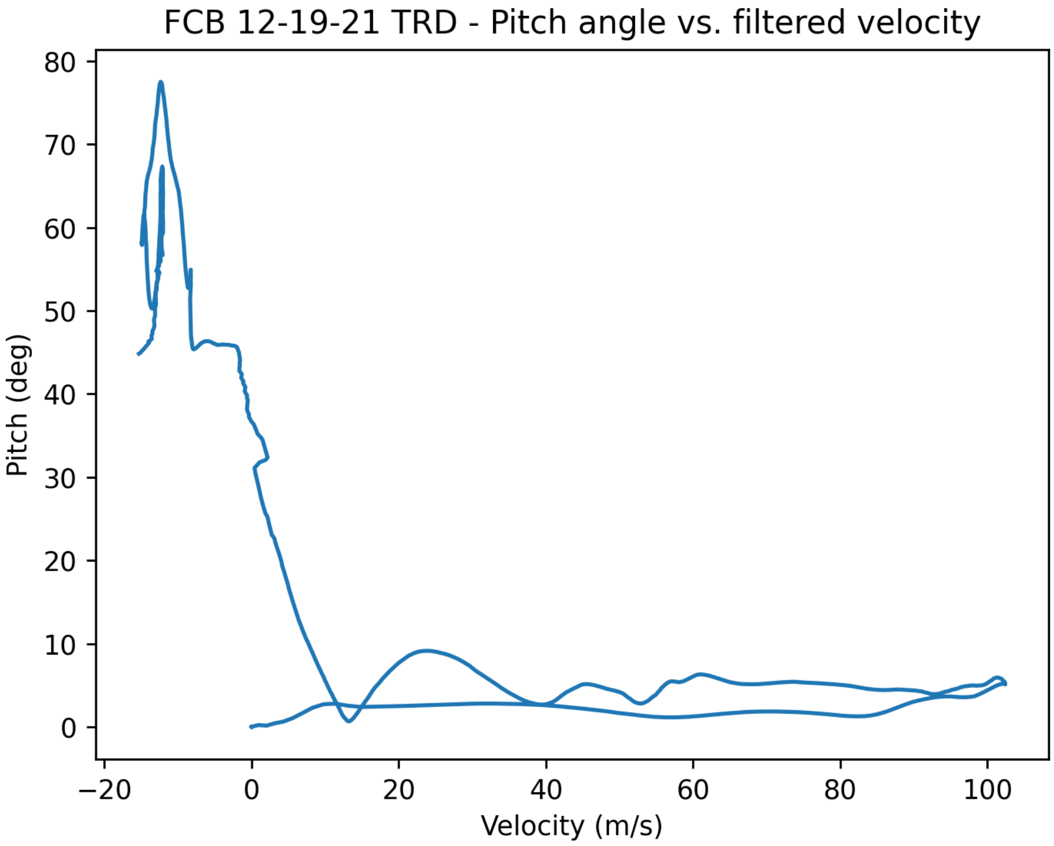

Figure 25: FCB 12-19-21 TRD - Pitch angle vs. filtered velocity

5 Author's recommendation

Given the current set of flight data, the author recommends designing rockets for an angle of attack of 10 degrees at the rocket's maximum predicted velocity. Based on the available data, this seems like a conservative estimate, and given more data in the future, it may be able to be relaxed. However, caution is always recommended, especially when taking forces or stresses from simulations. Computational Fluid Dynamics (CFD) calculations are generally required to make this specification useful, and those calculations are highly prone to user error. Finite Element Analysis (FEA) calculations are generally considered more reliable, but this still relies on a competent and knowledgeable user. **It is very easy to get meaningless results from both of these types of analysis - make sure you know what you're doing**.

However, finding the expected loads on each rocket section does not end with the CFD results. The overall force on the rocket must be broken down into internal and external forces and moments on each rocket section of interest. The external forces are easy - inputs from CFD and thrust as estimated from manufacturer specification. Calculating the internal forces and moments (between each pair of rocket sections) involves a lot of math, and **crucially, the mass and moment of inertia of each section**. Moment of inertia can be reasonably well estimated if the distribution of mass is known, but mass is hard to estimate early in the design of a rocket.

With this in mind, even though the CFD likely has inaccuracy on the order of 10-30% (even if the user is experienced and doing things properly), this is acceptable in the scope of relevant errors. Those being the velocity - angle-of-attack pair chosen, and the mass distribution, both of which have a critical impact on the results. Regarding a factor of safety in an integrated calculation (CFD to internal force to FEA / hand calculation), the author recommends proceeding assuming all inputs are accurate, then reporting a single factor of safety in the stress calculation. When assessing this factor of safety, the engineer should keep in mind the many uncertainties in the inputs to this calculation.

6 Fun bonus data

This is a look at roll rates of our rockets, as that is easy to look at with the existing data processing. These plots will show roll rate as a function of upwards velocity. For some flights there is a clear linear trend, suggesting that the force causing roll is constantly in balance with the force resisting roll. The flights that don't follow a strong trend tend to have very low roll rates, on the order of ¡.1 Hz. This is an interesting case of quasi-equilibrium dynamics. Though none of these rockets were designed intentionally to spin, this suggests this data suggests that they de-spin themselves as they slow down during coast. This could potentially be applied to a rocket that is designed to spin itself, meaning that in theory a spin rocket may not need a de-spin mechanism. Your results may vary, author is not responsible for spin-induced rocket failure.

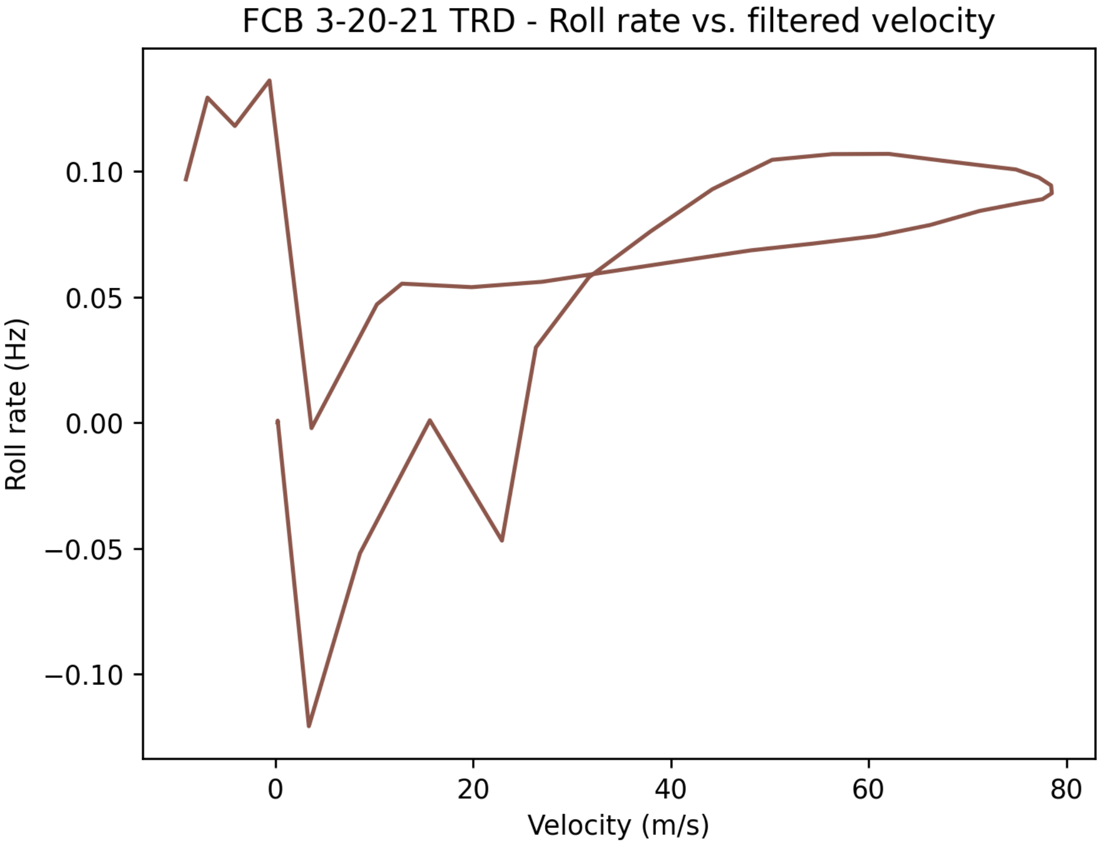

Figure 26: FCB 3-20-21 TRD - Roll rate vs. filtered velocity

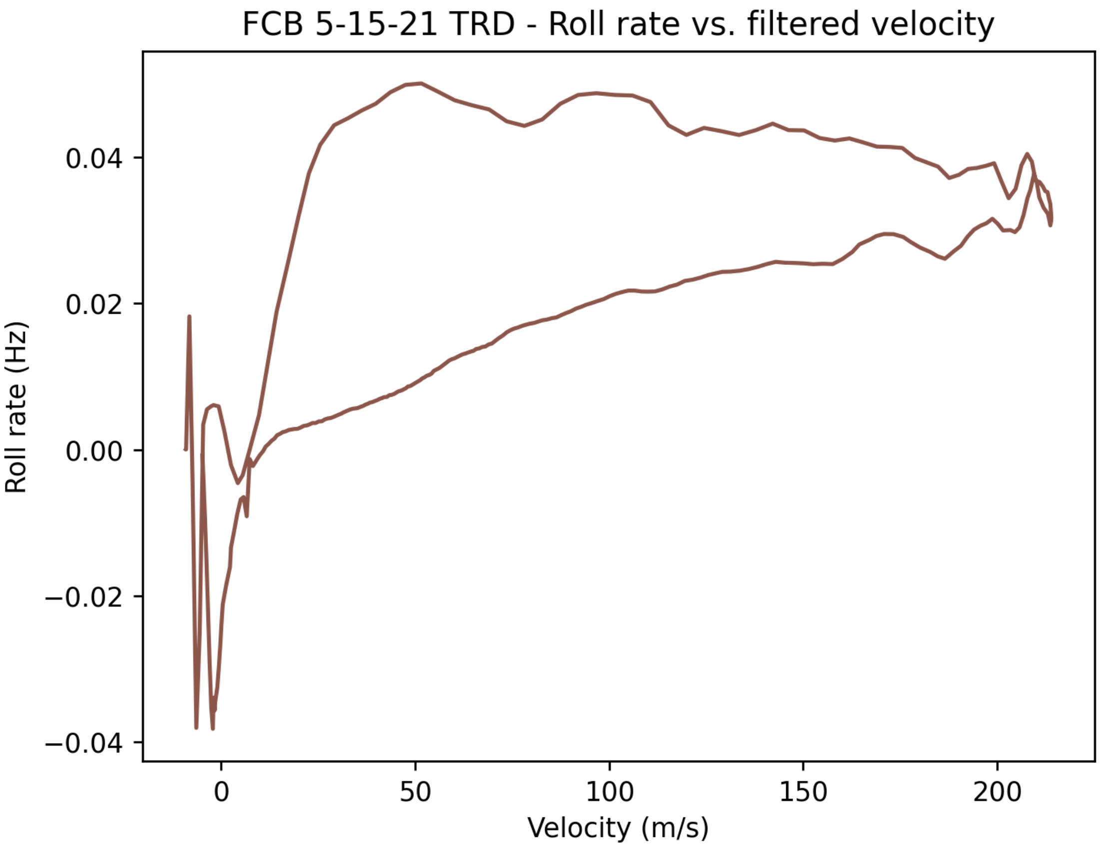

Figure 27: FCB 5-15-21 TRD - Roll rate vs. filtered velocity

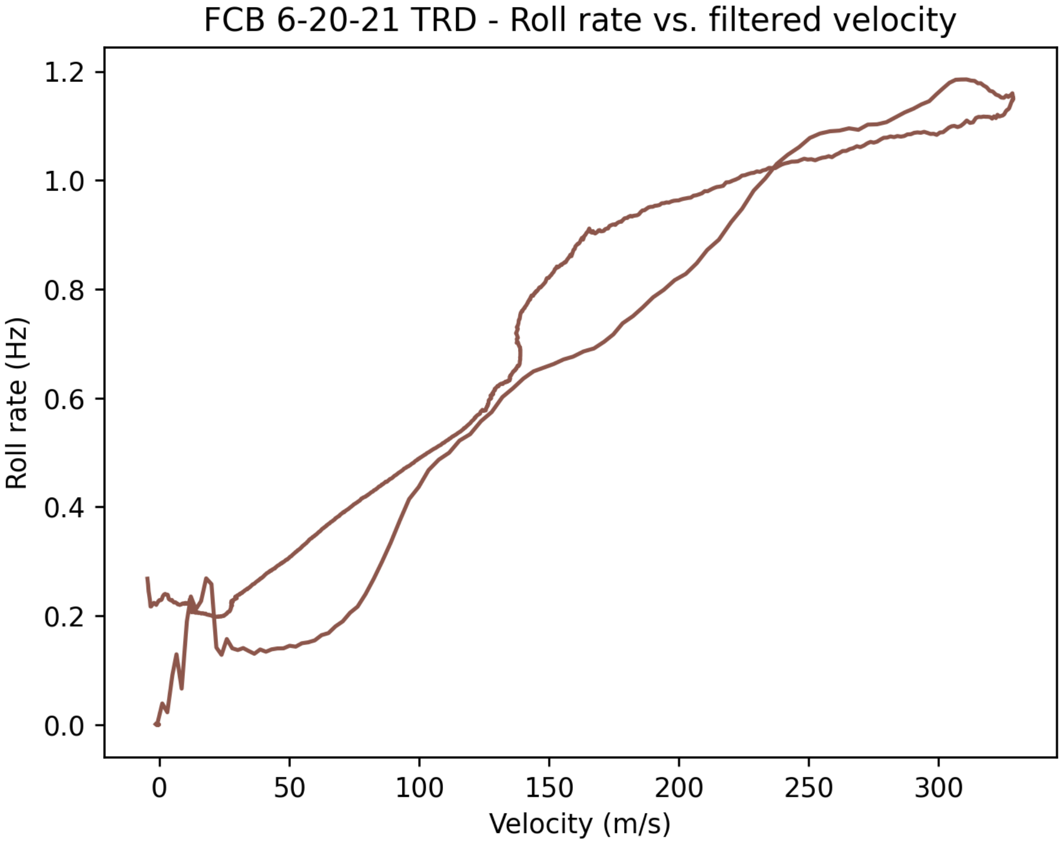

Figure 28: FCB 6-20-21 TRD - Roll rate vs. filtered velocity

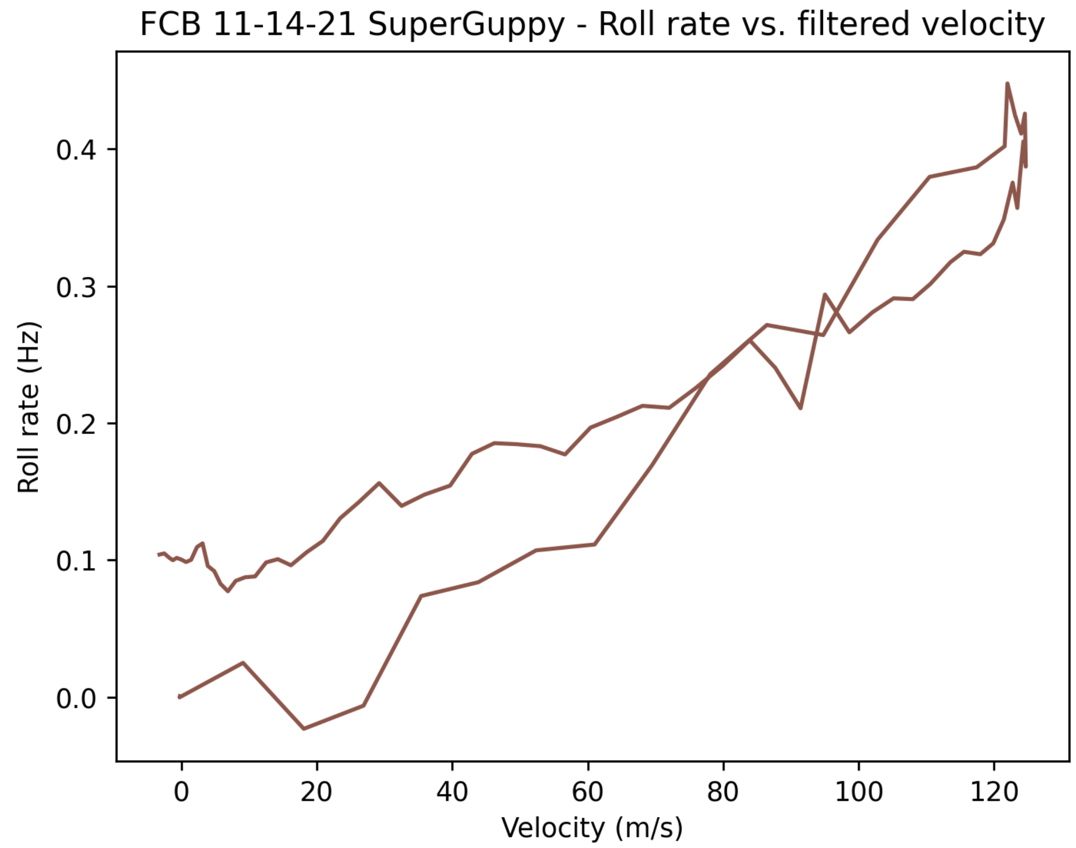

Figure 29: FCB 11-14-21 SuperGuppy - Roll rate vs. filtered velocity

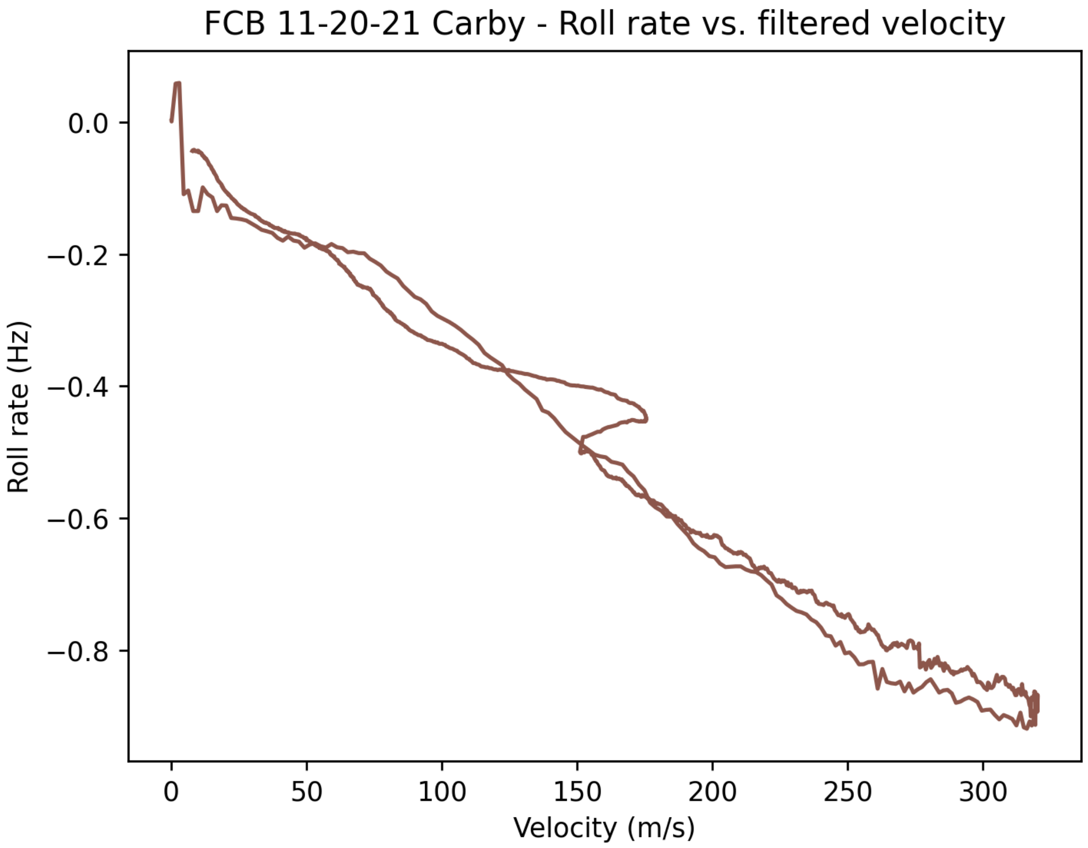

Figure 30: FCB 11-20-21 Carby - Roll rate vs. filtered velocity

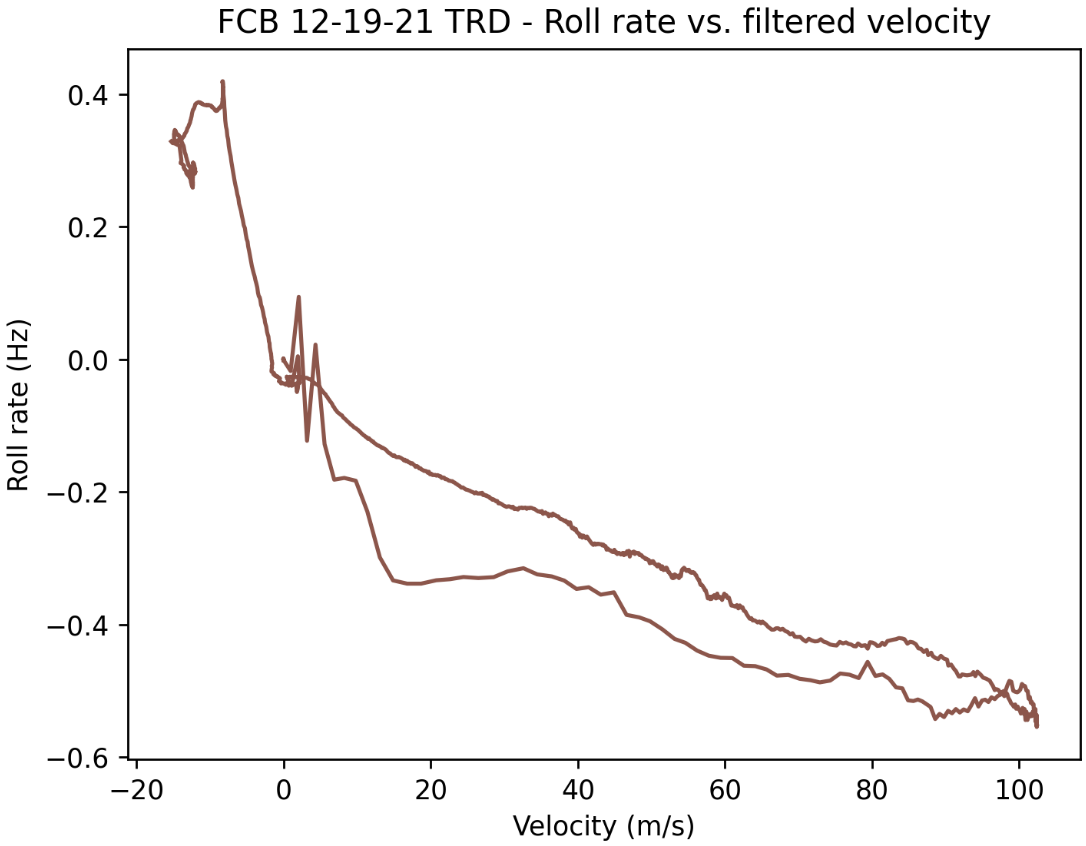

Figure 31: FCB 12-19-21 TRD - Roll rate vs. filtered velocity