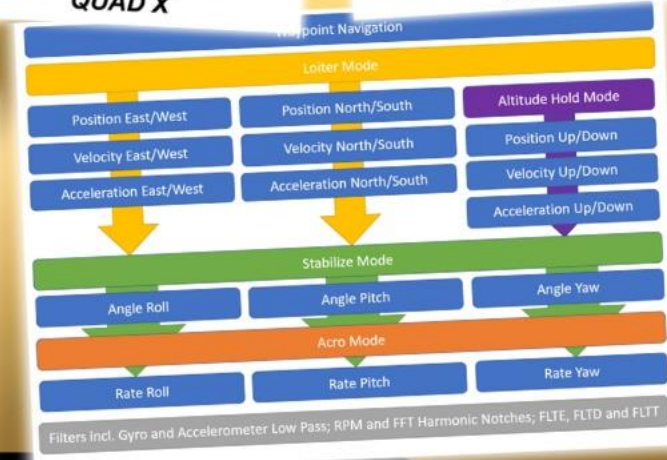
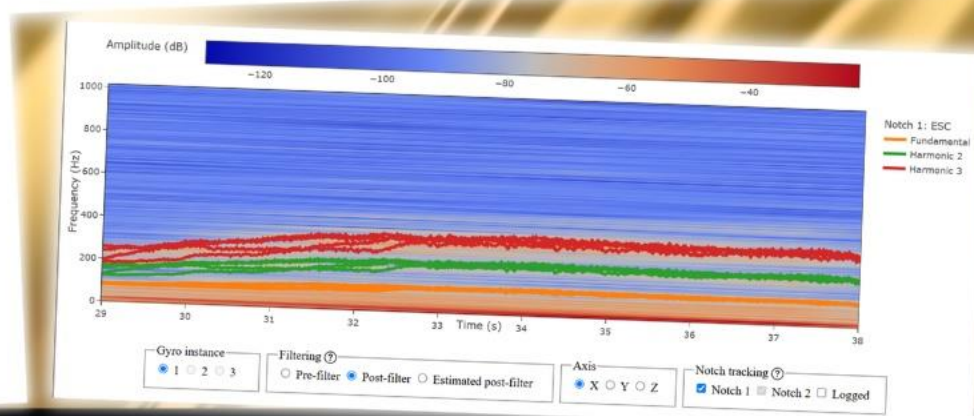
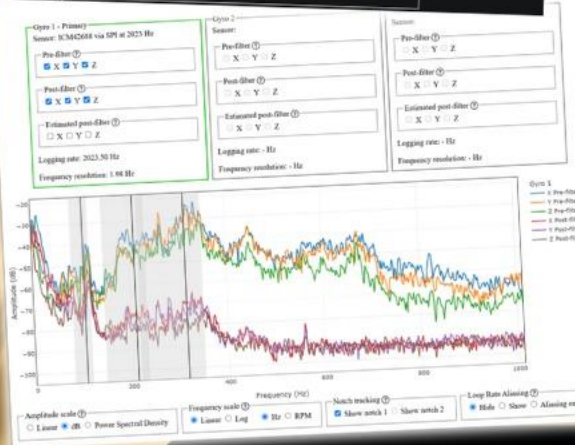
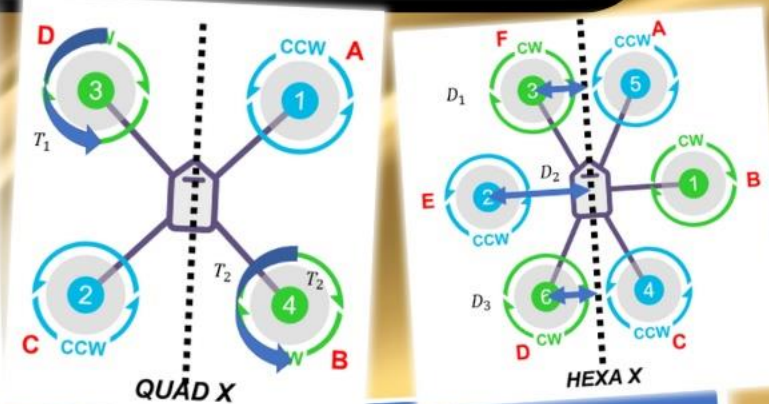
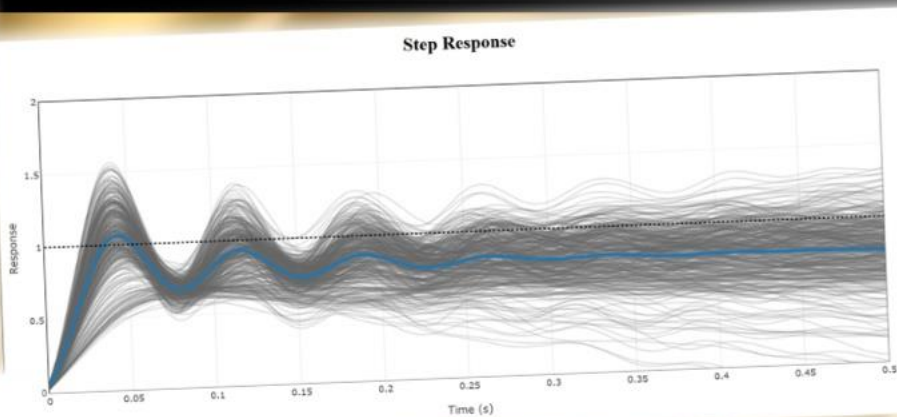


TUNING

ARDUPILOT



COMPLETE PDF GUIDE

Hardware and Set-up

Waypoint Navigation

Loiter Mode

Position East/West

Position North/South

Altitude Hold Mode

Velocity East/West

Velocity North/South

Position Up/Down

Acceleration East/West

Acceleration North/South

Velocity Up/Down

Acceleration Up/Down

Stabilize Mode

Angle Roll

Angle Pitch

Angle Yaw

Acro Mode

Rate Roll

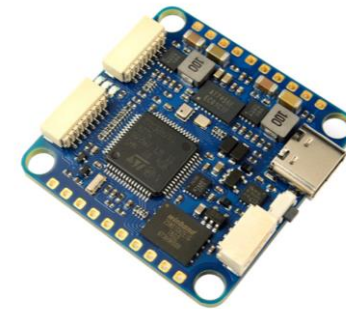
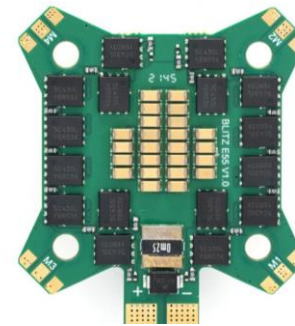
Rate Pitch

Rate Yaw

Filters incl. Gyro and Accelerometer Low Pass; RPM and FFT Harmonic Notches; FLTE, FLTD and FLTT

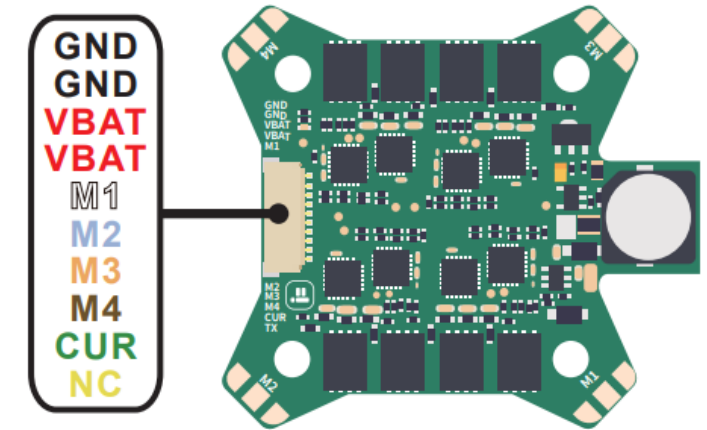
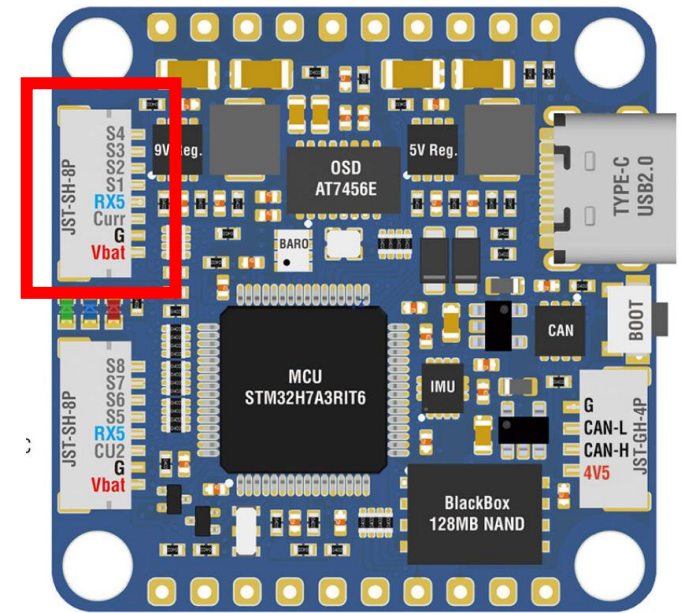
Hardware used

- AOS UL8 Frame
- Matek H7A3 Flight Controller (or any FC with an Ardupilot target)
- 4in1 ESC
- M10 GPS and Compass module
- ELRS 2.4GHz Receiver
- DJI O3 Air Unit (also works with O4)



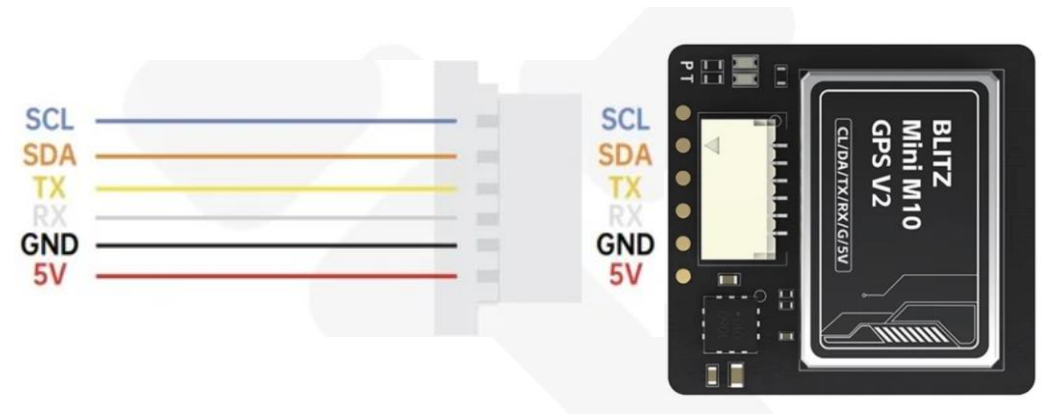
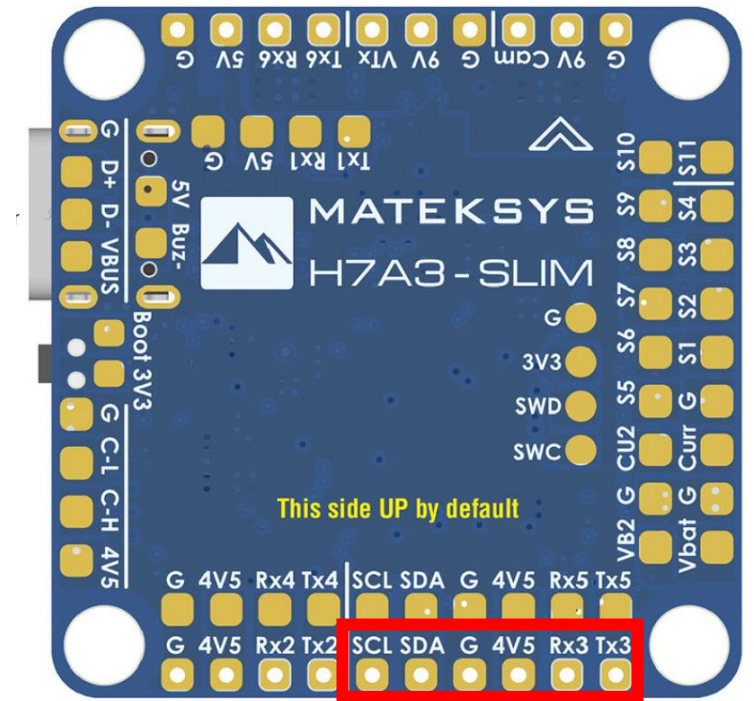
Wiring – 4in1 ESC

- Wiring from the FC to ESC is very important
- If you have not bought a “stack” then you **MUST** carefully check the pin-outs between FC and ESC
- Some combinations will apply reverse polarity and **burn your flight controller** on first power up! 🤖
- If pinouts don't match then you can re-pin the plug using a pair of tweezers 👍



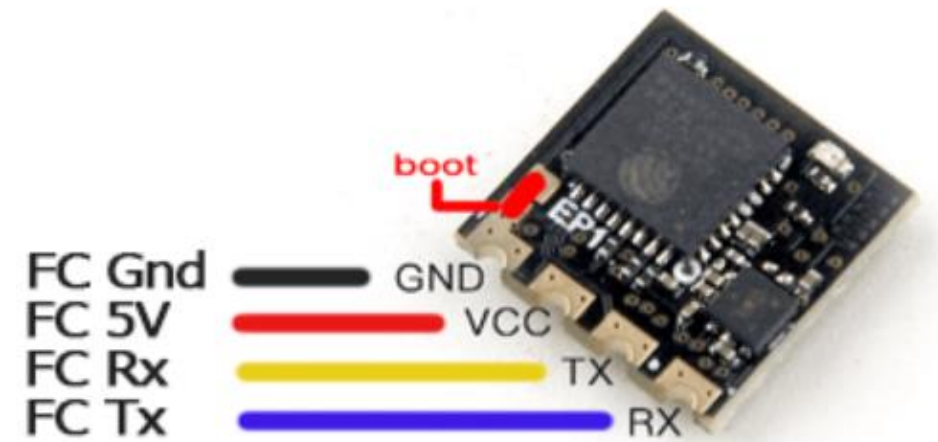
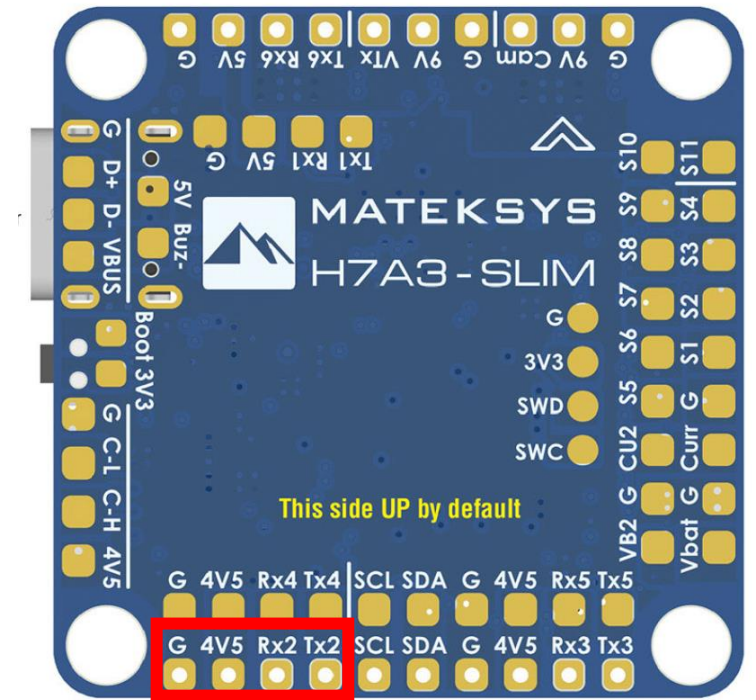
Wiring – GPS + Compass

- Wiring from the FC to GPS is pretty easy
- For Ardupilot you'll need to connect SCL-SCL, SDA-SDA, TX-RX, RX-TX, GND and 5V
- Make a note of the number of the serial port (TX/RX) for the GPS
- SCL/SDA are for the Compass
- TX/RX are for the GPS



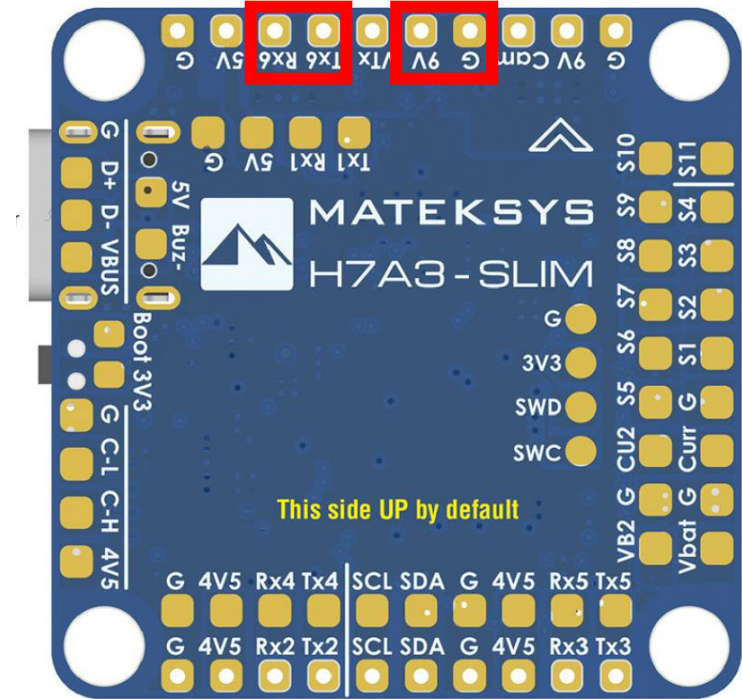
Wiring – Receiver

- Wiring from the FC to ELRS is pretty easy
- You'll need to connect TX-RX, RX-TX, GND and 5V
- Make a note of the number of the serial port (TX/RX) for the Receiver



Wiring – DJI O3/O4

- Wiring from the FC to the Air Unit is pretty easy
- You'll need to connect TX-RX, RX-TX, GND and PWR (7.4 – 26.4V)
- Make a note of the number of the serial port (TX/RX) for the Air Unit



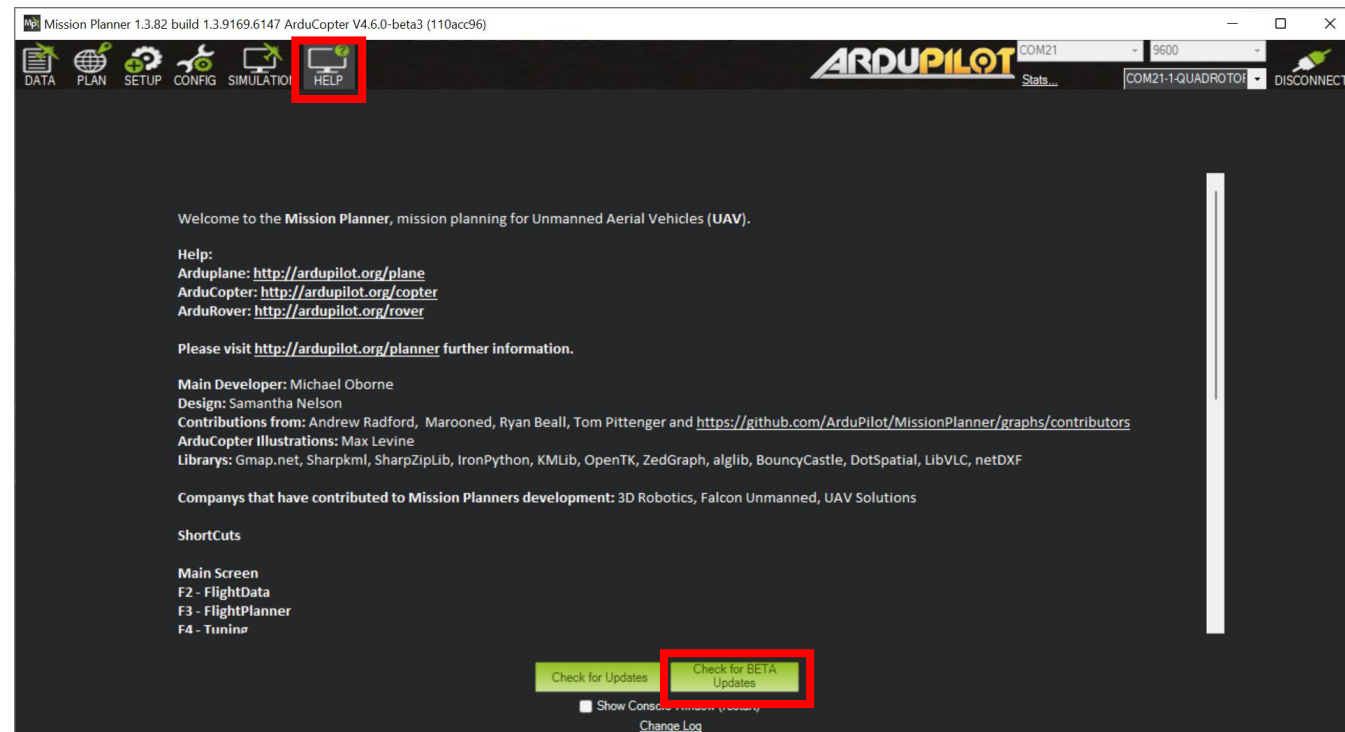
- | | | |
|-------|--------|--|
| PIN 1 | RED | RED: Power (7.4-26.4 V) |
| PIN 2 | BLACK | BLACK: Power GND |
| PIN 3 | WHITE | WHITE: UART RX (Connects to Flight Controller OSD TX, 0-3.3 V) |
| PIN 4 | GRAY | GRAY: UART TX (Connects to Flight Controller OSD RX, 0-3.3 V) |
| PIN 5 | BROWN | BROWN: Signal GND |
| PIN 6 | YELLOW | YELLOW: DJI HDL (Connects to Flight Controller S.Bus, 0-3.3 V) |

Setup – Flashing Ardupilot

- If your FC does not have Ardupilot installed
- <https://firmware.ardupilot.org/>
- Copter
- Check **Latest** for your target
- If you can't find it there try **Beta**
- Download [arducopter_with_bl.hex](#) (with bootloader)
- Flash with STM32 Cube Programmer (full chip erase)

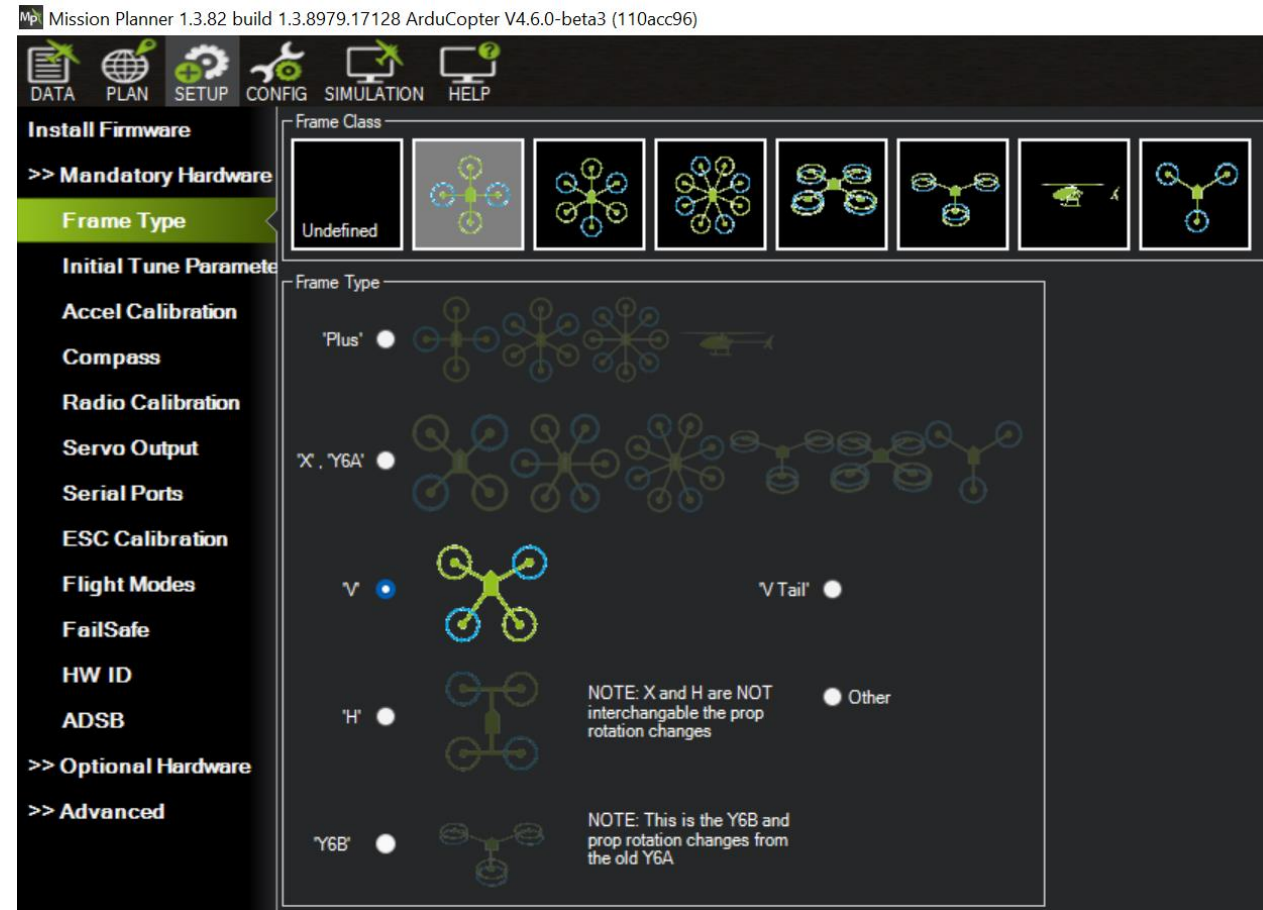
Mission Planner

- There is a log download bug with the latest version of Mission Planner 1.3.82
- Use 1.3.81 or apply **Beta Updates** from the Help Page!



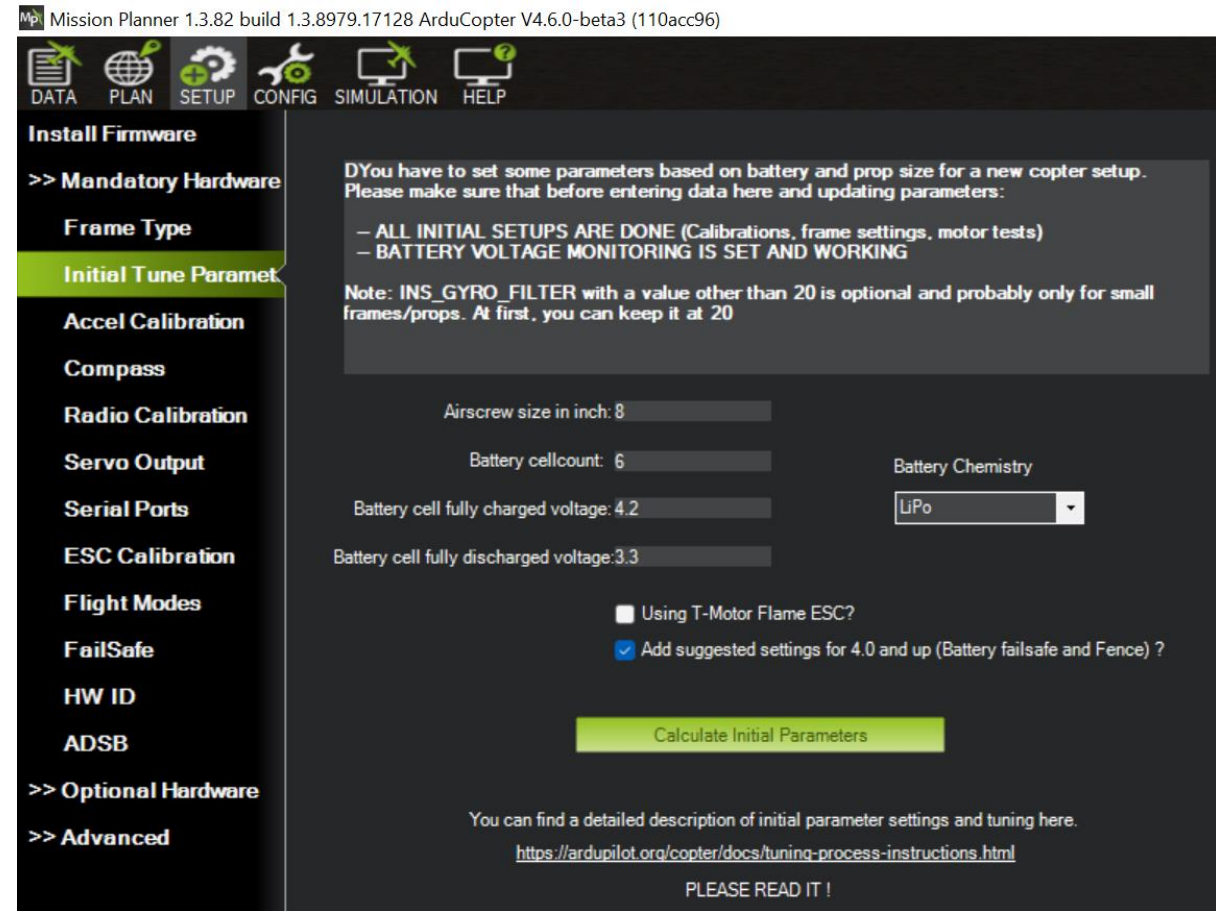
Setup – Frame Type

- Mission Planner > Setup Tab > Mandatory Hardware > Frame Type
- Frame Class > Quadcopter
- Frame Type > X (probably) or V



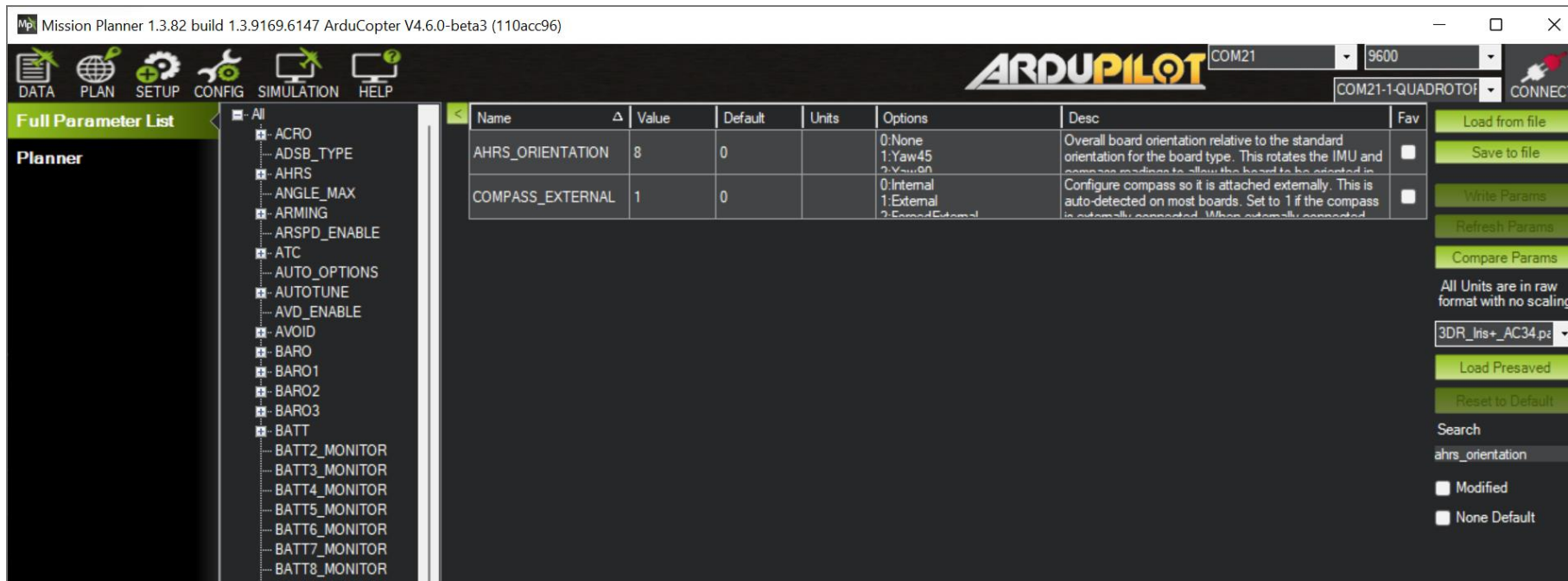
Setup – Initial Tune Parameters

- Mission Planner > Setup Tab > Mandatory Hardware > Initial Tune Parameters
- Airscrew Size > Prop Diameter
- Battery Cell Count
- Battery Chemistry
- Add suggested settings for 4.0+



Setup – Board Alignment

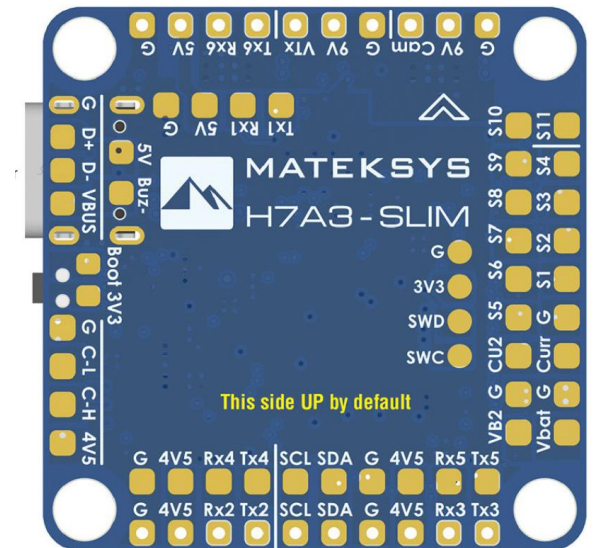
- Mission Planner > Config Tab > Full Parameter List > **AHRS_ORIENTATION**
- You only need to change this if your board orientation is different to the manufacturers default



The screenshot shows the Mission Planner interface with the 'Full Parameter List' tab selected. The 'AHRS_ORIENTATION' parameter is highlighted in the table below.

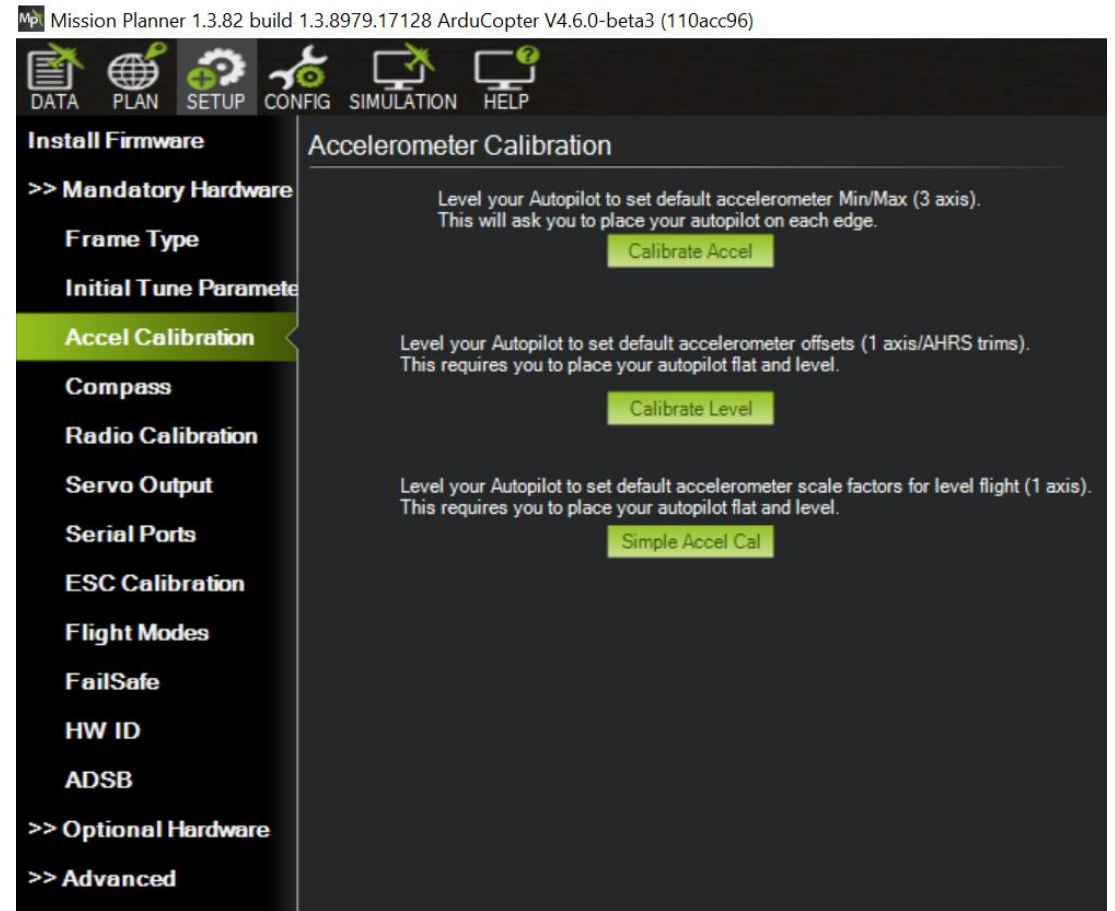
Name	Value	Default	Units	Options	Desc	Fav
AHRS_ORIENTATION	8	0		0:None 1:Yaw45 2:Yaw90	Overall board orientation relative to the standard orientation for the board type. This rotates the IMU and compass readings to allow the board to be oriented in a different direction.	<input type="checkbox"/>
COMPASS_EXTERNAL	1	0		0:Internal 1:External 2:External	Configure compass so it is attached externally. This is auto-detected on most boards. Set to 1 if the compass is externally connected. When externally connected,	<input type="checkbox"/>

Additional controls on the right side of the parameter list include: Load from file, Save to file, Write Params, Refresh Params, Compare Params, All Units are in raw format with no scaling, Load Presaved (3DR_Iris+_AC34.ps), Reset to Default, Search (ahrs_orientation), Modified (checkbox), and None Default (checkbox).



Setup – Accel Calibration

- Mission Planner > Setup Tab > Mandatory Hardware > Accel Calibration
- Calibrate Accel
- Reboot!
- Calibrate Level



Setup – Compass

- Mission Planner > Setup Tab > Mandatory Hardware > Compass
- Onboard Mag Calibration > Start
- Reboot!

Mission Planner 1.3.82 build 1.3.8979.17128 ArduCopter V4.6.0-beta3 (110acc96)

DATA PLAN SETUP CONFIG SIMULATION HELP

Install Firmware

>> Mandatory Hardware

Frame Type

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Accel Calibration

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Servo Output

Serial Ports

ESC Calibration

Flight Modes

FailSafe

HW ID

ADSB

>> Optional Hardware

>> Advanced

Compass Priority

Set the Compass Priority by reordering the compasses in the table below (Highest at the top)

Priority	DevID	BusType	Bus	Address	DevType	Missing	External	Orientation	Up	Down
1	855297	I2C	0	13	QMC5883L	<input type="checkbox"/>	<input checked="" type="checkbox"/>	Yaw180	⬆	⬇

Do you want to disable any of the first 3 compasses?
 Use Compass 1 Use Compass 2 Use Compass 3 Automatically learn offsets

A reboot is required to adjust the ordering.

A mag calibration is required to remap the above changes.

Onboard Mag Calibration

Mag 1

Mag 2

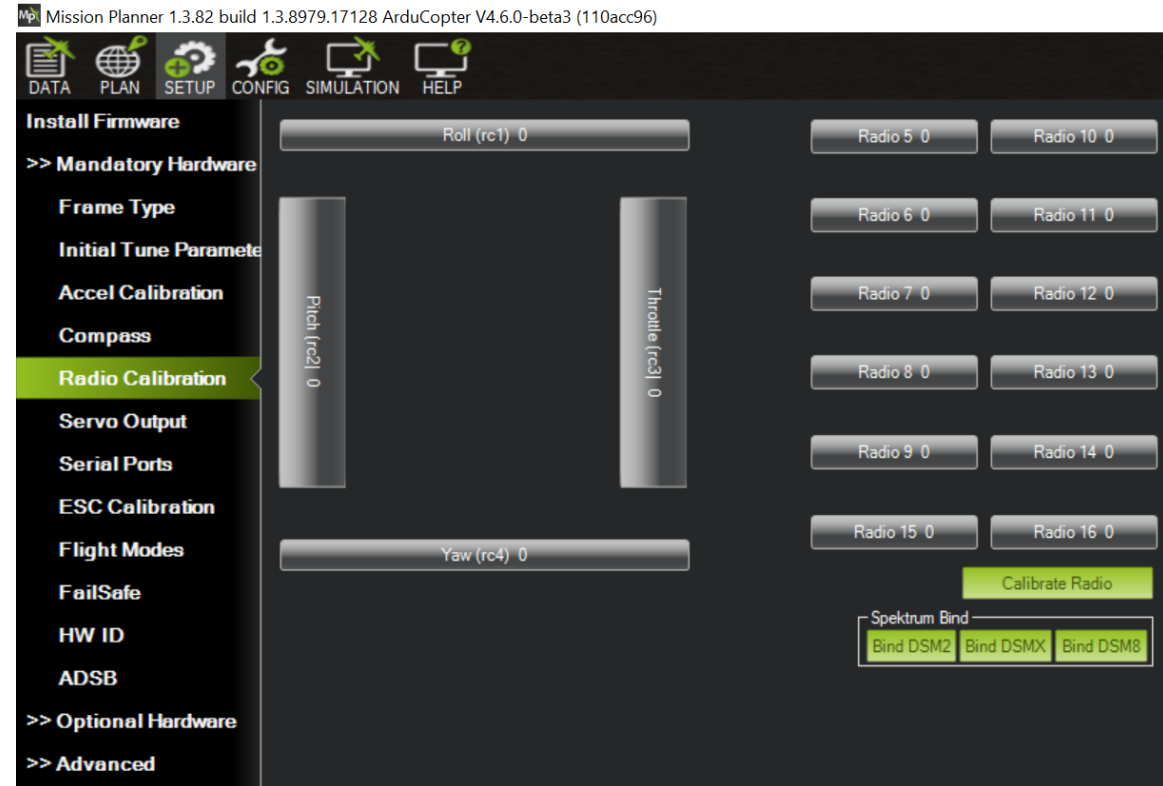
Mag 3

Fitness: Relaxed

Large Vehicle
MagCal

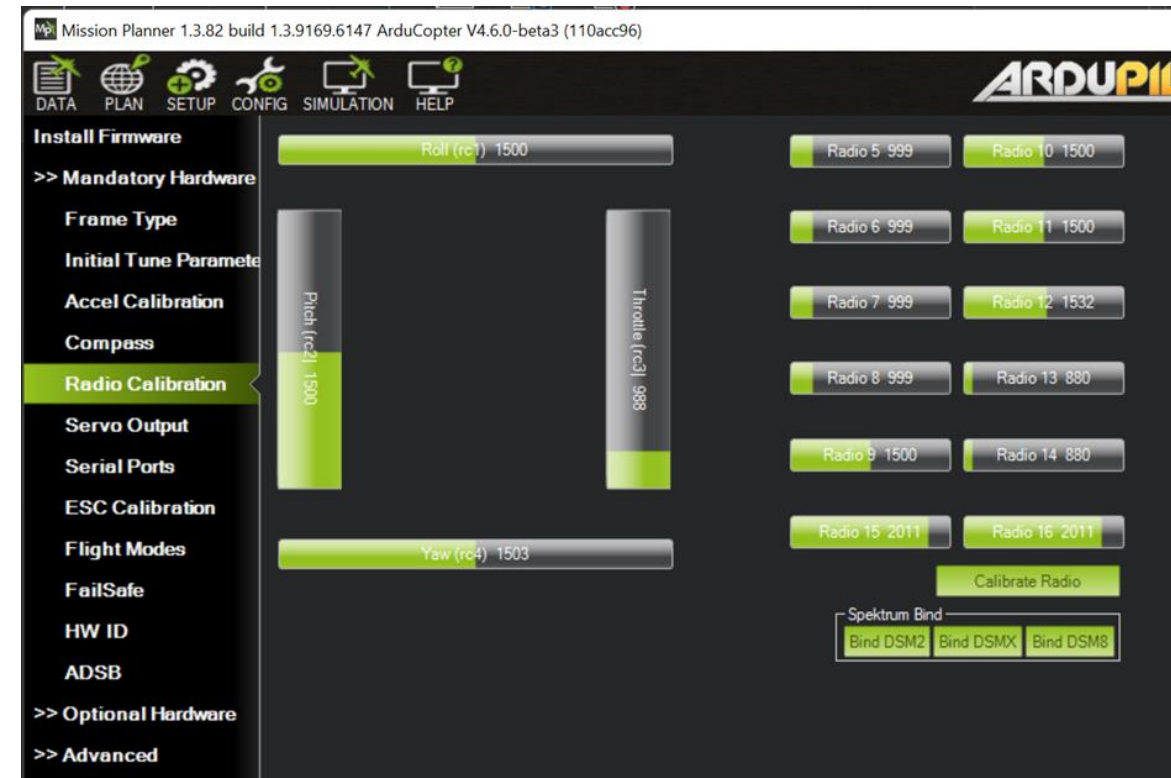
Setup – Radio Calibration

- Mission Planner > Setup Tab > Mandatory Hardware > Radio Calibration
- Calibrate Radio
- Check Roll, Pitch, Yaw, Throttle channels are correct
- Centre stick should be exactly 1500
- Low stick < 1000
- High stick > 2000



Setup – Radio Calibration

- Mission Planner > Setup Tab > Mandatory Hardware > Radio Calibration
- Calibrate Radio
- Check Roll, Pitch, Yaw, Throttle channels are correct
- Centre stick should be exactly 1500
- Low stick < 1000
- High stick > 2000



Setup – Servo Output

- Mission Planner > Setup Tab > Mandatory Hardware > Servo Output
- Set servo outputs 1-4 as Motor Outputs 1-4
- For typical 4in1 ESCs the correct Servo Number and Motor Number **won't match**
- This will be addressed in **Motor Test** later on

Mp Mission Planner 1.3.82 build 1.3.8979.17128 ArduCopter V4.6.0-beta3 (110acc96)

DATA PLAN SETUP CONFIG SIMULATION HELP

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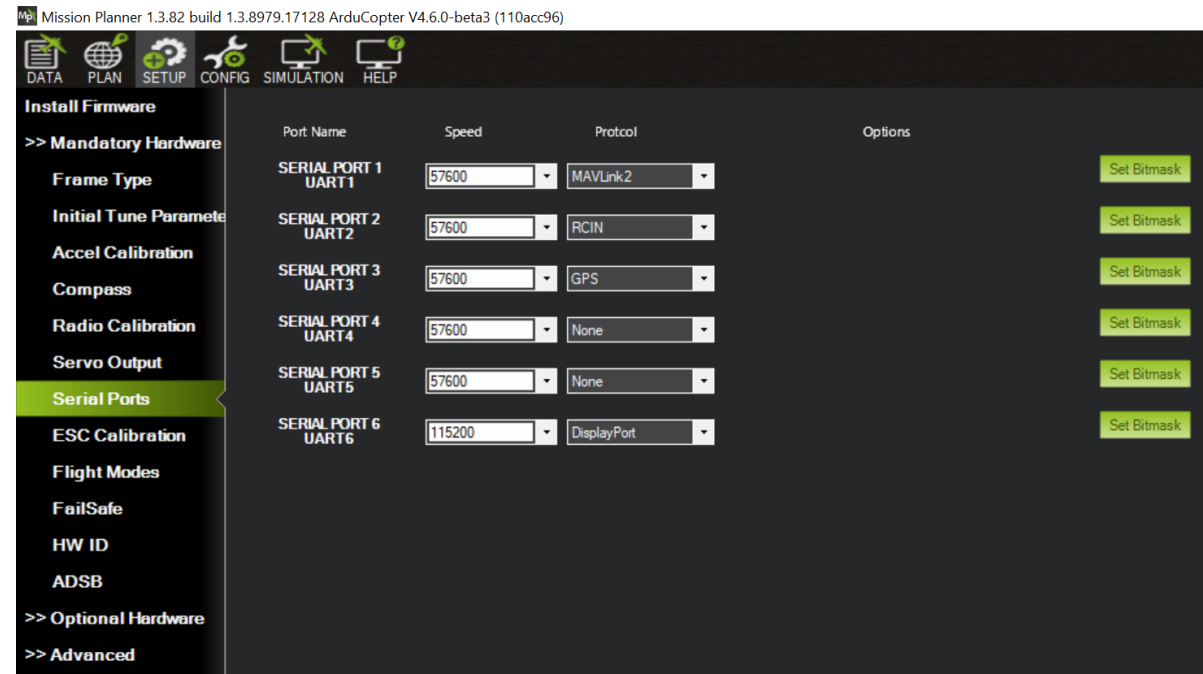
>> Optional Hardware

>> Advanced

#	Position	Reverse	Function	Min	Trim	Max
1	1000	<input type="checkbox"/>	Motor1	1000	1000	2000
2	1000	<input type="checkbox"/>	Motor3	1000	1000	2000
3	1000	<input type="checkbox"/>	Motor4	1000	1000	2000
4	1000	<input type="checkbox"/>	Motor2	1000	1000	2000
5	0	<input type="checkbox"/>	Disabled	1100	1500	1900
6	0	<input type="checkbox"/>	Disabled	1100	1500	1900
7	0	<input type="checkbox"/>	Disabled	1100	1500	1900
8	0	<input type="checkbox"/>	Disabled	1100	1500	1900
9	0	<input type="checkbox"/>	Disabled	1100	1500	1900
10	0	<input type="checkbox"/>	Disabled	1100	1500	1900
11	0	<input type="checkbox"/>	Disabled	1100	1500	1900
12	0	<input type="checkbox"/>	Disabled	1100	1500	1900
13	0	<input type="checkbox"/>	Disabled	1100	1500	1900
14	0	<input type="checkbox"/>	Disabled	1100	1500	1900
15	0	<input type="checkbox"/>	Disabled	1100	1500	1900
16	0	<input type="checkbox"/>	Disabled	1100	1500	1900

Setup – Serial Ports

- Mission Planner > Setup Tab > Mandatory Hardware > Serial Ports
- Set serial ports according to your wiring
 - Receiver -> RCIN, baud rate shouldn't matter
 - GPS -> GPS, baud rate is usually 57600
 - DJI O3/O4 -> Display Port , baud rate is 115200



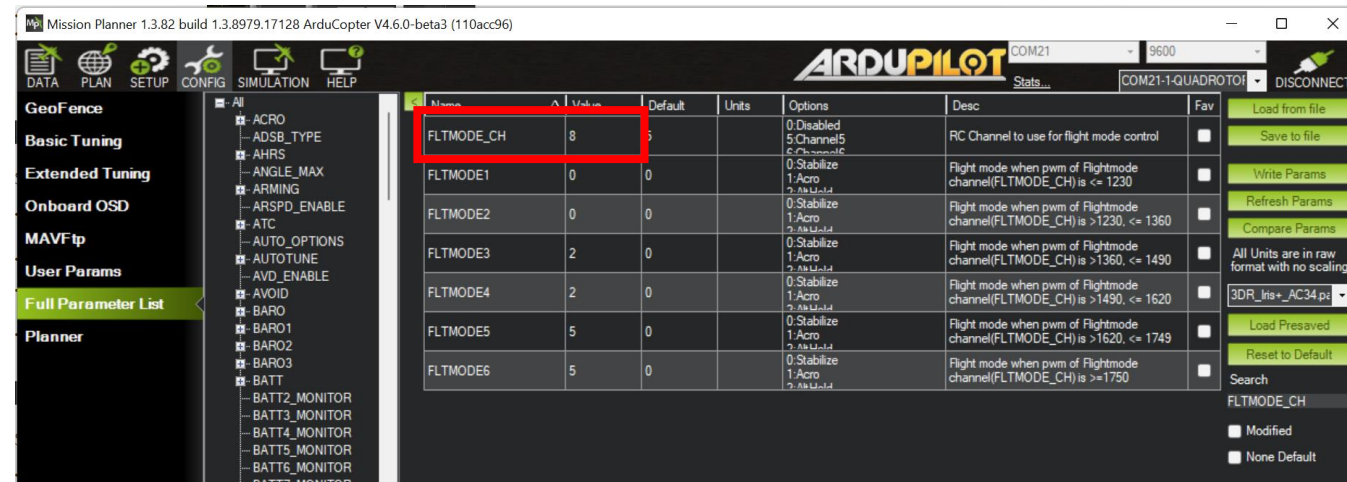
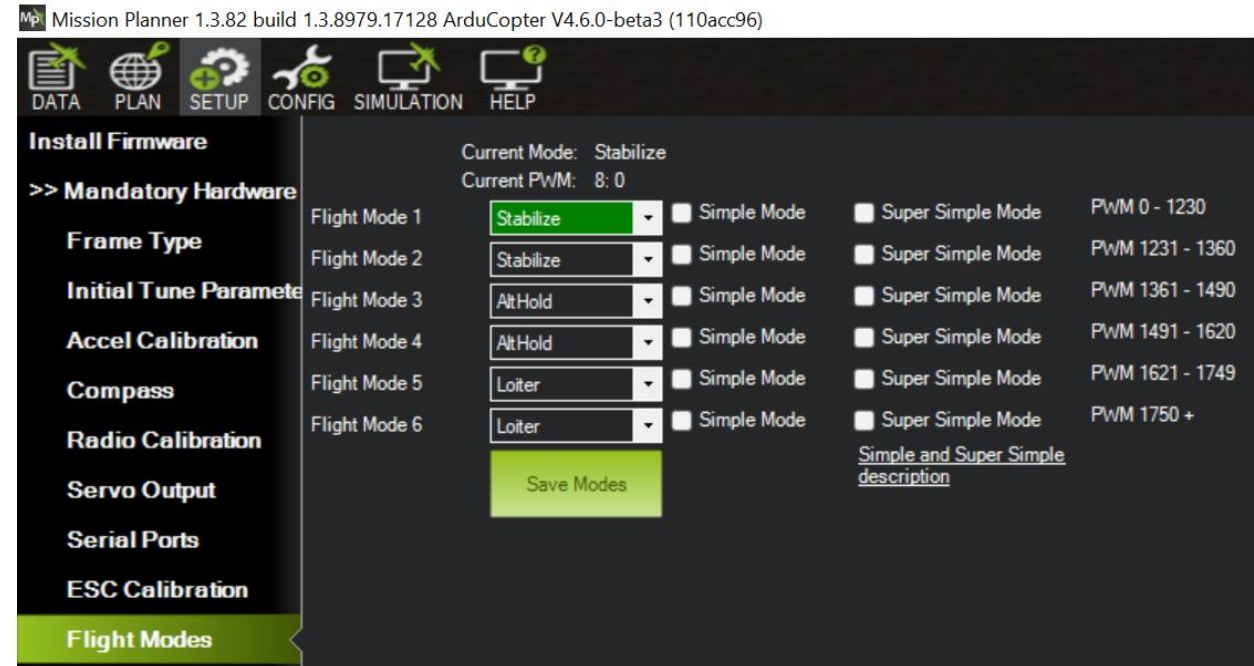
Setup – ESC Calibration

- **Don't click Calibrate ESCs** this can get your FC stuck in a loop and cause issues with digital ESCs that don't support PWM protocol (E.g. BlueJay)
- Set ESC Type to DShot300
 - Spin when armed -> 0.05 to 0.1
 - Spin minimum -> 0.1 to 0.15
 - Spin maximum -> 1.0



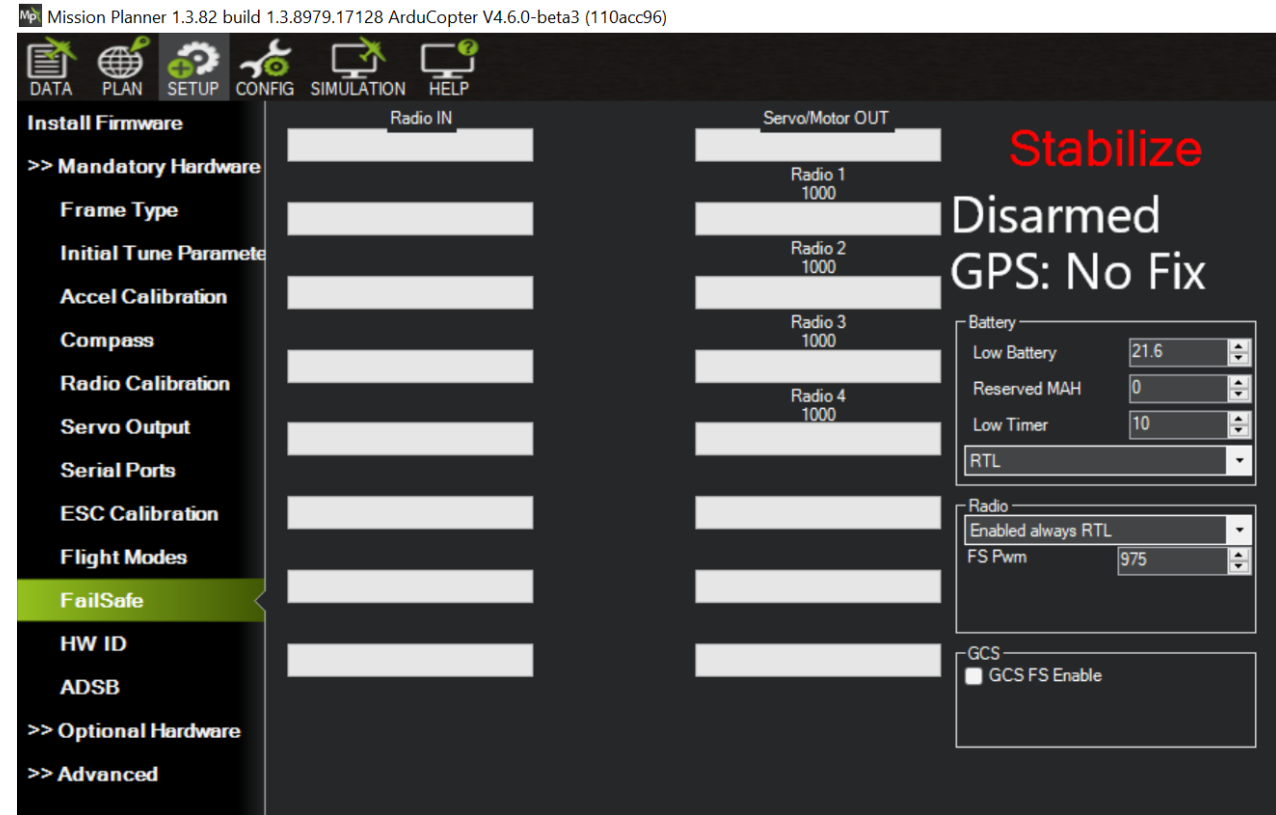
Setup – Flight Modes

- Set up your flight mode switch
- You may want to change which channel on your radio controls flight modes
- Config > Full Parameter List > FLTMODE_CH will accomplish this
- Use Search!



Setup – Failsafe

- In general your Failsafe should probably be RTL (Return To Home and Land)
- Defaults are usually good but check low battery voltage and time



Setup – Battery Voltage

- Mission Planner > Setup Tab > Optional Hardware > Battery Monitor
- The voltage measurement should be correct by default if you've flashed the right target
- The current measurement will depend on the value of the current sense resistor on the ESC
- Typical values
 - 25 mOhm -> 40 Amps per Volt
 - 10 mOhm -> 100 Amps per Volt

Mp Mission Planner 1.3.82 build 1.3.8979.17128 ArduCopter V4.6.0-beta3 (110acc96)

DATA PLAN SETUP CONFIG SIMULATION HELP

Install Firmware

>> **Mandatory Hardware**

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>> **Optional Hardware**

RTK/GPS Inject

CubeID Update

Sik Radio

CAN GPS Order

Battery Monitor

Monitor: Analog Voltage and Current Battery Capacity: 5200 mAh

Sensor: 0: Other MP Alert on Low Battery

HW Ver: 5: VR Brain 4.5 - 5

Calibration

1. Measured battery voltage:	0.03001964508
2. Battery voltage (Calced):	0.03000707366
3. Voltage divider (Calced):	21
4. Measured current:	
5. Current (Calced):	0.07000000029
6. Amperes per volt:	40

Setup – Motor Test

- Mission Planner > Setup Tab > Optional Hardware > Motor Test
- **REMOVE PROPS!**
- For typical 4in1 ESCs the motor order will be wrong!
- You must test and check that the correct motor spins and that it spins in the right direction according to your diagram
- **Double check** or you will have a **big** crash on take-off!
- If you are using a typical Betaflight 4in1 ESC in the usual orientation
 - Servo 1 -> Motor 4
 - Servo 2 -> Motor 1
 - Servo 3 -> Motor 2
 - Servo 4 -> Motor 3

Motor Test

Throttle % 5 Duration (s) 2

Set Motor Spin Arm Set the min % that will be output when armed, but still on the ground

Set Motor Spin Min Set the min % that will be output when flying

NOTE: PLEASE HOLD DOWN YOUR UAV
This will test your motors are working.
Motors are tested in a clockwise rotation starting at the front right.

Please click here to see your motor numbers, scroll to the bottom of the page.

Class: Quad Type: V

Test motor A	Motor Number: 1, CCW
Test motor B	Motor Number: 4, CW
Test motor C	Motor Number: 2, CCW
Test motor D	Motor Number: 3, CW

Test all motors

Stop all motors

Test all in Sequence

QUAD X

QUAD V

DATA PLAN SETUP CONFIG SIMULATION HELP

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>> Optional Hardware

RTK/GPS Inject

CubeID Update

Sik Radio

CAN GPS Order

Battery Monitor

Battery Monitor 2

DroneCAN/UAVCAN

Joystick

Compass/Motor Calib

Range Finder

Airspeed

PX4Flow

Optical Flow

OSD

Camera Gimbal

Motor Test

Setup – Motor Test

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- **Double check** or you will have a **big** crash on take-off!
- If you are using a typical Betaflight 4in1 ESC in the usual orientation
 - Servo 1 -> Motor 4
 - Servo 2 -> Motor 1
 - Servo 3 -> Motor 2
 - Servo 4 -> Motor 3

Mission Planner 1.3.82 build 1.3.8979.17128 ArduCopter V4.6.0-beta3 (110acc96)

DATA PLAN SETUP CONFIG SIMULATION HELP

Install Firmware

>> Mandatory Hardware

Frame Type

Initial Tune Parameters

Accel Calibration

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Radio Calibration

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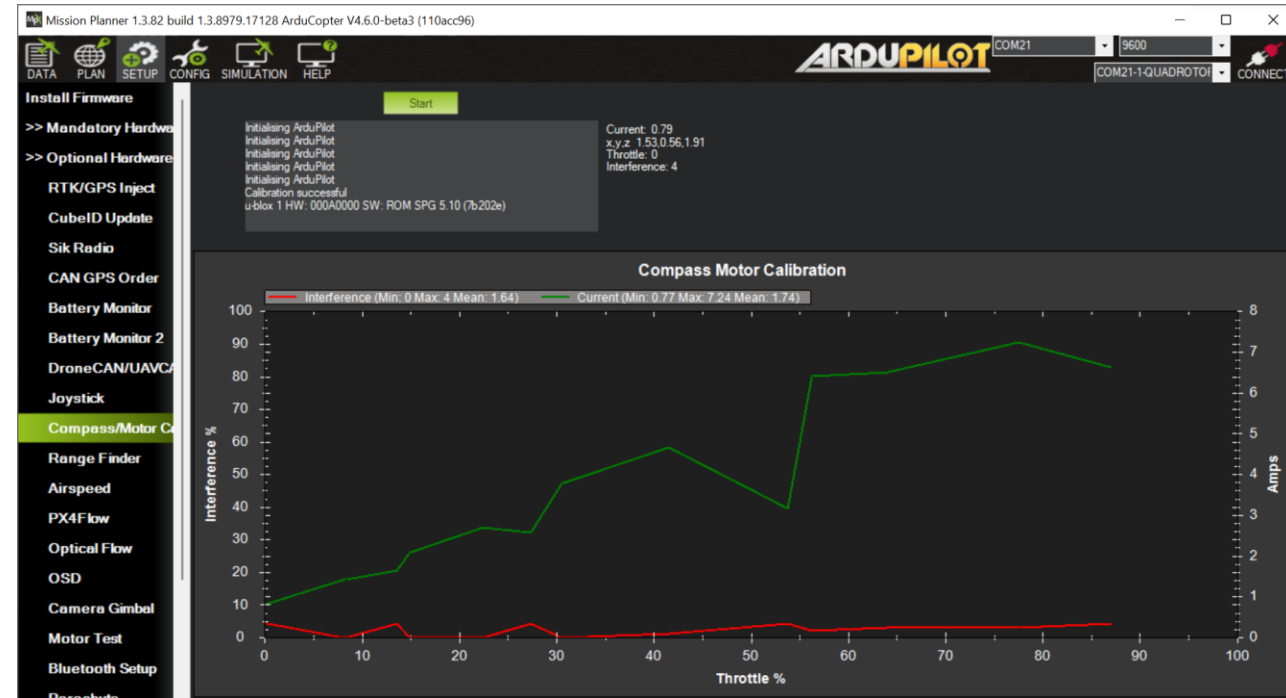
>> Optional Hardware

>> Advanced

#	Position	Reverse	Function	Min	Trim	Max
1	1000	<input type="checkbox"/>	Motor1	1000	1000	2000
2	1000	<input type="checkbox"/>	Motor3	1000	1000	2000
3	1000	<input type="checkbox"/>	Motor4	1000	1000	2000
4	1000	<input type="checkbox"/>	Motor2	1000	1000	2000
5	0	<input type="checkbox"/>	Disabled	1100	1500	1900
6	0	<input type="checkbox"/>	Disabled	1100	1500	1900
7	0	<input type="checkbox"/>	Disabled	1100	1500	1900
8	0	<input type="checkbox"/>	Disabled	1100	1500	1900
9	0	<input type="checkbox"/>	Disabled	1100	1500	1900
10	0	<input type="checkbox"/>	Disabled	1100	1500	1900
11	0	<input type="checkbox"/>	Disabled	1100	1500	1900
12	0	<input type="checkbox"/>	Disabled	1100	1500	1900
13	0	<input type="checkbox"/>	Disabled	1100	1500	1900
14	0	<input type="checkbox"/>	Disabled	1100	1500	1900
15	0	<input type="checkbox"/>	Disabled	1100	1500	1900
16	0	<input type="checkbox"/>	Disabled	1100	1500	1900

Setup – Compass Interference

- Mission Planner > Setup Tab > Optional Hardware > Compass/Motor Calibration
- Not essential but can be good to check
- **Flip props over so drone is pulling down onto the ground**
- Run up to 50-75% throttle for 5-10 seconds to see the effect on the compass reading
- If interference is less than 30% then that's acceptable
- Less than 60% might be OK but consider relocating the compass away from motor wires/battery cables
- More than 60% you should relocate the compass



Gyro Settings

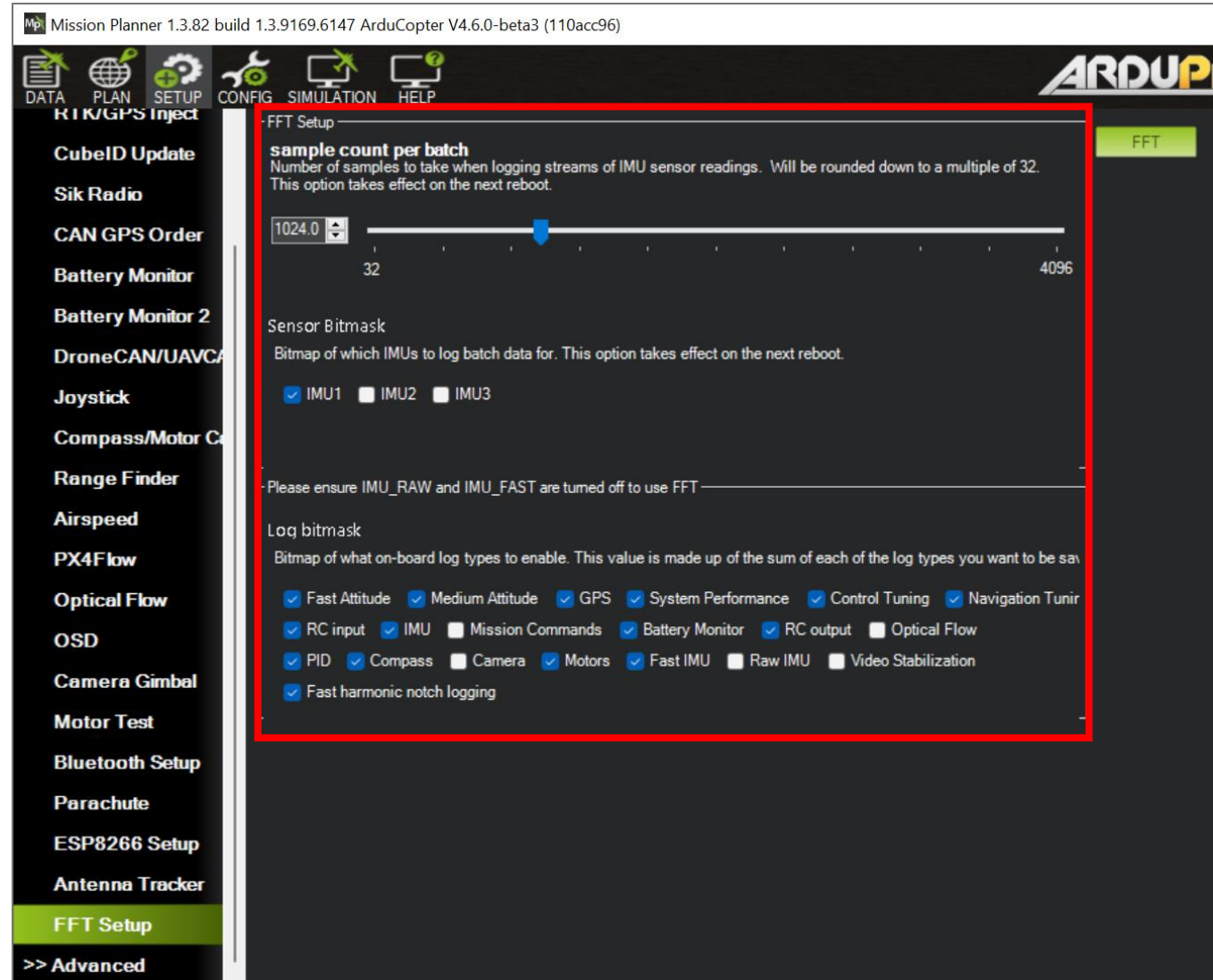
- Mission Planner > Config Tab > Full Parameter List
- For F7 and H7 boards it can be beneficial for flight performance and tuning of smaller drones to set
 - $INS_FAST_SAMPLE = 1$
 - $INS_GYRO_RATE = 1$ (2kHz)
- This avoids aliasing of motor frequencies above 500Hz
- It should be set by default on modern boards

The screenshot shows the Mission Planner interface with the 'Full Parameter List' tab selected. The parameters are listed in a table with columns for Name, Value, Default, Units, Options, and Desc. Two parameters are highlighted with red boxes:

Name	Value	Default	Units	Options	Desc
INS_FAST_SAMPLE	1	1			Mask of IMUs to enable fast sampling on, if available
INS_GYRO_RATE	1	1		0: 1k Hz 1: 2k Hz	Gyro rate for IMUs with fast sampling enabled. The gyro rate is the sample rate at which the IMU filters

Setup – Logging

- Mission Planner > Setup Tab > Optional Hardware > FFT Setup
- Correct logging settings are essential for tuning
- Sample count = 1024 or 2048
- Typically it is best to log only IMU1 to avoid overloading and logging drop-outs
- The logging bitmask should be set as shown
- This captures all the data needed for the tuning process



Mission Planner 1.3.82 build 1.3.9169.6147 ArduCopter V4.6.0-beta3 (110acc96)

DATA PLAN SETUP CONFIG SIMULATION HELP

RTK/GPS Inject

CubeID Update

Sik Radio

CAN GPS Order

Battery Monitor

Battery Monitor 2

DroneCAN/UAVCAN

Joystick

Compass/Motor Control

Range Finder

Airspeed

PX4Flow

Optical Flow

OSD

Camera Gimbal

Motor Test

Bluetooth Setup

Parachute

ESP8266 Setup

Antenna Tracker

FFT Setup

>> Advanced

FFT Setup

sample count per batch
Number of samples to take when logging streams of IMU sensor readings. Will be rounded down to a multiple of 32. This option takes effect on the next reboot.

1024.0 [Slider from 32 to 4096]

Sensor Bitmask
Bitmap of which IMUs to log batch data for. This option takes effect on the next reboot.

IMU1 IMU2 IMU3

Please ensure IMU_RAW and IMU_FAST are turned off to use FFT

Log bitmask
Bitmap of what on-board log types to enable. This value is made up of the sum of each of the log types you want to be saved.

Fast Attitude Medium Attitude GPS System Performance Control Tuning Navigation Tuning

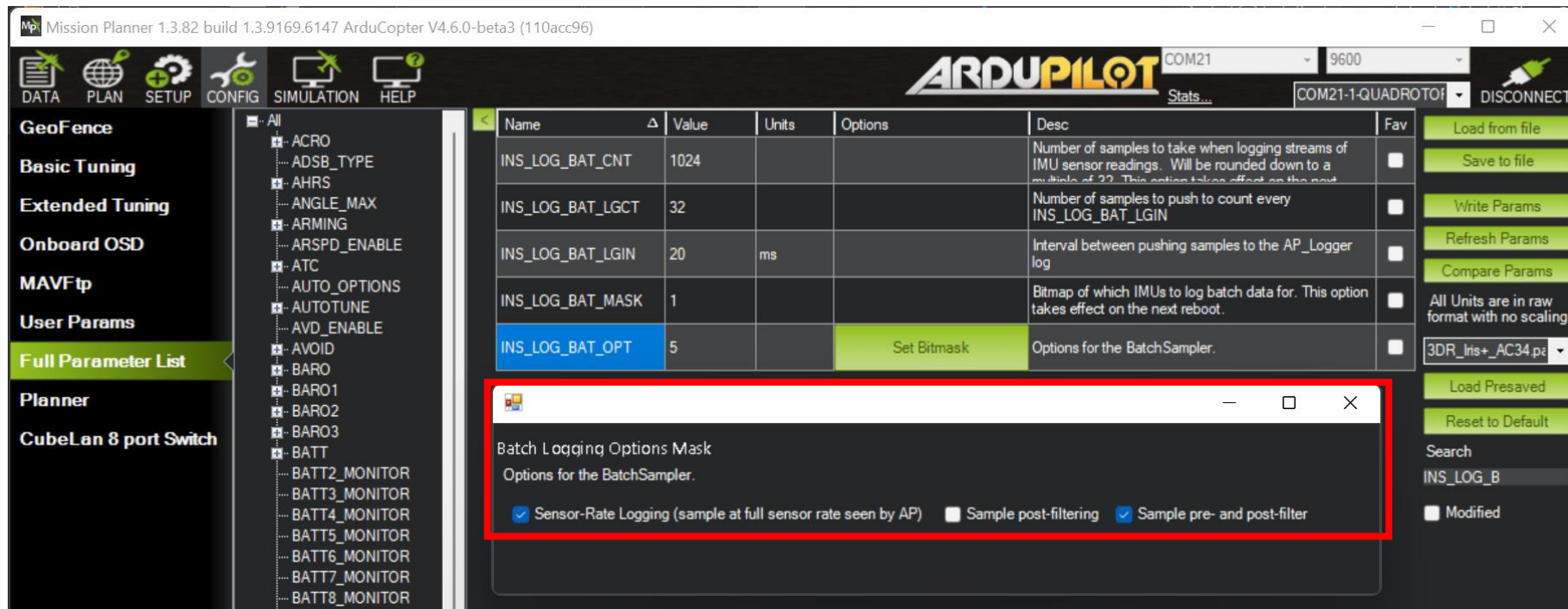
RC input IMU Mission Commands Battery Monitor RC output Optical Flow

PID Compass Camera Motors Fast IMU Raw IMU Video Stabilization

Fast harmonic notch logging

Setup – Logging

- Mission Planner > Config Tab > Full Parameter List
- INS_LOG_BAT_OPT = 5



The screenshot shows the Mission Planner 1.3.82 interface. The 'Full Parameter List' tab is selected in the left sidebar. The main window displays a table of parameters. The parameter 'INS_LOG_BAT_OPT' is highlighted in blue, and its value is set to 5. A red box highlights a pop-up window titled 'Batch Logging Options Mask' which is open over the parameter table. This window shows the following options:

Name	Value	Units	Options	Desc	Fav
INS_LOG_BAT_CNT	1024			Number of samples to take when logging streams of IMU sensor readings. Will be rounded down to a multiple of 20. This option takes effect on the next reboot.	<input type="checkbox"/>
INS_LOG_BAT_LGCT	32			Number of samples to push to count every INS_LOG_BAT_LGIN	<input type="checkbox"/>
INS_LOG_BAT_LGIN	20	ms		Interval between pushing samples to the AP_Logger log	<input type="checkbox"/>
INS_LOG_BAT_MASK	1			Bitmap of which IMUs to log batch data for. This option takes effect on the next reboot.	<input type="checkbox"/>
INS_LOG_BAT_OPT	5		Set Bitmask	Options for the BatchSampler.	<input type="checkbox"/>

Batch Logging Options Mask
Options for the BatchSampler.

- Sensor-Rate Logging (sample at full sensor rate seen by AP)
- Sample post-filtering
- Sample pre- and post-filter

Hover Test!

- Do the hover test in the **Stabilized** Flight Mode
- You may find that the **Pitch Axis is reversed** compared to Betaflight
- If so set parameter **RC2_REVERSED = 1** to fix this

Filter Tuning

Waypoint Navigation

Loiter Mode

Position East/West

Position North/South

Altitude Hold Mode

Velocity East/West

Velocity North/South

Position Up/Down

Acceleration East/West

Acceleration North/South

Velocity Up/Down

Acceleration Up/Down

Stabilize Mode

Angle Roll

Angle Pitch

Angle Yaw

Acro Mode

Rate Roll

Rate Pitch

Rate Yaw

Filters incl. Gyro and Accelerometer Low Pass; RPM and FFT Harmonic Notches; FLTE, FLTD and FLTT

Download the log

- You can download logs within Mission Planner > Data > DataFlash Logs
- Logging space is finite so unless you have a big SD card periodically clean the logs
- Once the log has downloaded you can review it within Mission Planner
- Make a note of where your logs are saved
 - Usually \Documents\Mission Planner\logs\QUADROTOR\1

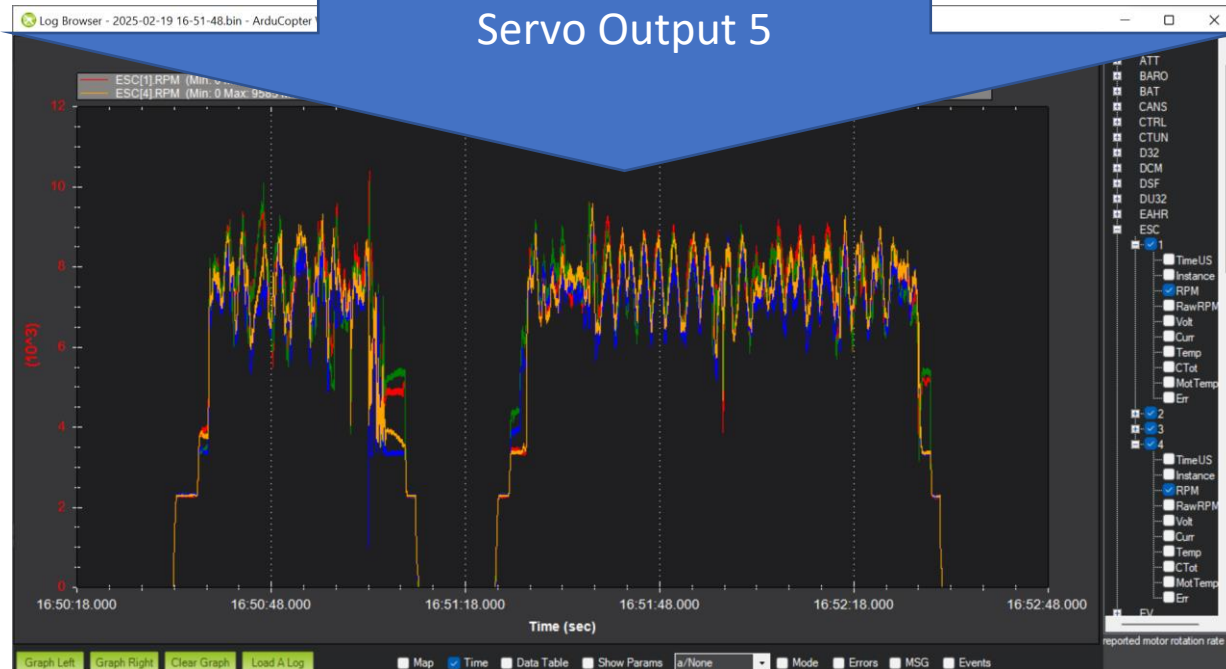


Check RPM Data

- After a hover test check the RPM data in the log
- As you can see I am getting random spikes only on ESC[0]
- This is a conflict on the Servo Output 1 pin for the Matek H7A3
- If you see this:
 - Consider rewiring and using a different servo output pin for that motor 👍
 - Change SERVO_BLH_BDMASK to ignore that channel 😞
 - Use FFT rather than BDSHOT for Harmonic Notch 👍

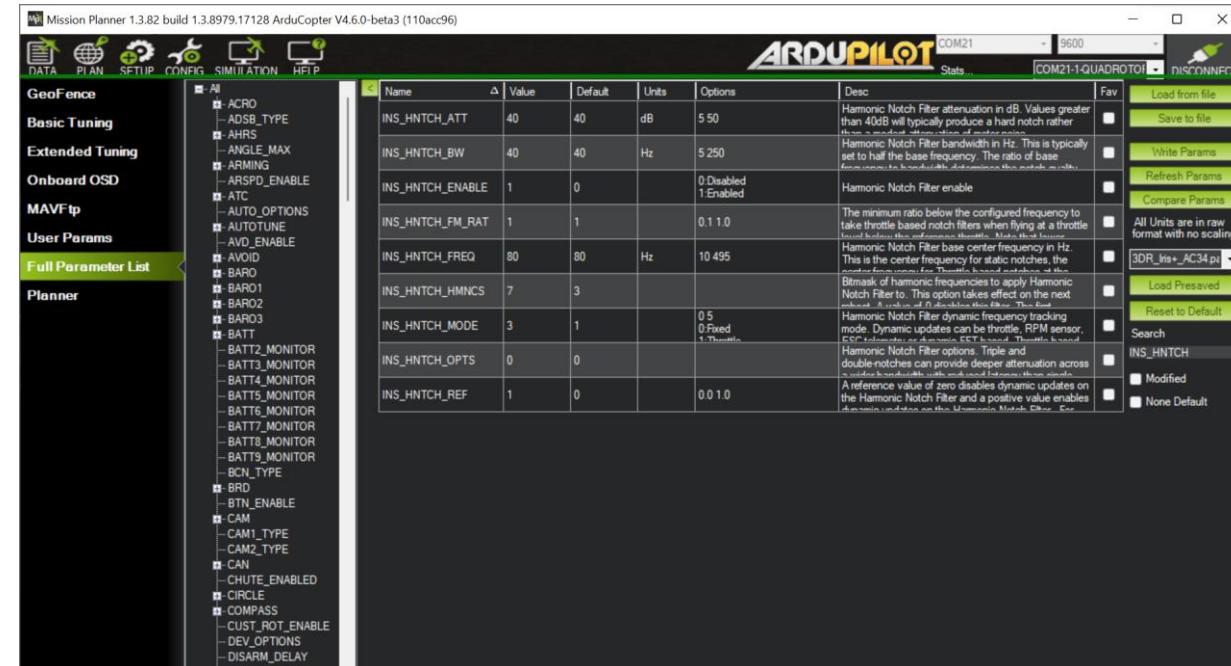


Rewire Servo Output 1 to Servo Output 5



Setup - Harmonic Notches

- Mission Planner > Config Tab > Full Parameter List
- Set **INS_HNTCH_ENABLE = 1** to show notch parameters
- **INS_HNTCH_HMNCS = 7** for 3 harmonics (tri-blade props)
- **INS_HNTCH_MODE = 3** (RPM)
- **INS_HNTCH_OPTIONS = 0** (to begin with)

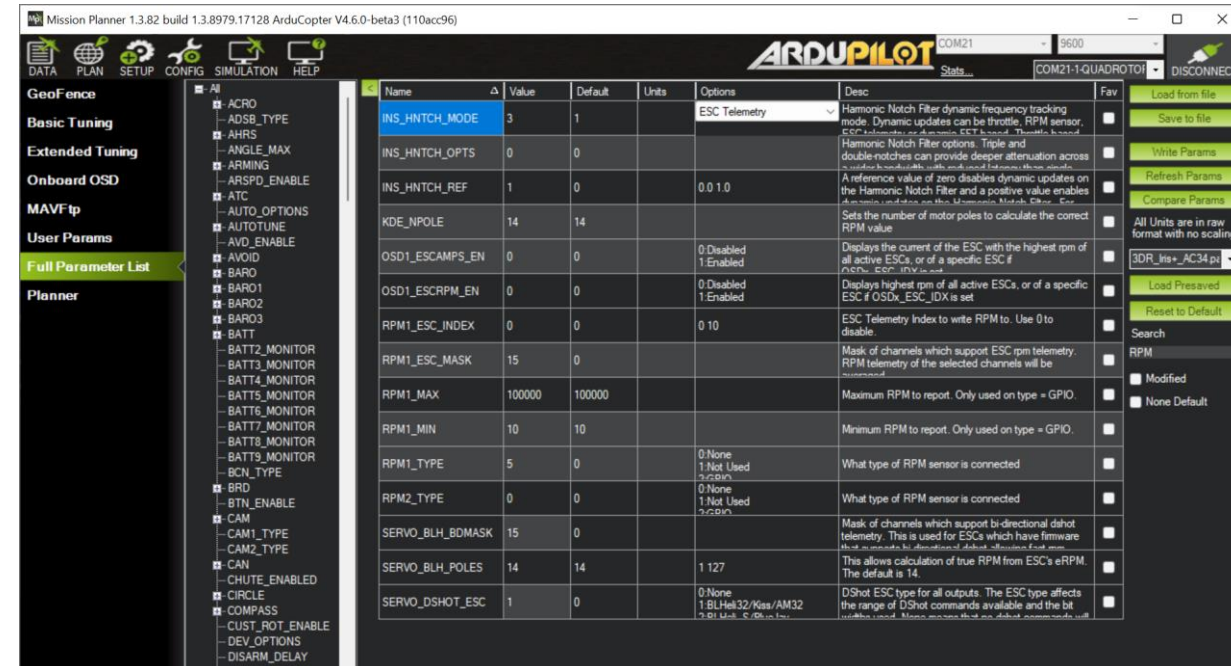


The screenshot shows the Mission Planner 1.3.82 interface with the 'Full Parameter List' tab selected. The parameters are listed in a table with columns for Name, Value, Default, Units, Options, Desc, Fav, and Load from file. The parameters shown are:

Name	Value	Default	Units	Options	Desc	Fav	Load from file
INS_HNTCH_ATT	40	40	dB	5 50	Harmonic Notch Filter attenuation in dB. Values greater than 40dB will typically produce a hard notch rather than a gradual attenuation of the signal.	<input type="checkbox"/>	Load from file
INS_HNTCH_BW	40	40	Hz	5 250	Harmonic Notch Filter bandwidth in Hz. This is typically set to half the base frequency. The ratio of base frequency to bandwidth determines the notch width.	<input type="checkbox"/>	Save to file
INS_HNTCH_ENABLE	1	0		0 Disabled 1 Enabled	Harmonic Notch Filter enable	<input type="checkbox"/>	Write Params
INS_HNTCH_FM_RAT	1	1		0 1 1.0	The minimum ratio below the configured frequency to take throttle based notch filters when flying at a throttle level below this performance throttle. Must be less than 1.	<input type="checkbox"/>	Refresh Params
INS_HNTCH_FREQ	80	80	Hz	10 495	Harmonic Notch Filter base center frequency in Hz. This is the center frequency for static notches, the point from which the throttle based notches are set.	<input type="checkbox"/>	Compare Params
INS_HNTCH_HMNCS	7	3			Mask of harmonic frequencies to apply Harmonic Notch Filter to. This option takes effect on the next instant. A value of 0 disables the filter. The bit 0 is reserved.	<input type="checkbox"/>	All Units are in raw format with no scaling
INS_HNTCH_MODE	3	1		0 5 0 Fixed 1 Throttle	Harmonic Notch Filter dynamic frequency tracking mode. Dynamic updates can be throttle, RPM sensor, ESC telemetry, or dynamic. RCT is used. Throttle based.	<input type="checkbox"/>	3DR_its+_AC34.pl
INS_HNTCH_OPTS	0	0			Harmonic Notch Filter options. Triple and double-notches can provide deeper attenuation across a wider frequency range, but will not be applied when updates are not available. A reference value of zero disables dynamic updates on the Harmonic Notch Filter and a positive value enables dynamic updates on the Harmonic Notch Filter. For	<input type="checkbox"/>	Load Presaved
INS_HNTCH_REF	1	0		0 0 1.0		<input type="checkbox"/>	Reset to Default

Setup – Bi-Directional DShot for RPM (best)

- Set **RPM1_TYPE = 5** for bidirectional DShot
- Set **RPM1_ESC_MASK = 15** for all 4 motors
- Set **SERVO_BLH_BDMASK = 15** for all 4 motors
- Set **SERVO_BLH_POLES = N**
 - N = number of magnets in the motor
 - 14 is typical for 4" to 10" motors
 - 12 is typical for 3" motors
 - If in doubt, count 😊
- Set **SERVO_DSHOT_ESC =**
 - **1** for Kiss/AM32/BL32
 - **2** for BlueJay
 - All latest ESC FWs supports Extended DShot Telemetry (EDT) so you can try **3** and **4** instead if you want the extra information

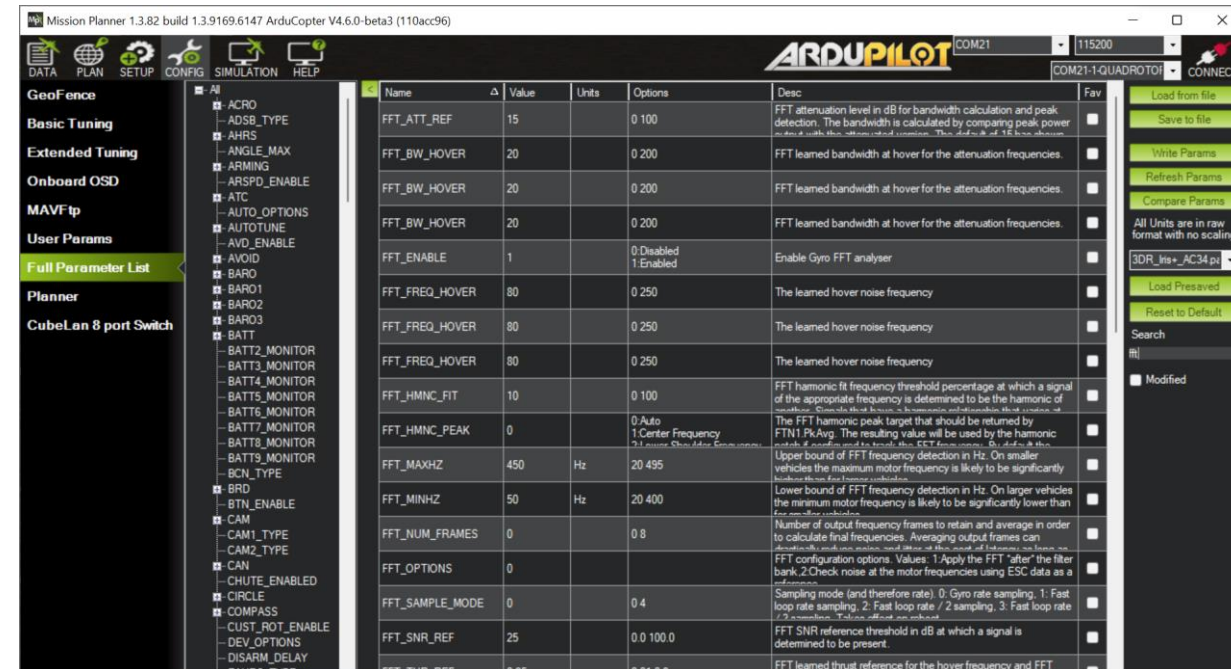


The screenshot shows the Mission Planner interface with the 'Full Parameter List' tab selected. The parameters are listed in a table with columns for Name, Value, Default, Units, Options, Desc, and Fav. The parameters are:

Name	Value	Default	Units	Options	Desc	Fav
INS_HNTCH_MODE	3	1		ESC Telemetry	Hamonic Notch Filter dynamic frequency tracking mode. Dynamic updates can be throttle, RPM sensor, ESC telemetry, or a specific ESC ID.	
INS_HNTCH_OPTS	0	0			Hamonic Notch Filter options. Triple and double-notches can provide deeper attenuation across a wider bandwidth, with increased latency. The Hamonic Notch Filter and a positive value enables dynamic updates on the Hamonic Notch Filter.	
INS_HNTCH_REF	1	0	0.0 1.0		A reference value of zero disables dynamic updates on the Hamonic Notch Filter.	
KDE_NPOLE	14	14			Sets the number of motor poles to calculate the correct RPM value.	
OSD1_ESCAMPS_EN	0	0		0 Disabled 1 Enabled	Displays the current of the ESC with the highest rpm of all active ESCs, or of a specific ESC if OSD1_ESC_IDX is set.	
OSD1_ESCRPM_EN	0	0		0 Disabled 1 Enabled	Displays highest rpm of all active ESCs, or of a specific ESC if OSD1_ESC_IDX is set.	
RPM1_ESC_INDEX	0	0		0 10	ESC Telemetry Index to write RPM to. Use 0 to disable.	
RPM1_ESC_MASK	15	0			Mask of channels which support ESC rpm telemetry. RPM telemetry of the selected channels will be reported.	
RPM1_MAX	100000	100000			Maximum RPM to report. Only used on type = GPIO.	
RPM1_MIN	10	10			Minimum RPM to report. Only used on type = GPIO.	
RPM1_TYPE	5	0		0 None 1 Not Used 2 GPIO	What type of RPM sensor is connected.	
RPM2_TYPE	0	0		0 None 1 Not Used 2 GPIO	What type of RPM sensor is connected.	
SERVO_BLH_BDMASK	15	0			Mask of channels which support bi-directional dshot telemetry. This is used for ESCs which have firmware that supports bi-directional DShot telemetry.	
SERVO_BLH_POLES	14	14		1 127	This allows calculation of true RPM from ESC's eRPM. The default is 14.	
SERVO_DSHOT_ESC	1	0		0 None 1 BLHeli32/Kiss/AM32 2 BlueJay 3 EDT 4 EDT	DShot ESC type for all outputs. The ESC type affects the range of DShot commands available and the bit width used. More recent DShot commands will	

Setup – Dynamic FFT (if no RPM available)

- Set **FFT_ENABLE = 1** to enable FFT and show parameters
- Set **INS_HNTCH_MODE = 4** to use FFT to drive the notches
- Set **FFT_MAXHZ = X**
 - $X = 0.8 * V_{batt} * K_V / 60$
 - V_{batt} = Fully charged battery voltage
 - K_V = Motor KV
- Set **FFT_MINHZ = Y**
 - $Y = 500 / D_{prop}$
 - D_{prop} = Prop Diameter in Inches
- Set **FFT_WINDOW_SIZE = 256 (F7) or 512 (H7)**
 - Resolution is $INS_GYRO_RATE / FFT_WINDOW_SIZE$
 - ~8Hz for 256
 - ~4Hz for 512
 - You will benefit from **FFT_WINDOW_SIZE = 1024** on an H7 if CPU speed allows!



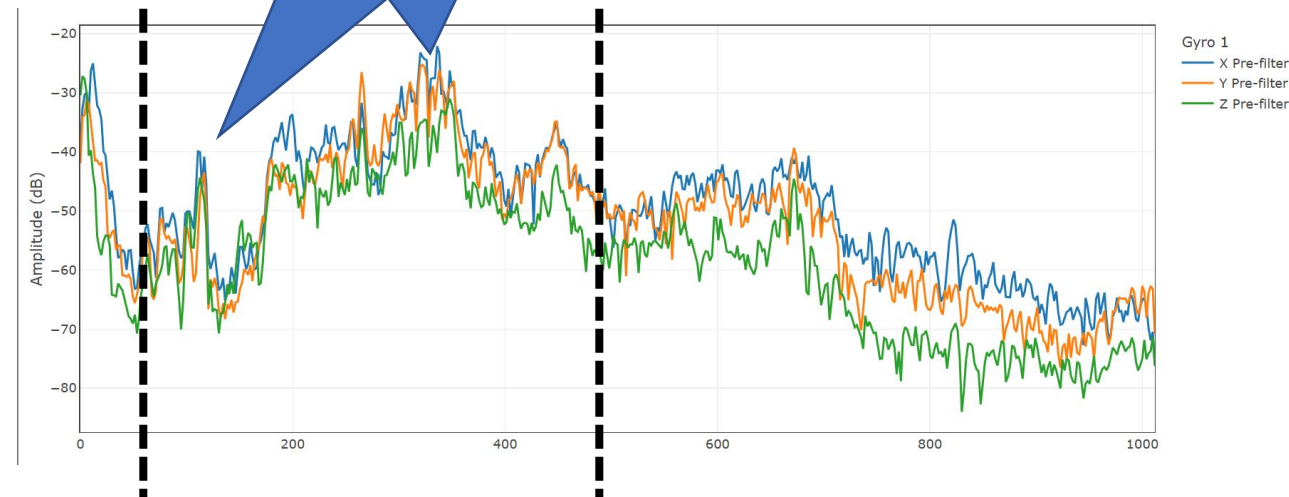
The screenshot shows the Mission Planner interface with the 'Full Parameter List' tab selected. The parameters are organized into a table with columns for Name, Value, Units, Options, and Desc. The parameters are as follows:

Name	Value	Units	Options	Desc
FFT_ATT_REF	15		0 100	FFT attenuation level in dB for bandwidth calculation and peak detection. The bandwidth is calculated by comparing peak power with the attenuated portion. The value of 15 has shown
FFT_BW_HOVER	20		0 200	FFT learned bandwidth at hover for the attenuation frequencies.
FFT_BW_HOVER	20		0 200	FFT learned bandwidth at hover for the attenuation frequencies.
FFT_BW_HOVER	20		0 200	FFT learned bandwidth at hover for the attenuation frequencies.
FFT_ENABLE	1		0:Disabled 1:Enabled	Enable Gyro FFT analyser
FFT_FREQ_HOVER	80		0 250	The learned hover noise frequency
FFT_FREQ_HOVER	80		0 250	The learned hover noise frequency
FFT_FREQ_HOVER	80		0 250	The learned hover noise frequency
FFT_HMNC_FIT	10		0 100	FFT harmonic fit frequency threshold percentage at which a signal of the appropriate frequency is determined to be the harmonic of another. One note that because of harmonics, it is possible that a signal of a certain frequency is determined to be the harmonic of another, but the resulting value will be used by the harmonic notch filter to notch the FFT frequency. Do not set this
FFT_HMNC_PEAK	0		0 Auto 1 Center Frequency 2 Lower Threshold Frequency	The FFT harmonic peak target that should be returned by FFT_HMNC_FIT. The resulting value will be used by the harmonic notch filter to notch the FFT frequency. Do not set this
FFT_MAXHZ	450	Hz	20 495	Upper bound of FFT frequency detection in Hz. On smaller vehicles the maximum motor frequency is likely to be significantly higher than the maximum motor frequency.
FFT_MINHZ	50	Hz	20 400	Lower bound of FFT frequency detection in Hz. On larger vehicles the minimum motor frequency is likely to be significantly lower than the minimum motor frequency.
FFT_NUM_FRAMES	0		0 8	Number of output frequency frames to retain and average in order to calculate final frequencies. Averaging output frames can smooth out noise and provide more accurate data. All settings are done on FFT configuration options. Values: 1: Apply the FFT "after" the filter bank, 2: Check noise at the motor frequencies using ESC data as a reference.
FFT_OPTIONS	0			Sampling mode (and therefore rate): 0: Gyro rate sampling, 1: Fast loop rate sampling, 2: Fast loop rate / 2 sampling, 3: Fast loop rate / 2 sampling. Values: 1: Apply the FFT "after" the filter bank, 2: Check noise at the motor frequencies using ESC data as a reference.
FFT_SAMPLE_MODE	0		0 4	Sampling mode (and therefore rate): 0: Gyro rate sampling, 1: Fast loop rate sampling, 2: Fast loop rate / 2 sampling, 3: Fast loop rate / 2 sampling. Values: 1: Apply the FFT "after" the filter bank, 2: Check noise at the motor frequencies using ESC data as a reference.
FFT_SNR_REF	25		0 0 100 0	FFT SNR reference threshold in dB at which a signal is determined to be present.
FFT_THR_REF	0.25		0 0 1 0	FFT learned thrust reference for the hover frequency and FFT

What is Dynamic FFT

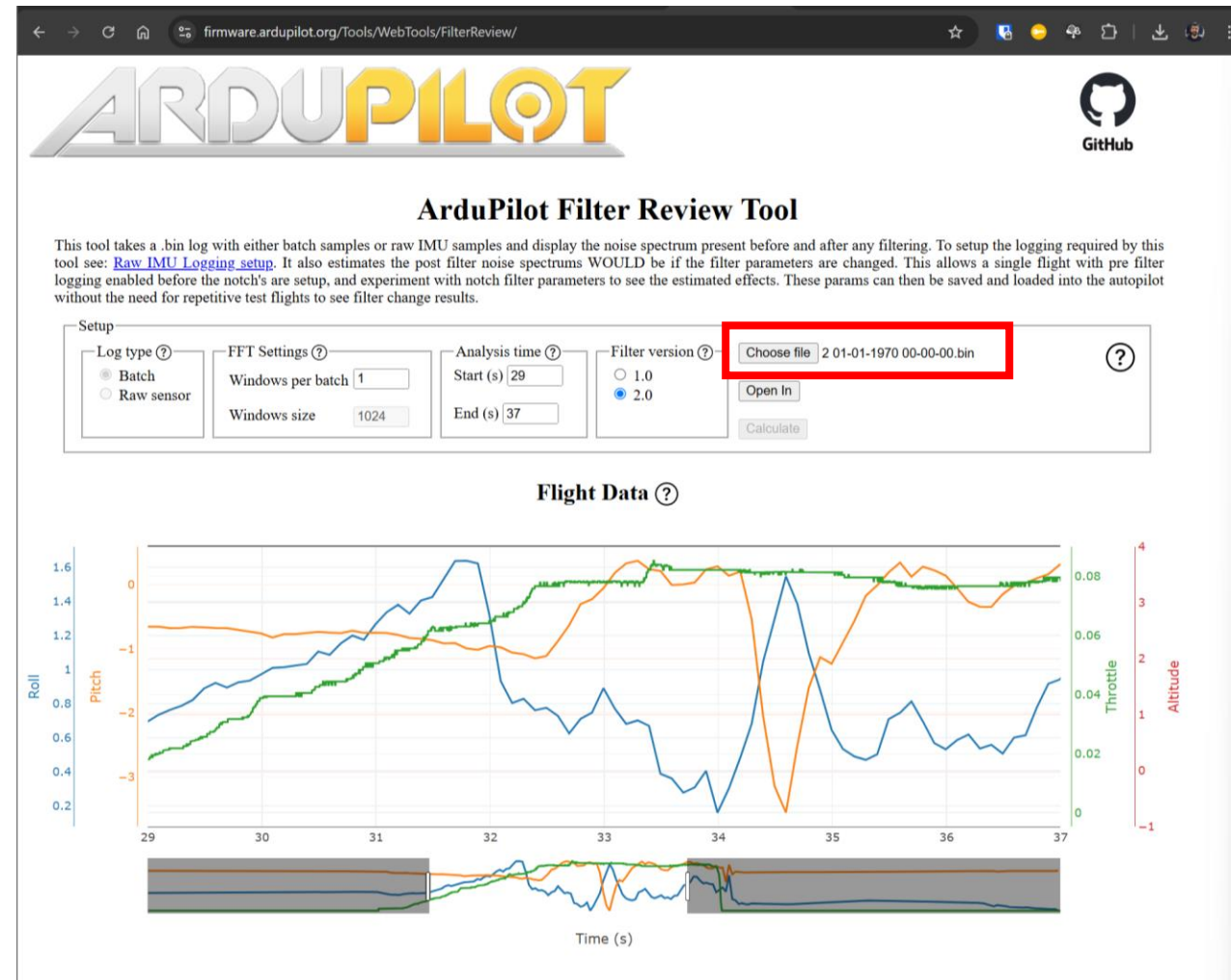
- Dynamic FFT looks at a sample of data from the gyro to try and determine the presence of noise peaks and their frequency
- This can be used to drive notch filters to reduce the effect of noise
- It is slower and less precise than RPM data for motor noise
- It can be useful for frame resonances but is CPU intensive

Dynamic FFT uses gyro data to locate noise peaks between a minimum and maximum frequency



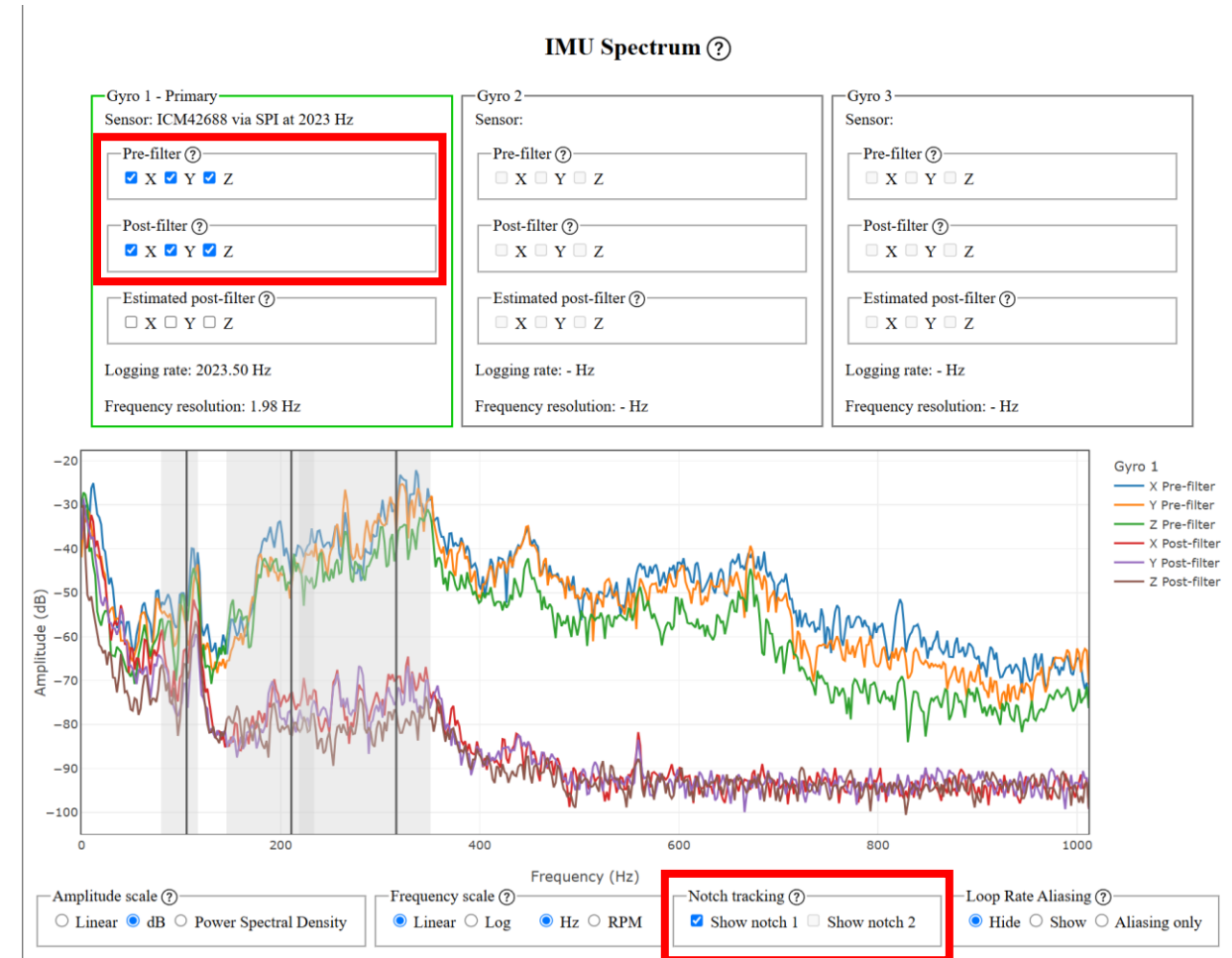
Filter Review – Load Log

- Open your log in ArduPilot WebTools Filter Review:
<https://firmware.ardupilot.org/Tools/WebTools/FilterReview/>
- Check that the Flight Data Graph looks correct and there are no gaps (logging drop outs)



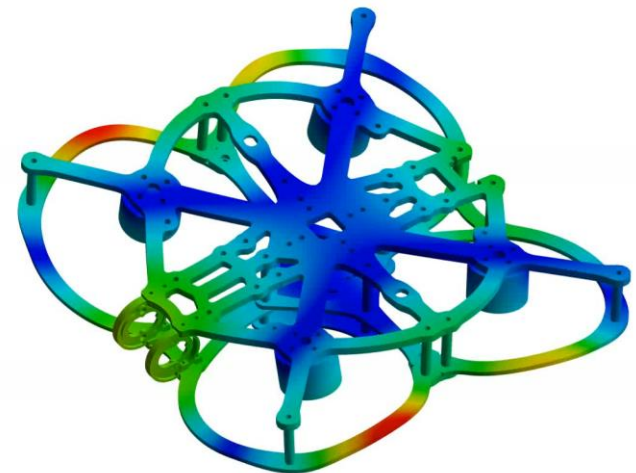
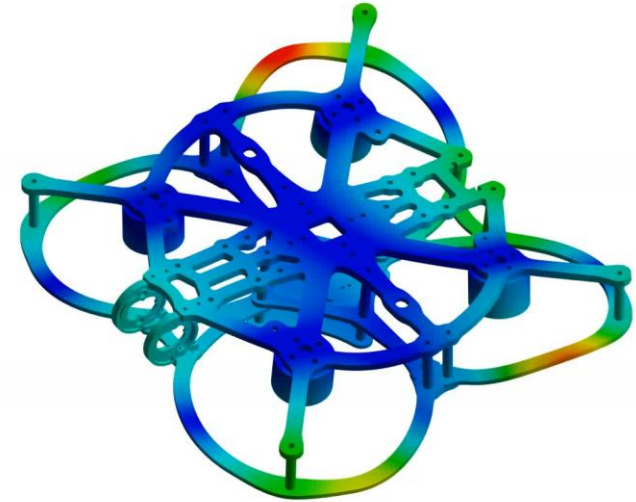
Filter Review – IMU Spectrum

- Scroll Down to the IMU Spectrum
- With my logging settings you should be able to see
 - Pre-Filter Gyro Data
 - Post-Filter Gyro Data
 - Notch Tracking
- You will also see the effect of the Gyro Low Pass filter reducing the noise power at high frequencies



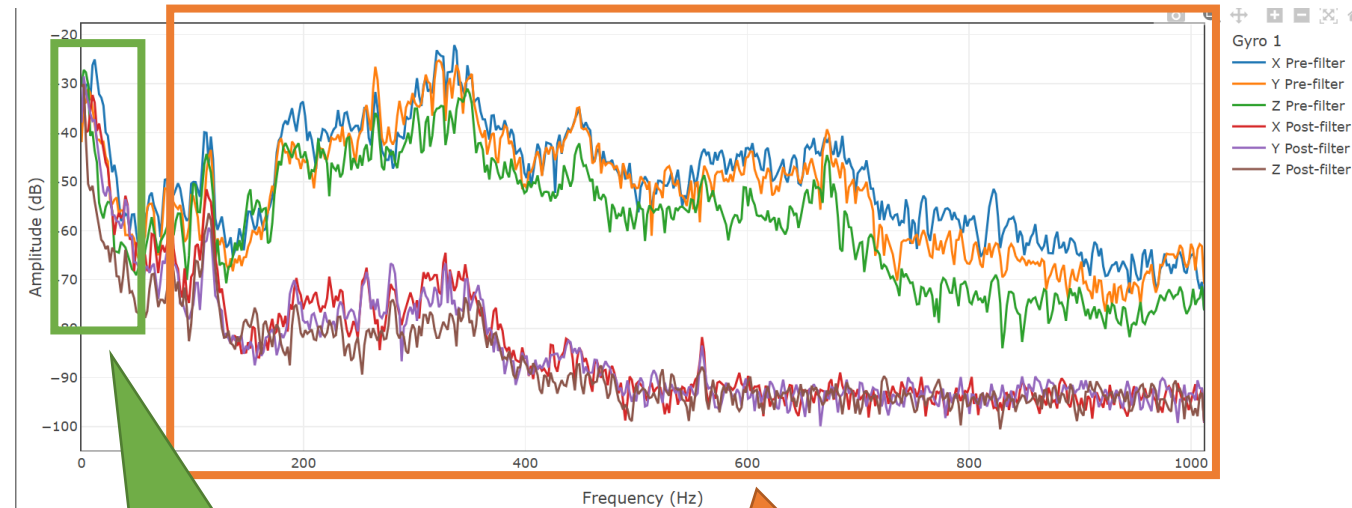
Gyro Low Pass Filter (INS_GYRO_FILTER)

- The Gyro in a Drone is sensitive both to the rigid body movements of the drone (signal) but also to vibrations (noise)
- Vibration is generated by the spinning motors and props (and some payloads)
- Resonance of the drone's airframe and payload can also amplify certain frequencies



Gyro Low Pass Filter (INS_GYRO_FILTER)

- The energy in vibrations (noise) is usually much higher than the energy in the rigid body movement of the drone (signal)!
- Fortunately the real movements are at a low frequency and the vibrations are at higher frequencies
- The Gyro Low Pass Filter takes advantage of this to reduce the noise without compromising the signal too much!

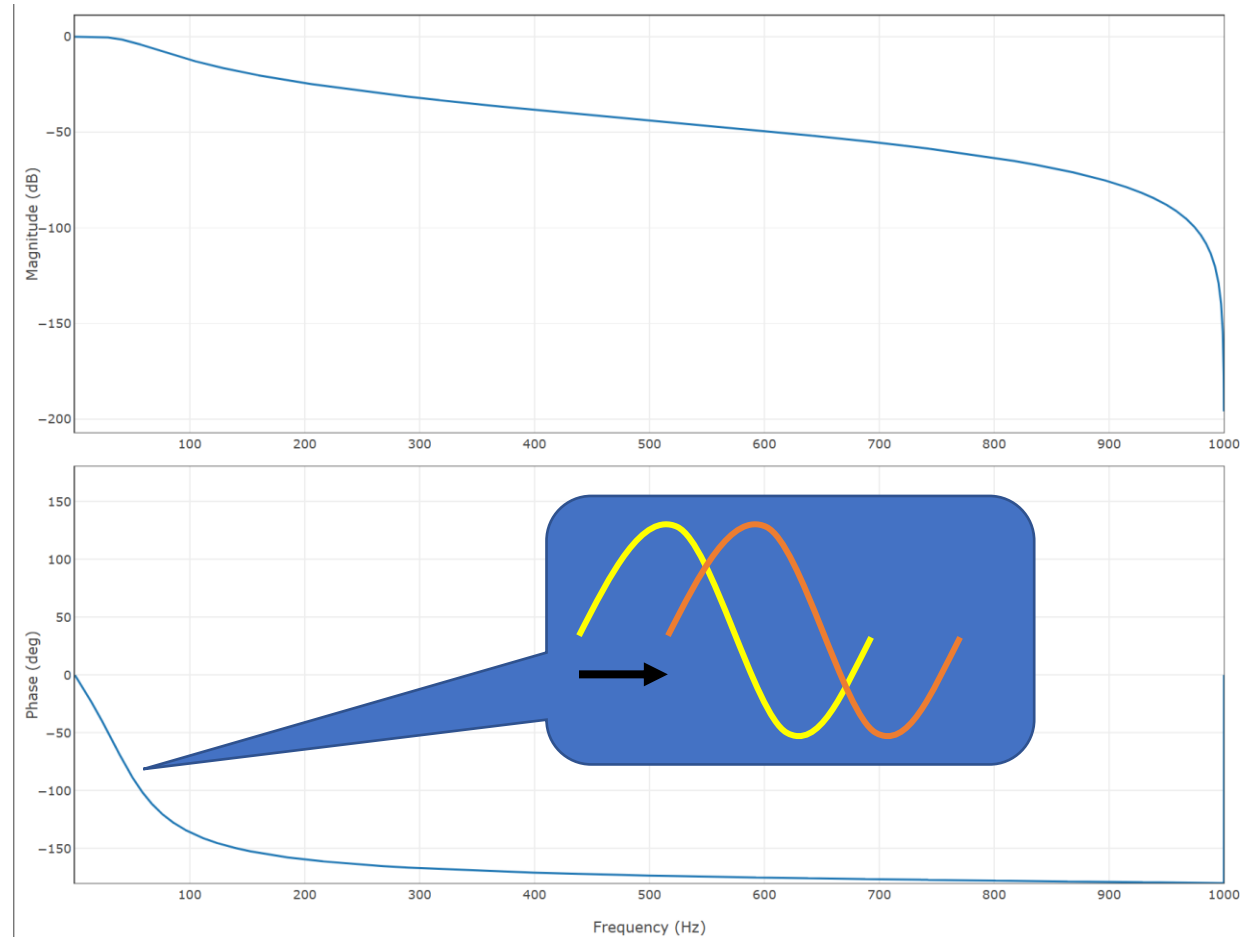


Real movements of the drone are usually below ~30Hz

Vibrations are usually above ~50Hz but depend on Prop RPM!

Gyro Low Pass Filter (INS_GYRO_FILTER)

- Unfortunately the Gyro Low Pass Filter has some trade-offs
- Any low pass filter attenuates high frequencies but also adds delay
- The lower the 3dB cut-off frequency of the filter the more delay is added
- This delay slows the reaction of the drone to air turbulence and control inputs



Tuning the Gyro Low Pass Filter

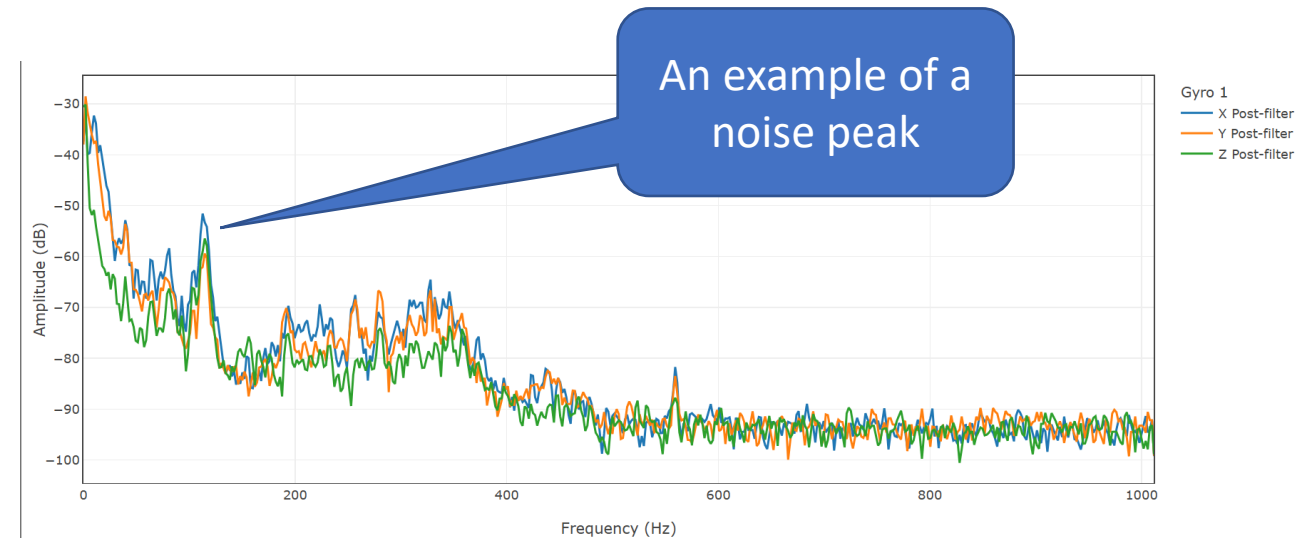
- We want to gradually increase the cut-off frequency of the Gyro low pass filter as high as possible without letting noise through
- Our main adversary is the fundamental motor frequency / lowest frame resonance
- We want this peak to be below -50dB in the post-filter data
- We will tackle this peak using Ardupilot's **Harmonic Notch Filters**



RPM Based Harmonic Notch Filtering

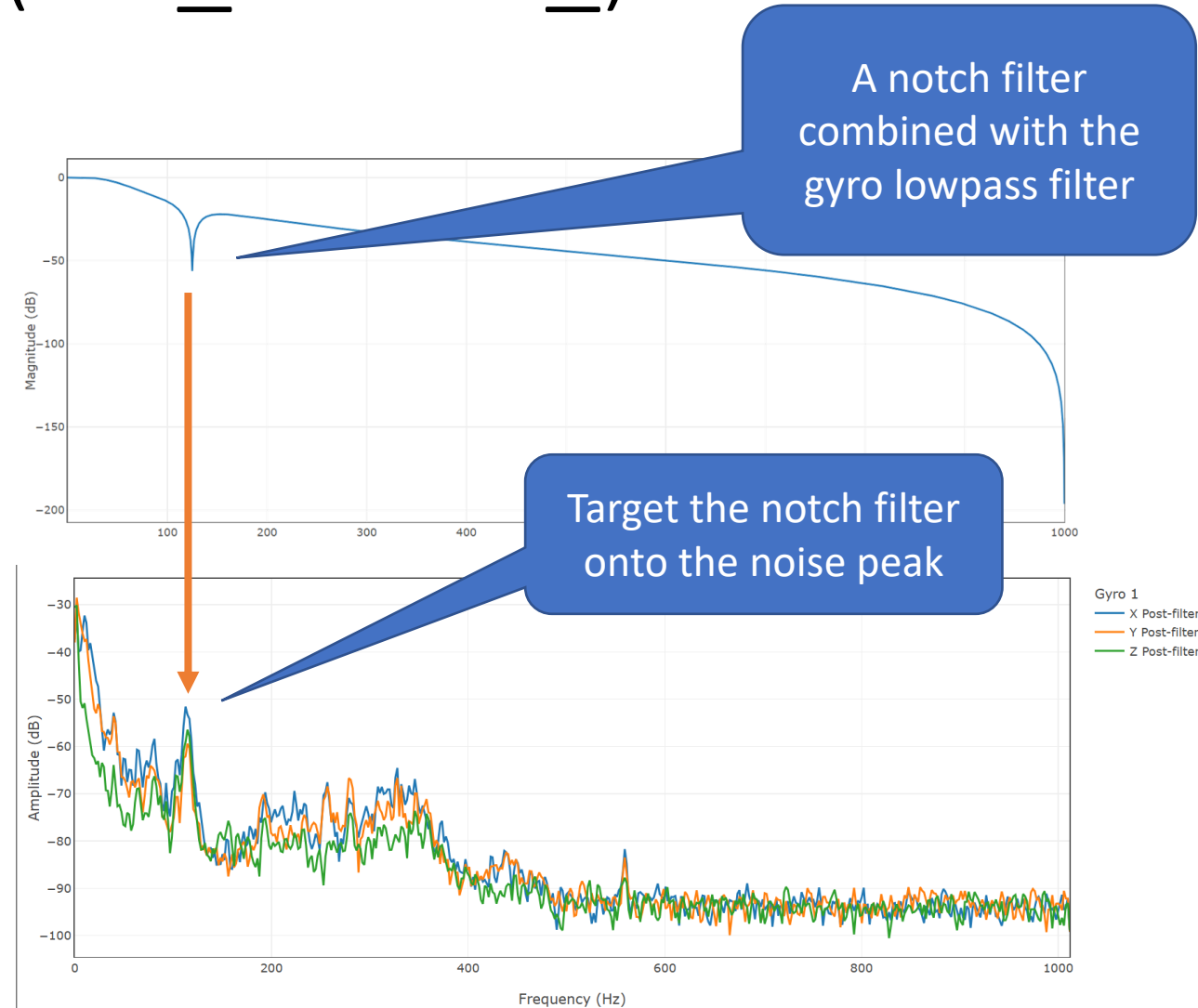
Harmonic Notch Filter (INS_HNTCH_)

- As well as broad band high frequency noise drones also experience peaks of noise at specific frequencies
- These peaks are created by the rotation frequency of the motors and airframe resonances
- Peaks of noise are best handled by notch filtering



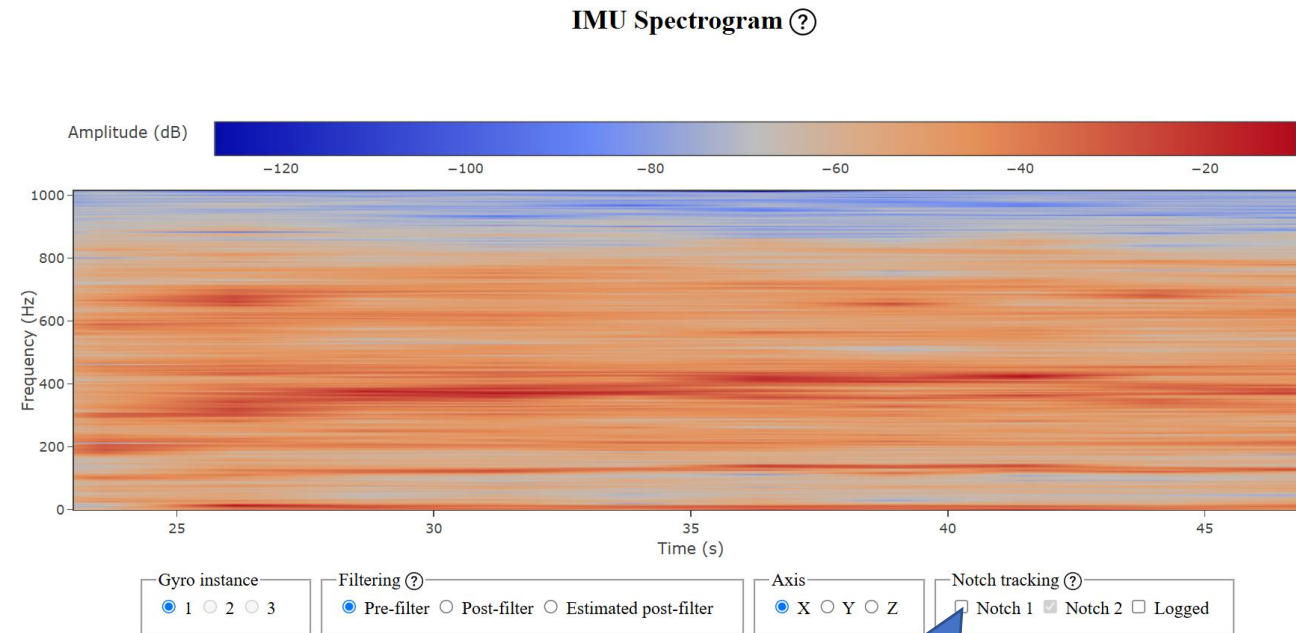
Harmonic Notch Filter (INS_HNTCH_)

- Notch filters provide a very high degree of attenuation of noise around a target frequency
- They create much less delay than an equivalent low pass filter
- The narrower the notch the less delay it creates but the more precisely the target frequency must match the noise peak
- Tuning notch filters is about targeting narrow notches precisely where there are noise peaks



Filter Review – IMU Spectrogram

- The IMU Spectrogram is used to validate and tune the Harmonic Notch Filters
- It shows the noise power at different frequencies over time
- Zooming in to a few seconds of Hovering allows us to look at the key features (Turn **off** Notch tracking for now)

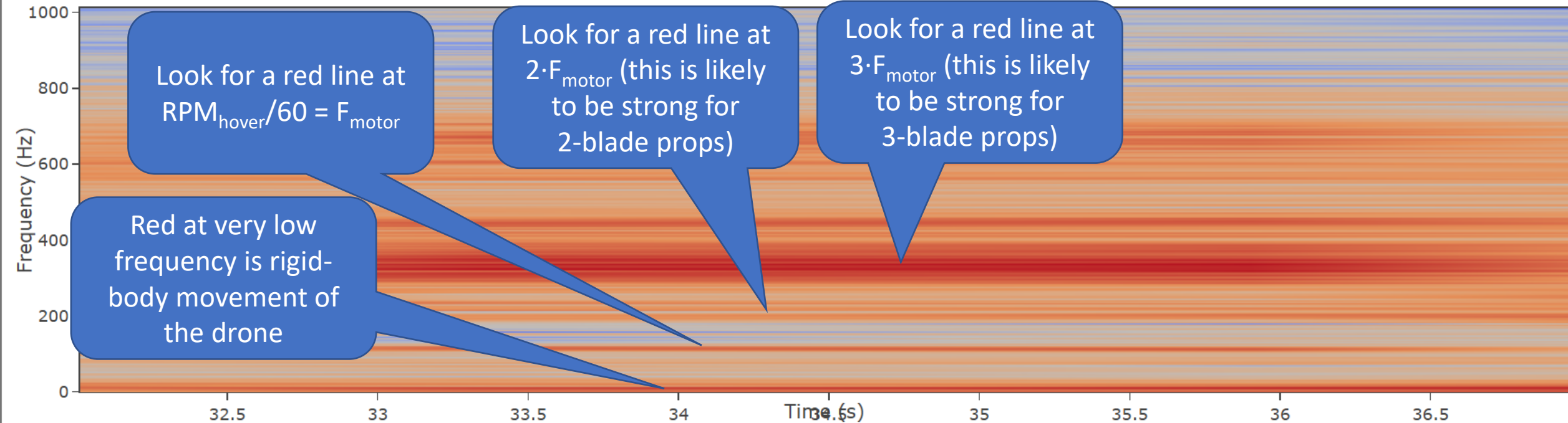


Turn off Notch Tracking for now

Filter Review – IMU Spectrogram

$$\text{RPM}_{\text{hover}} \approx V_{\text{batt}} \cdot K_V \cdot T_{\text{hover}}$$

Amplitude (dB)



Gyro instance

1 2 3

Filtering (?)

Pre-filter Post-filter Estimated post-filter

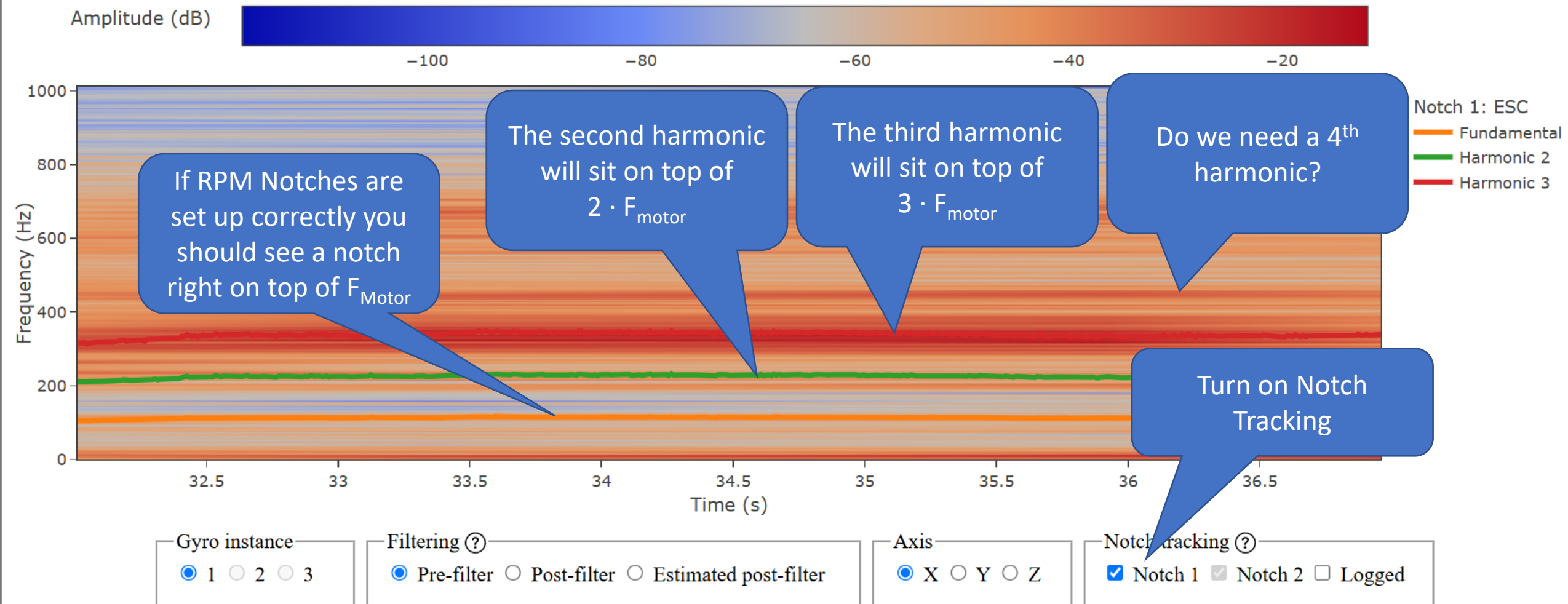
Axis

X Y Z

Notch tracking (?)

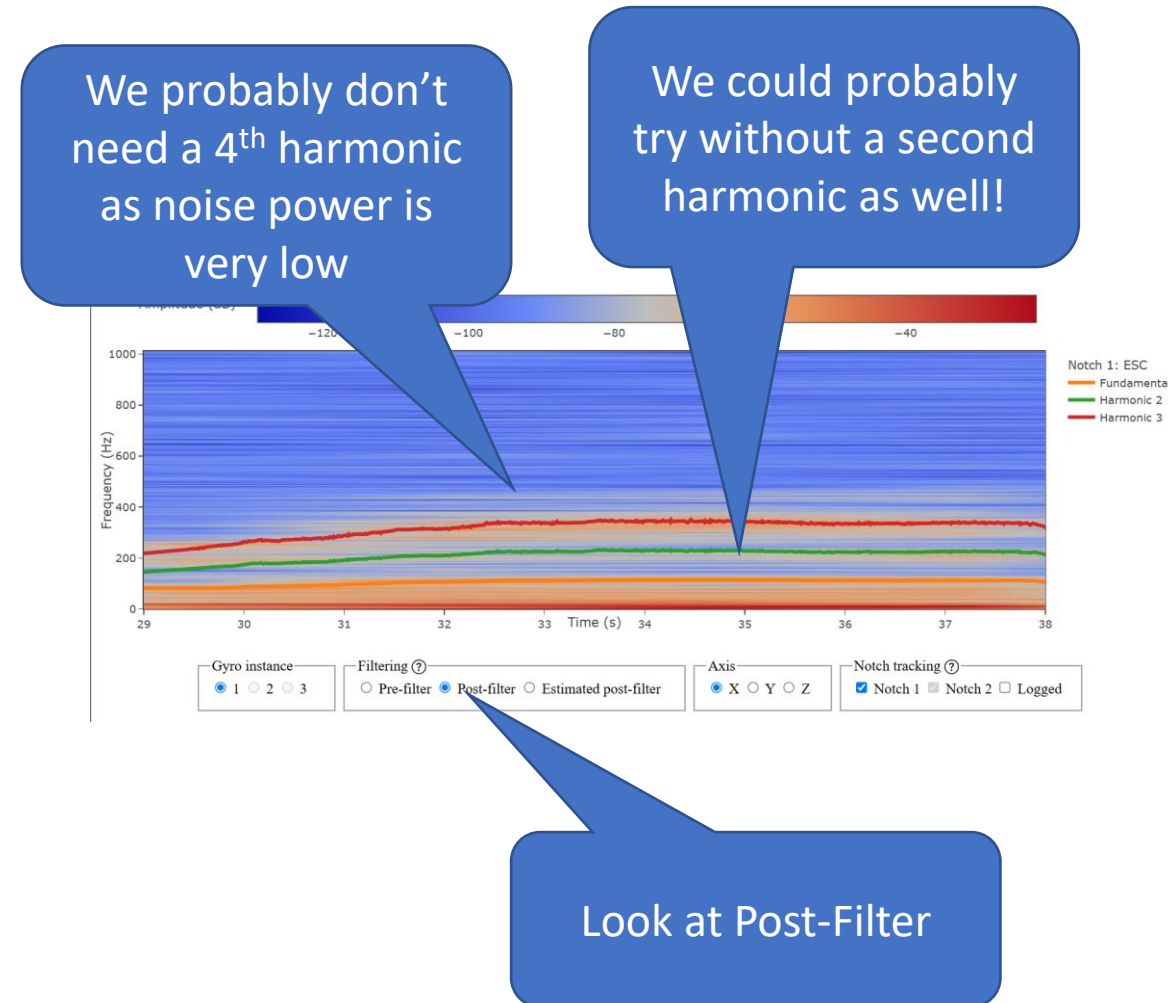
Notch 1 Notch 2 Logged

Filter Review – IMU Spectrogram – RPM Filter

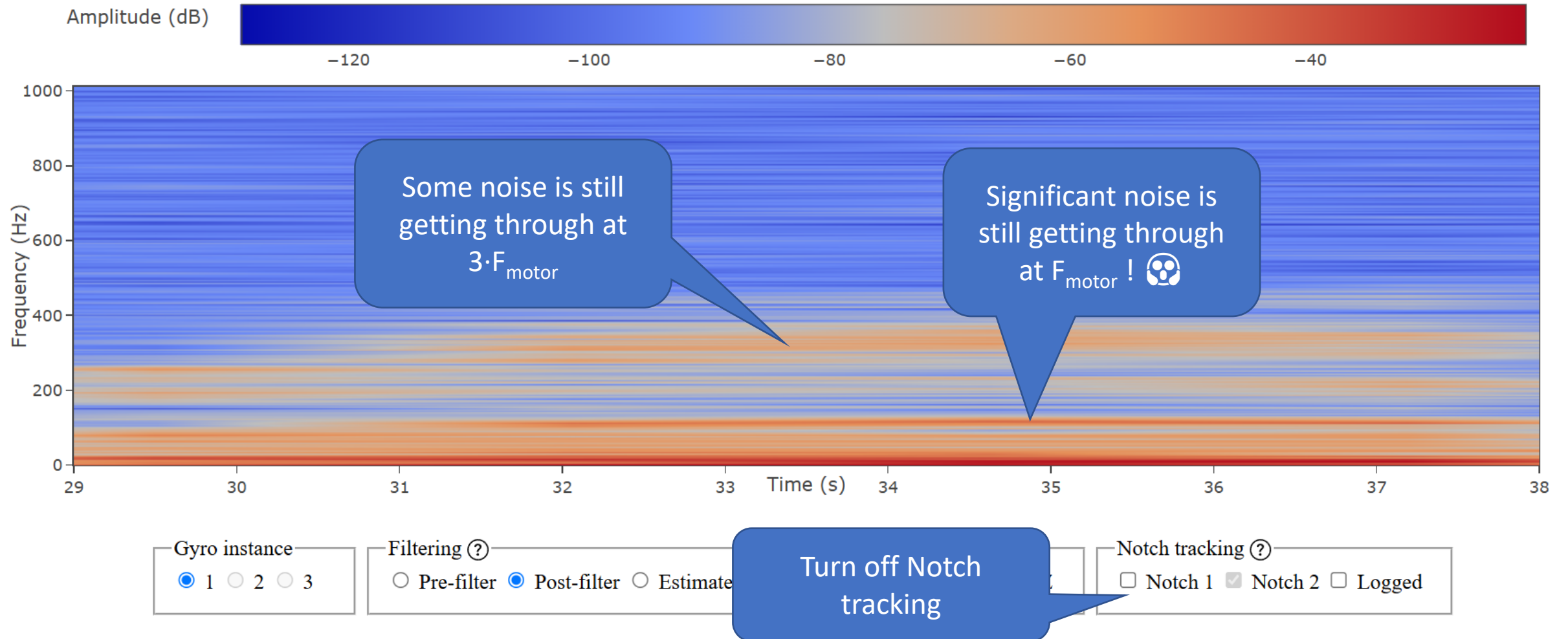


Filter Review – IMU Spectrogram – RPM Filter

- Tri-blade props typically need 3 harmonics, but sometimes only the first and third are needed
INS_HNTCH_HMNCS = 7 (or 5)
- Bi-blade props typically need at least 2 harmonics but sometimes more, check logs!
- **INS_HNTCH_HMNCS = 3 (or more)**



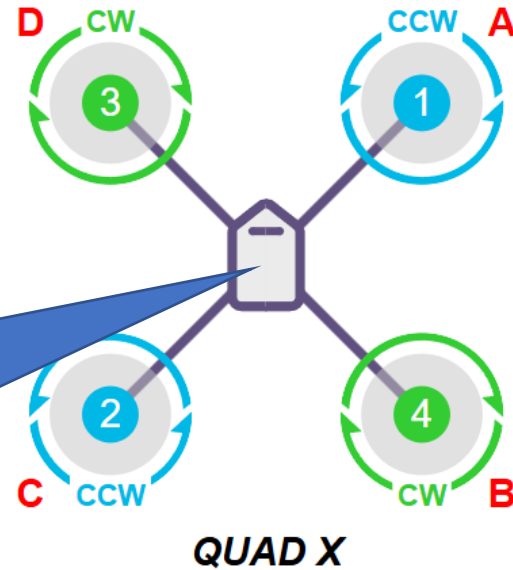
Filter Review – IMU Spectrogram – RPM Filter



RPM Filtering

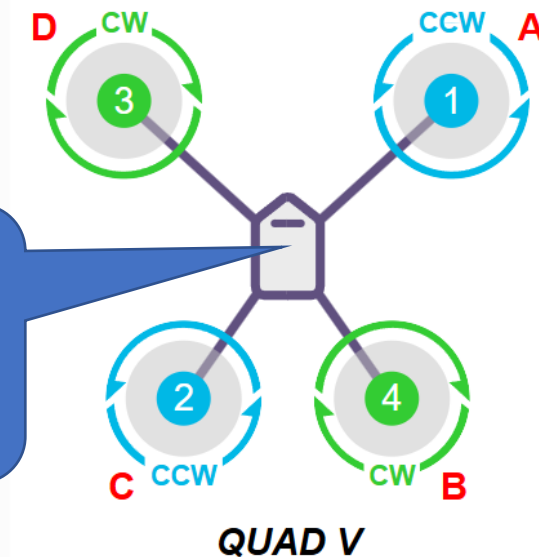
- At the moment the Notches are tracking the **Average** of all 4 motor RPMs
- This works great if all 4 motors are at the same RPM (perfect CoG and no Yaw inputs)
- However often the motors will be spinning at different RPMs (even in a stable hover if CoG is not perfect)

Central CoG,
all motors at
same RPM in
hover



Yaw input
causes **big**
Motor RPM
differentials

Off centre
CoG, front and
rear motors at
different RPMs



Multi-Source RPM Filter

- The solution is to use Ardupilot's Multi-Source RPM filtering to apply a separate notch to each motor RPM
 - **INS_HNTCH_BW = INS_HNTCH_FREQ / 4** (reduce the bandwidth of each notch to keep latency under control with 4x as many notches)
 - **INS_HNTCH_OPTIONS = 6** to enable Multi-Source and update the notches at the loop rate (important for narrower notches)
- Recalculate the filters to see the effect on Notch Tracking

Setup ?

Recalculate filters Save Parameters Load Parameters

First Notch Filter

INS_HNTCH_ENABLE 1:Enabled ▾

INS_HNTCH_MODE 3:ESC Telemetry ▾

INS_HNTCH_FREQ 80 Hz

INS_HNTCH_BW 20 Hz

INS_HNTCH_ATT 40 dB

INS_HNTCH_REF 1

INS_HNTCH_FM_RAT 1

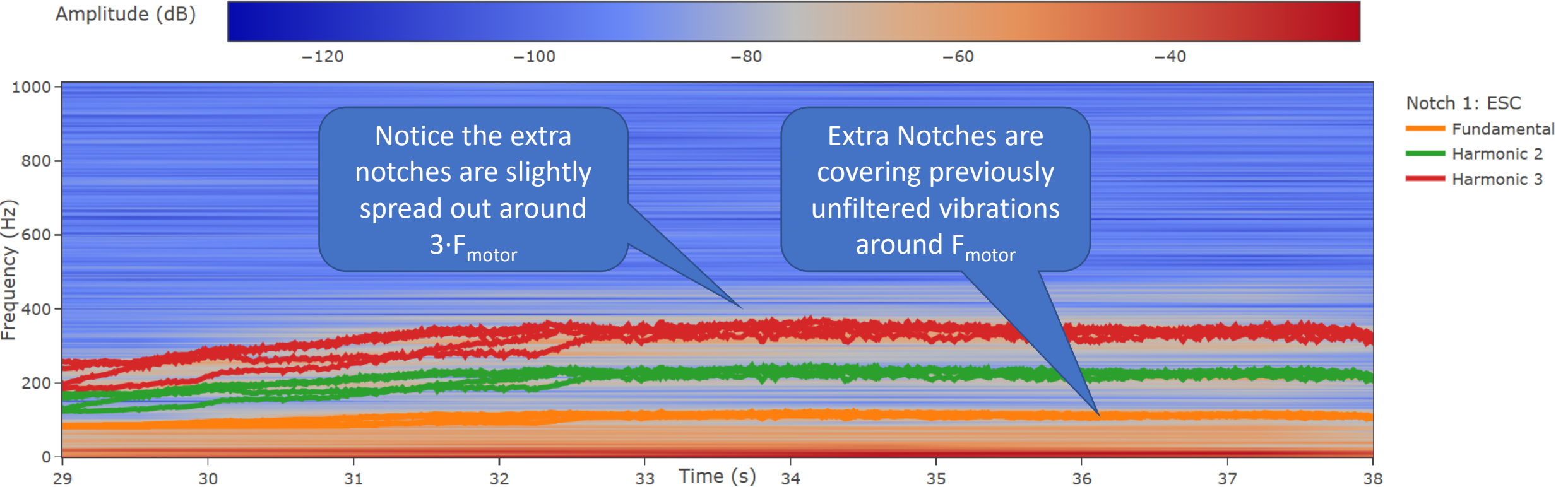
INS_HNTCH_HMNCS 7

1st harmonic 2nd harmonic 3rd harmonic
 4th harmonic 5th harmonic 6th harmonic
 7th harmonic 8th harmonic 9th harmonic
 10th harmonic 11th harmonic 12th harmonic
 13th harmonic 14th harmonic 15th harmonic
 16th harmonic

INS_HNTCH_OPTS 6

Double notch Multi-Source Update at loop rate
 EnableOnAllIMUs Triple notch Use min freq on RPM source failure

Multi-Source RPM Filter



Gyro instance

1 2 3

Filtering (?)

Pre-filter Post-filter Estimated post-filter

Axis

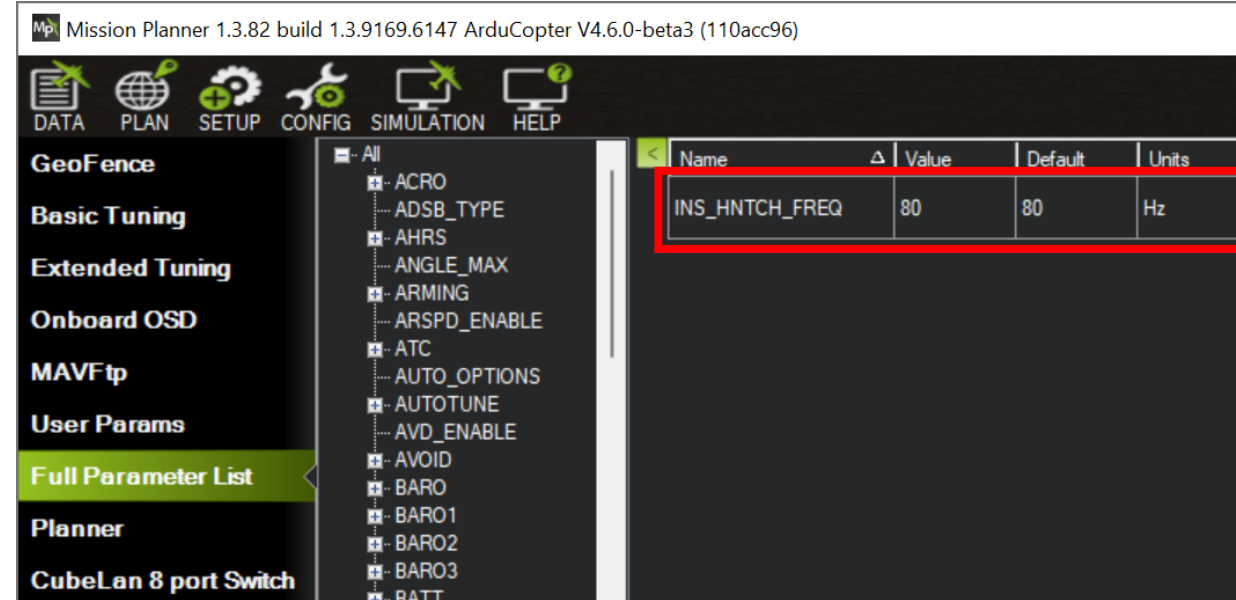
X Y Z

Notch tracking (?)

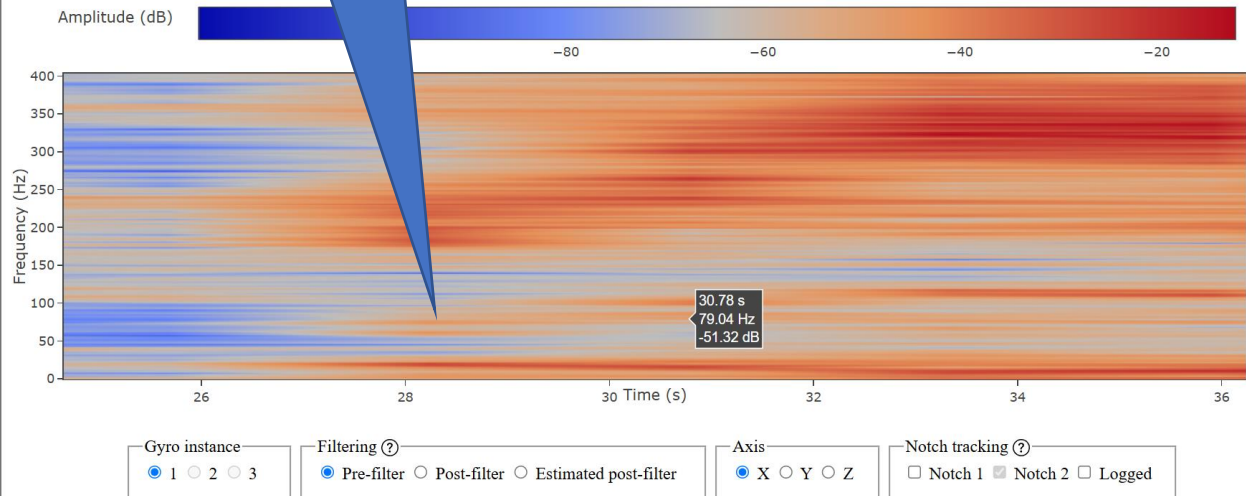
Notch 1 Notch 2 Logged

Tuning the RPM Filter

- Once you have good coverage of motor noise with the RPM filters we can tune them for best performance and minimum delay
- **INS_HNTCH_FREQ** should be set at the frequency at which motor noise starts to become a problem
- This can be found by slowly throttling up from zero and looking at the log



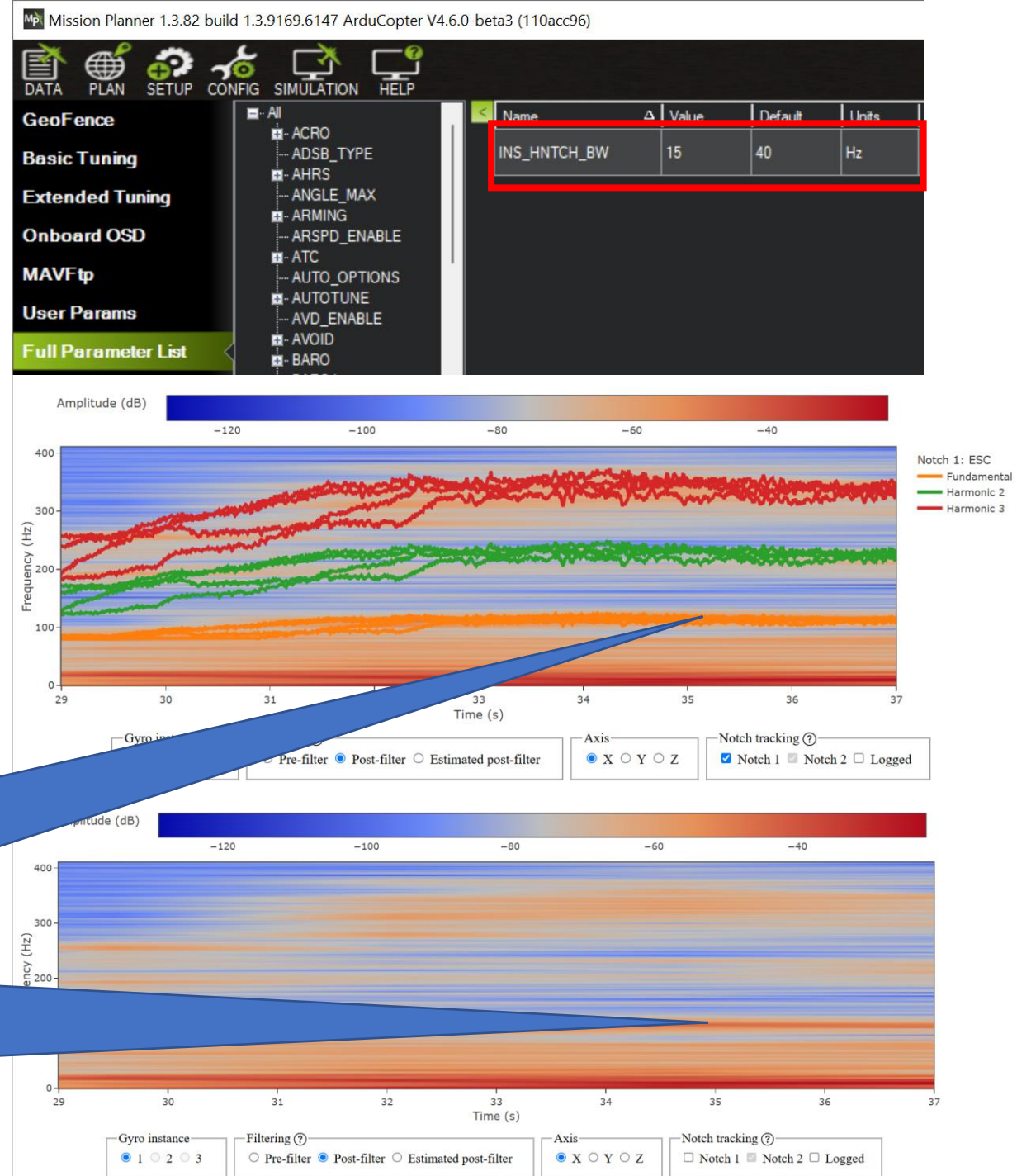
Here the noise starts around 80Hz



Tuning the RPM Filter

- **INS_HNTCH_BW** should be reduced as far as possible
- Go until you start seeing motor noise bleeding through in the post filter data then step back a bit from there (~10%)

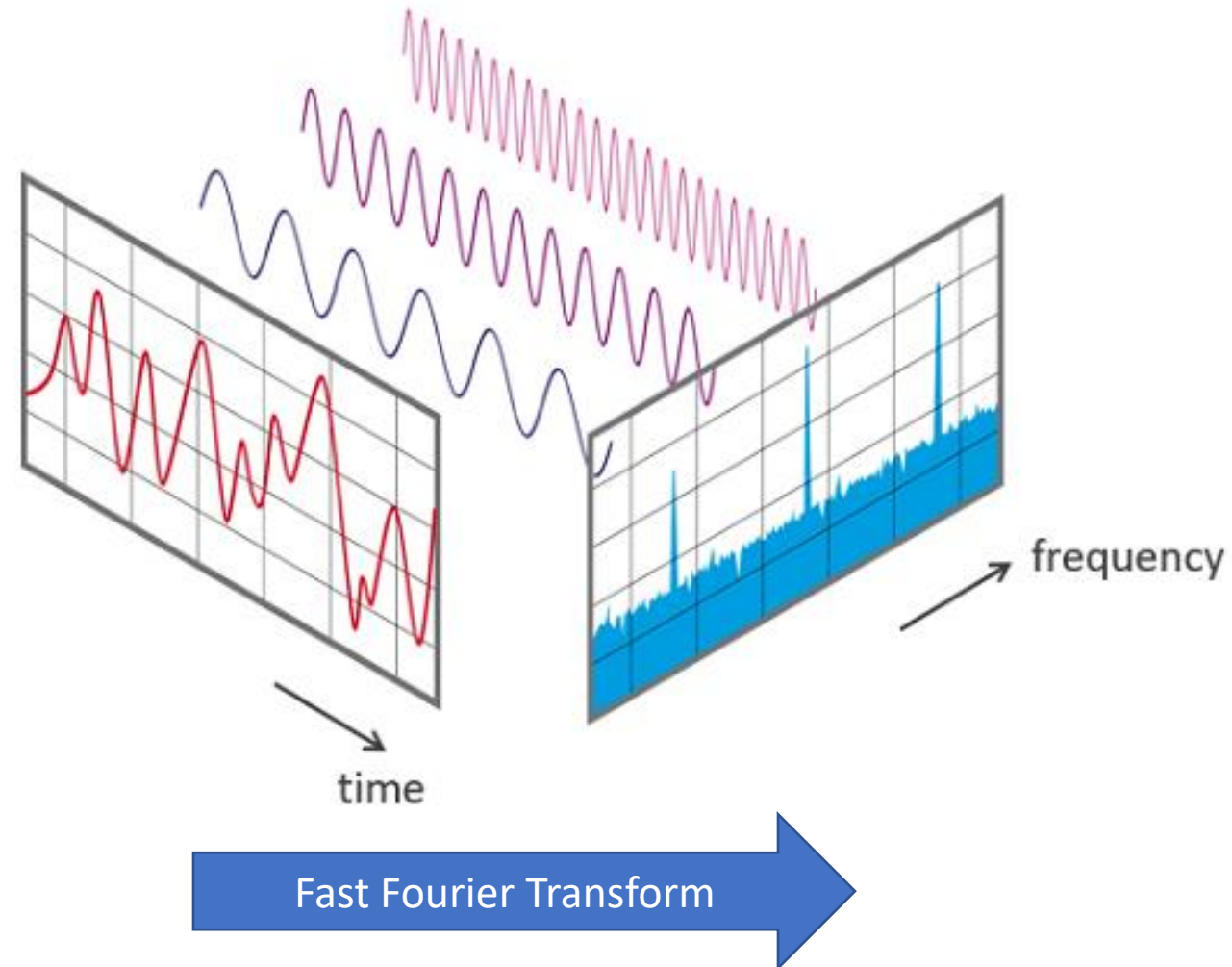
Here you can see noise coming through despite notches being correctly applied



FFT Based Harmonic Notch Filtering

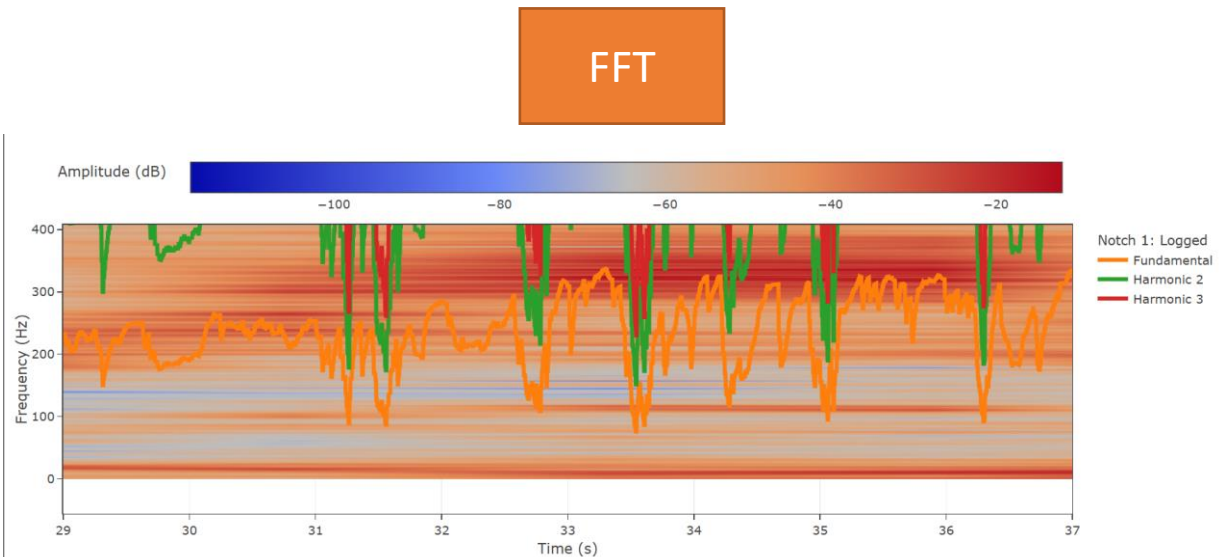
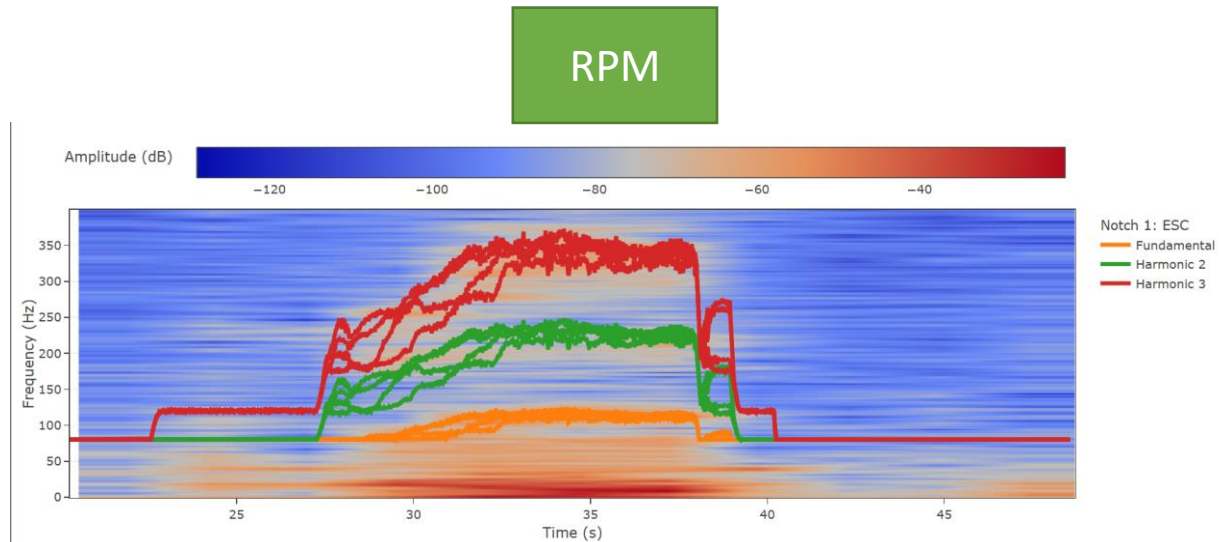
What is the Dynamic FFT?

- FFT stands for Fast Fourier Transform
- It takes a chunk of gyro data (~0.5 seconds) and uses it to calculate the amount of energy at each frequency
- The frequency of the biggest peak(s) detected can then be passed to the harmonic notch filters



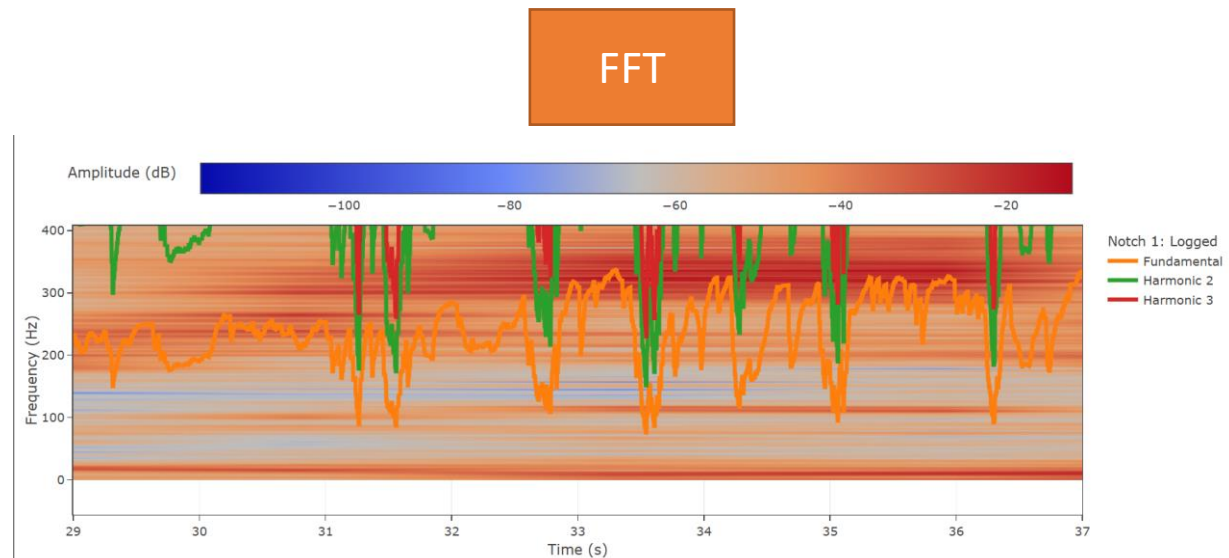
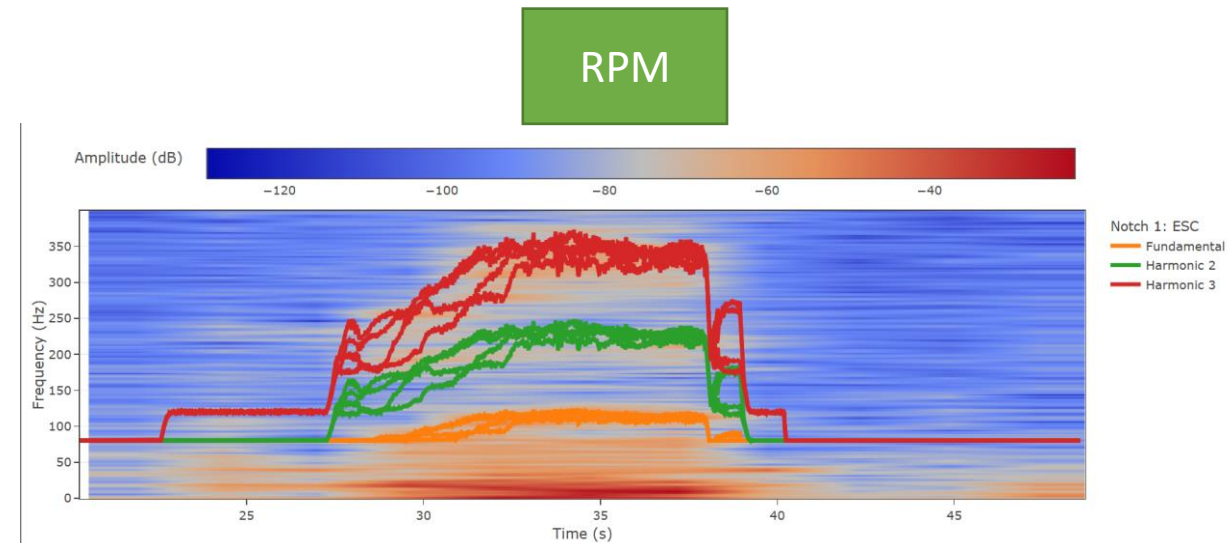
FFT vs RPM

- For Motor Noise RPM based harmonic notch filtering is superior to Dynamic FFT based filtering
- If you know the motor RPM you know the exact noise frequency immediately with no delay
- With Dynamic FFT you have to calculate it with a nasty trade-off, the higher your frequency resolution the lower your temporal resolution:
 - For 2Hz frequency resolution you need to sample for 0.5 seconds, and that's a long time in the world of notch filters!



FFT vs RPM

- Dynamic FFT is extremely useful in addition to RPM filtering for dealing with airframe resonance
- It can also be used for motor noise when RPM data is not available (RPM data should be available!)
- It is much more difficult to get working perfectly and requires careful tuning with logs



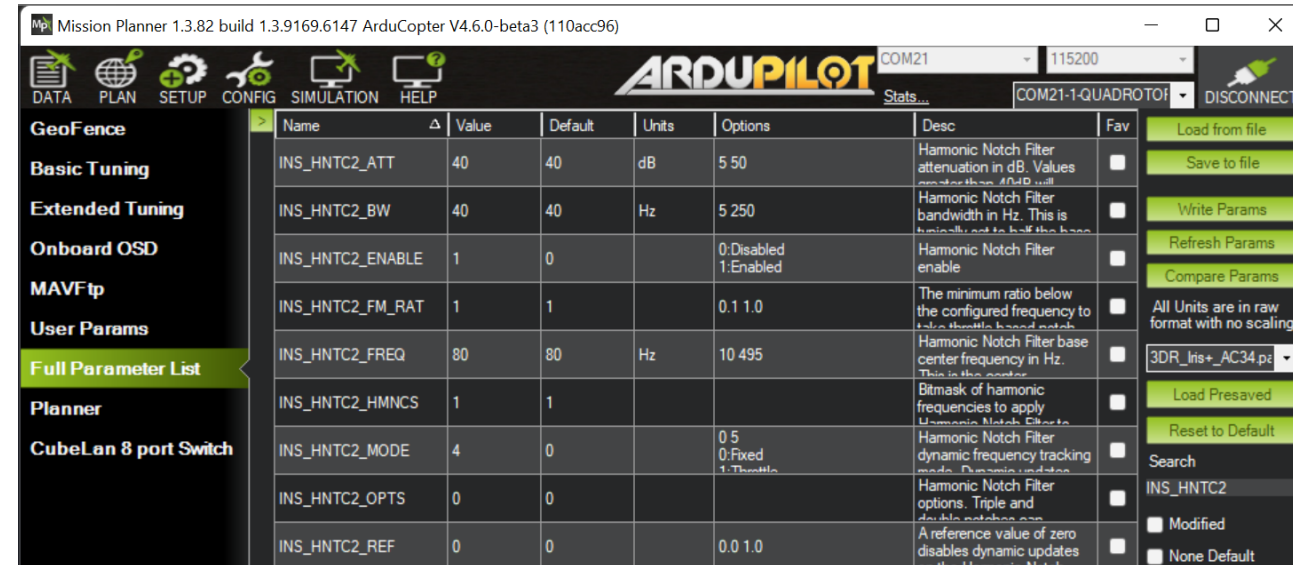
FFT for Frame Resonance (NOTCH 2)

- **FFT_ENABLE = 1**
- **FFT_MAXHZ** the upper limit where problematic frame resonances are seen
- **FFT_MINHZ** the lower limit where frame resonances are seen
- **FFT_NUM_FRAMES = 0 - 3**
average FFT frames together to reduce noise (not usually needed for large FFT_WINDOW)
- **FFT_OPTIONS = 1** to apply gyro lowpass and RPM filters before doing the FFT
- **FFT_WINDOW = 1024** if CPU load allows or as high as possible
- **INS_HNTC2_MODE = 4** to use FFT for the second notch (First notch is RPM)

Name	Δ	Value	Default	Units	Options	Desc	Fav
FFT_ATT_REF		15	15		0 100	FFT attenuation level in dB for bandwidth calculation and peak detection. The bandwidth is calculated by comparing peak power output with the threshold.	<input checked="" type="checkbox"/>
FFT_BW_HOVER		20	20		0 200	FFT learned bandwidth at hover for the attenuation frequencies.	<input checked="" type="checkbox"/>
FFT_ENABLE		1	0		0:Disabled 1:Enabled	Enable Gyro FFT analyser	<input checked="" type="checkbox"/>
FFT_FREQ_HOVER		80	80		0 250	The learned hover noise frequency	<input checked="" type="checkbox"/>
FFT_HMNC_FIT		10	10		0 100	FFT harmonic fit frequency threshold percentage at which a signal of the appropriate frequency is determined to be the harmonic of another. Signals that	<input checked="" type="checkbox"/>
FFT_HMNC_PEAK		0	0		0:Auto 1:Center Frequency 2:Upper Shoulder Frequency	The FFT harmonic peak target that should be returned by FTN1.PkAvg. The resulting value will be used by the harmonic notch if applied to track the FFT	<input checked="" type="checkbox"/>
FFT_MAXHZ		450	450	Hz	20 495	Upper bound of FFT frequency detection in Hz. On smaller vehicles the maximum motor frequency is likely to be significantly higher than for larger vehicles.	<input checked="" type="checkbox"/>
FFT_MINHZ		50	50	Hz	20 400	Lower bound of FFT frequency detection in Hz. On larger vehicles the minimum motor frequency is likely to be significantly lower than for smaller vehicles.	<input checked="" type="checkbox"/>
FFT_NUM_FRAMES		0	0		0 8	Number of output frequency frames to retain and average in order to calculate final frequencies. Averaging output frames can drastically reduce noise.	<input checked="" type="checkbox"/>
FFT_OPTIONS		1	0			FFT configuration options. Values: 1:Apply the FFT "after" the filter bank 2:Check noise at the motor frequency using ESC data as a reference	<input checked="" type="checkbox"/>
FFT_SAMPLE_MODE		0	0		0 4	Sampling mode (and therefore rate). 0: Gyro rate sampling, 1: Fast loop rate sampling, 2: Fast loop rate / 2 sampling, 3: Fast loop rate / 2 sampling. Takes effect	<input checked="" type="checkbox"/>
FFT_SNR_REF		10	10		0.0 100.0	FFT SNR reference threshold in dB at which a signal is determined to be present.	<input checked="" type="checkbox"/>
FFT_THR_REF		0.35	0.35		0.01 0.9	FFT learned thrust reference for the hover frequency and FFT minimum frequency.	<input checked="" type="checkbox"/>
FFT_WINDOW_OLAP		0.75	0.75		0 0.9	Percentage of window to be overlapped before another frame is process. Takes effect on reboot. A good default is 0.75 window. Higher overlap results in	<input checked="" type="checkbox"/>
FFT_WINDOW_SIZE		1024	64		32 1024	Size of window to be used in FFT calculations. Takes effect on reboot. Must be a power of 2 and between 32 and 512. Larger windows give more frequency	<input checked="" type="checkbox"/>
INS_HNTC2_MODE		4	0		0 5 0:Fixed 1:Throttle	Harmonic Notch Filter dynamic frequency tracking mode. Dynamic updates can be throttle, RPM sensor, ESC telemetry or dynamic FFT based. Throttle based	<input checked="" type="checkbox"/>
INS_HNTC2_OPTS		0	0			Harmonic Notch Filter options. Triple and double-notches can provide deeper attenuation across a wider bandwidth with reduced latency than single	<input checked="" type="checkbox"/>
INS_HNTCH_MODE		3	1		0 5 0:Fixed 1:Throttle	Harmonic Notch Filter dynamic frequency tracking mode. Dynamic updates can be throttle, RPM sensor, ESC telemetry or dynamic FFT based. Throttle based	<input checked="" type="checkbox"/>
INS_HNTCH_OPTS		6	0			Harmonic Notch Filter options. Triple and double-notches can provide deeper attenuation across a wider bandwidth with reduced latency than single	<input checked="" type="checkbox"/>

FFT for Frame Resonance (NOTCH 2)

- **INS_HNTC2_ENABLE= 1** to enable the second notch
- **INS_HNTC2_MODE = 4** to use Dynamic FFT
- **INS_HNTC2_FREQ = FFT_MINHZ** the lower limit where frame resonances are seen
- **INS_HNTC2_BW = INS_HNTC2_FREQ / 2** start here initially, then tune
- **INS_HNTC2_REF = 1** no scaling required
- **INS_HNTC2_FM_RATIO = 1** prevent the notch going below **INS_HNTC2_FREQ**
- **INS_HNTC2_HMNCSS = 1** we are looking to target a frame resonances and they don't typically have harmonics
- **INS_HNTC2_OPTS = 0** for one frame resonance
- **INS_HNTC2_OPTS = 2** Use Multi-Source for multiple resonances



The screenshot shows the Mission Planner interface with the 'Full Parameter List' tab selected. The table below represents the data visible in the screenshot:

Name	Value	Default	Units	Options	Desc	Fav
INS_HNTC2_ATT	40	40	dB	5 50	Harmonic Notch Filter attenuation in dB. Values	<input type="checkbox"/>
INS_HNTC2_BW	40	40	Hz	5 250	Harmonic Notch Filter bandwidth in Hz. This is	<input type="checkbox"/>
INS_HNTC2_ENABLE	1	0		0:Disabled 1:Enabled	Harmonic Notch Filter enable	<input type="checkbox"/>
INS_HNTC2_FM_RATIO	1	1		0.1 1.0	The minimum ratio below the configured frequency to	<input type="checkbox"/>
INS_HNTC2_FREQ	80	80	Hz	10 495	Harmonic Notch Filter base center frequency in Hz.	<input type="checkbox"/>
INS_HNTC2_HMNCSS	1	1			Bitmask of harmonic frequencies to apply	<input type="checkbox"/>
INS_HNTC2_MODE	4	0		0:5 0:Fixed 1:Throttle	Harmonic Notch Filter dynamic frequency tracking	<input type="checkbox"/>
INS_HNTC2_OPTS	0	0			Harmonic Notch Filter options. Triple and	<input type="checkbox"/>
INS_HNTC2_REF	0	0		0.0 1.0	A reference value of zero disables dynamic updates	<input type="checkbox"/>

FFT for Motor Noise (NOTCH 1)

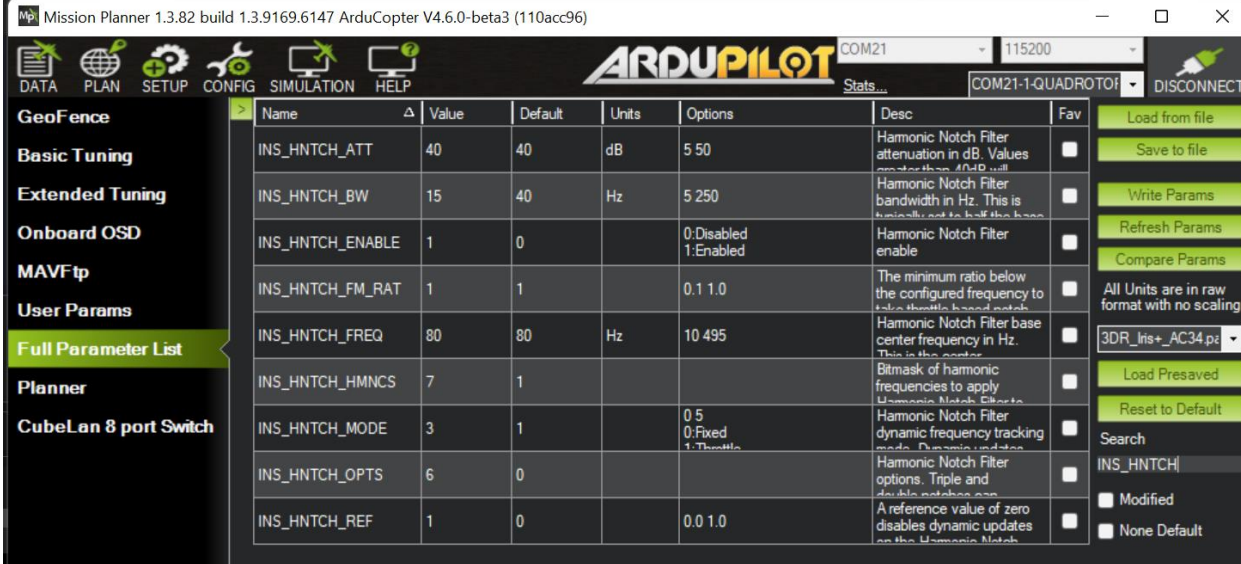
$$F_{\text{maxHz}} \approx 0.8 \cdot V_{\text{batt}} \cdot K_v / 60$$

- **FFT_ENABLE = 1**
- **FFT_MAXHZ** slightly above the fundamental motor frequency at full throttle
- **FFT_MINHZ** the lowest frequency where motor noise is seen at low throttle
- **FFT_NUM_FRAMES = 0**
FFT needs to be reactive to changing RPM
- **FFT_OPTIONS = 1** to apply low pass filters before doing the FFT
- **FFT_WINDOW = 1024** if CPU load allows or as high as possible

Name	Δ	Value	Default	Units	Options	Desc	Fav
FFT_ATT_REF		15	15		0 100	FFT attenuation level in dB for bandwidth calculation and peak detection. The bandwidth is calculated by comparing peak power output with the threshold.	<input type="checkbox"/>
FFT_BW_HOVER		20	20		0 200	FFT learned bandwidth at hover for the attenuation frequencies.	<input type="checkbox"/>
FFT_ENABLE		1	0		0:Disabled 1:Enabled	Enable Gyro FFT analyser	<input type="checkbox"/>
FFT_FREQ_HOVER		80	80		0 250	The learned hover noise frequency	<input type="checkbox"/>
FFT_HMNC_FIT		10	10		0 100	FFT harmonic fit frequency threshold percentage at which a signal of the appropriate frequency is determined to be the harmonic of another. Signals that	<input type="checkbox"/>
FFT_HMNC_PEAK		0	0		0:Auto 1:Center Frequency 2:Lower Shoulder Frequency	The FFT harmonic peak target that should be returned by FTN1.PkAvg. The resulting value will be used by the harmonic notch & confirmed to be the FFT	<input type="checkbox"/>
FFT_MAXHZ		450	450	Hz	20 495	Upper bound of FFT frequency detection in Hz. On smaller vehicles the maximum motor frequency is likely to be significantly higher than for larger vehicles.	<input type="checkbox"/>
FFT_MINHZ		50	50	Hz	20 400	Lower bound of FFT frequency detection in Hz. On larger vehicles the minimum motor frequency is likely to be significantly lower than for smaller vehicles.	<input type="checkbox"/>
FFT_NUM_FRAMES		0	0		0 8	Number of output frequency frames to retain and average in order to calculate final frequencies. Averaging output frames can drastically reduce noise.	<input type="checkbox"/>
FFT_OPTIONS		1	0			FFT configuration options. Values: 1:Apply the FFT "after" the filter bank, 2:Check noise at the motor frequencies using ESC data as a reference.	<input type="checkbox"/>
FFT_SAMPLE_MODE		0	0		0 4	Sampling mode (and therefore rate). 0: Gyro rate sampling, 1: Fast loop rate sampling, 2: Fast loop rate / 2 sampling, 3: Fast loop rate / 4 sampling. Takes effect	<input type="checkbox"/>
FFT_SNR_REF		10	10		0.0 100.0	FFT SNR reference threshold in dB at which a signal is determined to be present.	<input type="checkbox"/>
FFT_THR_REF		0.35	0.35		0.01 0.9	FFT learned thrust reference for the hover frequency and FFT minimum frequency.	<input type="checkbox"/>
FFT_WINDOW_OLAP		0.75	0.75		0 0.9	Percentage of window to be overlapped before another frame is process. Takes effect on reboot. A good default is 50% overlap. Higher overlap may be in	<input type="checkbox"/>
FFT_WINDOW_SIZE		1024	64		32 1024	Size of window to be used in FFT calculations. Takes effect on reboot. Must be a power of 2 and between 32 and 512. Larger windows allow for better frequency	<input type="checkbox"/>
INS_HNTC2_MODE		0	0		0 5 0:Fixed 1:Throttle	Harmonic Notch Filter dynamic frequency tracking mode. Dynamic updates can be throttle, RPM sensor, ESC telemetry or dynamic ESC board. Throttle board	<input type="checkbox"/>
INS_HNTC2_OPTS		0	0			Harmonic Notch Filter options. Triple and double-notches can provide deeper attenuation across a wider bandwidth with reduced latency than single	<input type="checkbox"/>
INS_HNTCH_MODE		4	1		0 5 0:Fixed 1:Throttle	Harmonic Notch Filter dynamic frequency tracking mode. Dynamic updates can be throttle, RPM sensor, ESC telemetry or dynamic ESC board. Throttle board	<input type="checkbox"/>
INS_HNTCH_OPTS		0	0			Harmonic Notch Filter options. Triple and double-notches can provide deeper attenuation across a wider bandwidth with reduced latency than single	<input type="checkbox"/>

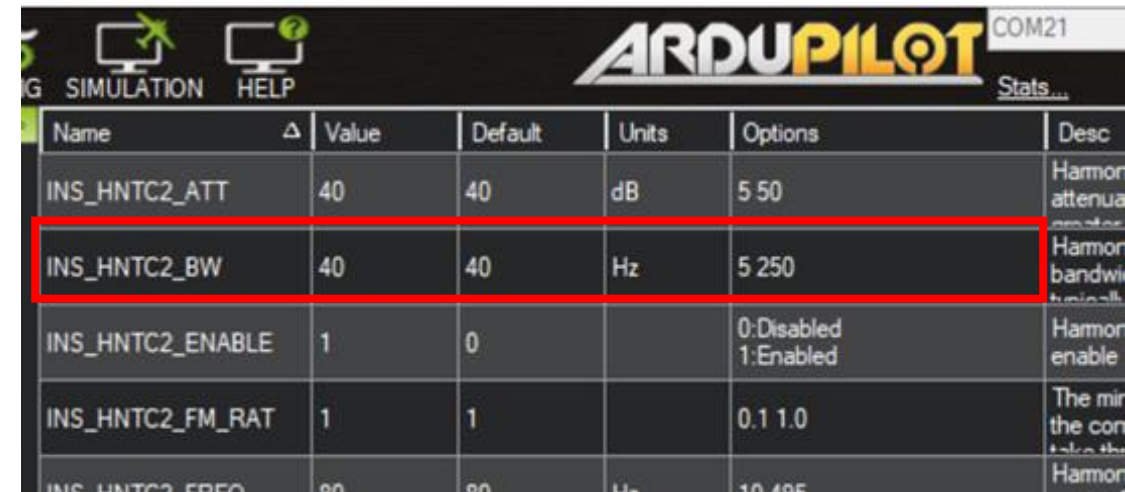
FFT for Motor Noise (NOTCH 1)

- **INS_HNTCH_ENABLE= 1** to enable the first notch
- **INS_HNTCH_MODE = 4** to use Dynamic FFT
- **INS_HNTCH_FREQ = FFT_MINHZ** the lowest frequency where motor noise is seen at low throttle
- **INS_HNTCH_BW = INS_HNTCH_FREQ / 2** start here initially, then tune
- **INS_HNTCH_REF = 1** no scaling required
- **INS_HNTCH_FM_RAT = 1** prevent the notch going below **INS_HNTCH_FREQ**
- **INS_HNTCH_HMNCS = 7** for tri-blade props (3 harmonics)



The screenshot shows the Mission Planner interface with the 'Full Parameter List' tab selected. The table below represents the data visible in the screenshot.

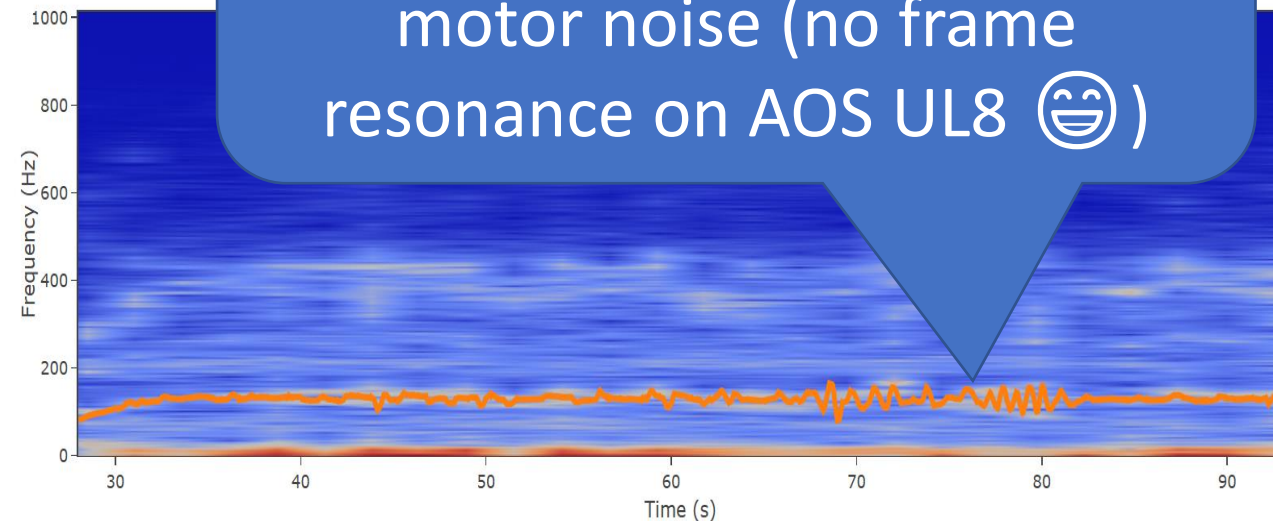
Name	Value	Default	Units	Options	Desc	Fav
INS_HNTCH_ATT	40	40	dB	5 50	Harmonic Notch Filter attenuation in dB. Values greater than 40dB will	<input type="checkbox"/>
INS_HNTCH_BW	15	40	Hz	5 250	Harmonic Notch Filter bandwidth in Hz. This is typically set to half the base	<input type="checkbox"/>
INS_HNTCH_ENABLE	1	0		0:Disabled 1:Enabled	Harmonic Notch Filter enable	<input type="checkbox"/>
INS_HNTCH_FM_RAT	1	1		0.1 1.0	The minimum ratio below the configured frequency to take the harmonic notch	<input type="checkbox"/>
INS_HNTCH_FREQ	80	80	Hz	10 495	Harmonic Notch Filter base center frequency in Hz. This is the motor	<input type="checkbox"/>
INS_HNTCH_HMNCS	7	1			Bitmask of harmonic frequencies to apply Harmonic Notch Effects	<input type="checkbox"/>
INS_HNTCH_MODE	3	1		0:Fixed 1:Throttle	Harmonic Notch Filter dynamic frequency tracking mode. Dynamic updates	<input type="checkbox"/>
INS_HNTCH_OPTS	6	0			Harmonic Notch Filter options. Triple and double notch are	<input type="checkbox"/>
INS_HNTCH_REF	1	0		0.0 1.0	A reference value of zero disables dynamic updates on the Harmonic Notch	<input type="checkbox"/>



Name	Value	Default	Units	Options	Desc
INS_HNTC2_ATT	40	40	dB	5 50	Harmon attenua
INS_HNTC2_BW	40	40	Hz	5 250	Harmon bandwi
INS_HNTC2_ENABLE	1	0		0:Disabled 1:Enabled	Harmon enable
INS_HNTC2_FM_RAT	1	1		0.1 1.0	The mir the con take the
INS_HNTC2_FREQ	80	80	Hz	10 105	Harmon

Tuning FFT Notch Filters

- **INS_HNTC2_BW** should be reduced as far as possible (just like the RPM notches)
- Go until you start seeing the resonance bleeding through in the post filter data then step back a bit from there (~10%)
- The FFT is less precise than RPM data so FFT notch bandwidth will always be greater

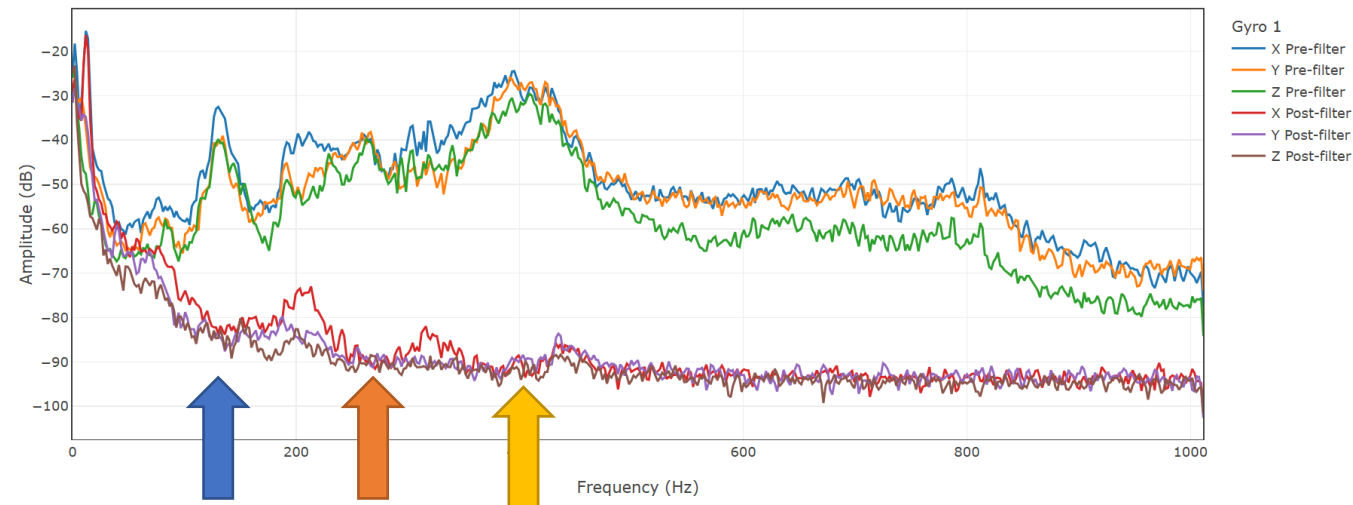
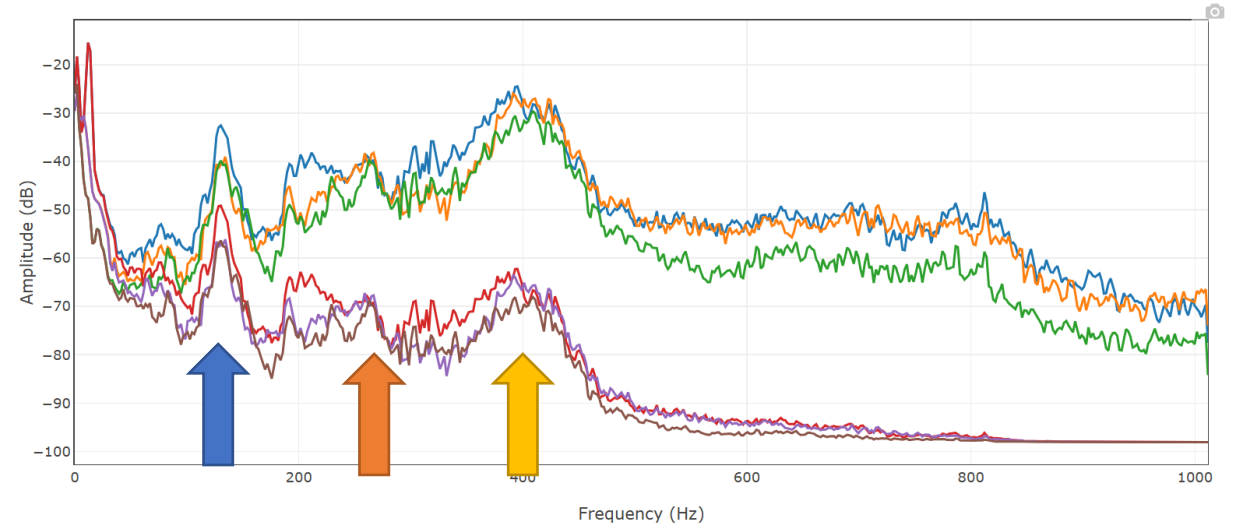


What about Static/Throttle Notches?

- I don't advise using static or throttle notches
- They are a brittle filtering approach because they can be rendered completely ineffective by changes such as
 - Changing Props
 - Operating Altitude
 - Manufacturing tolerances on frames
 - Payload
- RPM (HNTCH) [+ FFT (HNTC2)] based notch settings are effective across multiple drones of the same design even if parts and payloads change
- If you're using FFT for motor noise (no RPM data) then you may need to use a static notch for any frame resonance

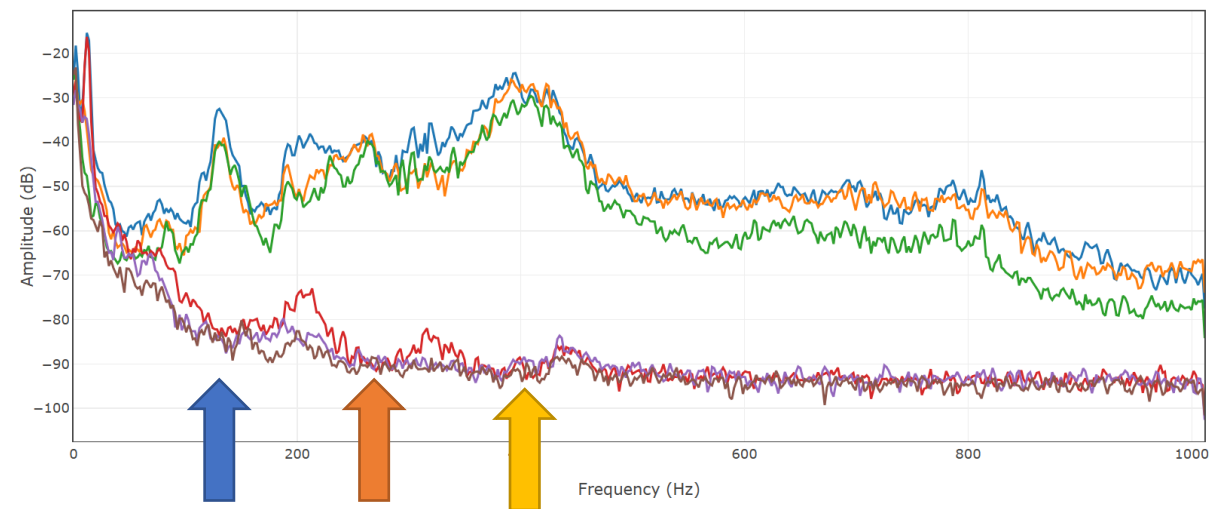
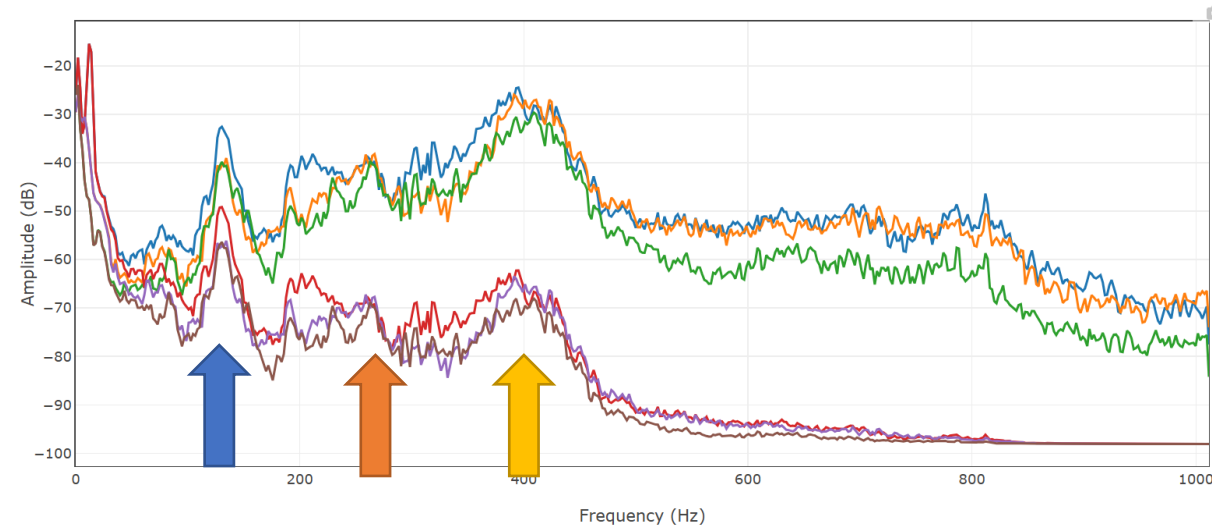
Tuning the Gyro Low Pass Filter

- Now that our notch filters are well tuned we should be able to gradually increase the cut-off frequency of the Gyro low pass filter
- **INS_GYRO_FILTER** in the **Full Parameter List**
- Increase it as far as possible whilst keeping post-filter noise below about -50dB or lower



Tuning the Gyro Low Pass Filter

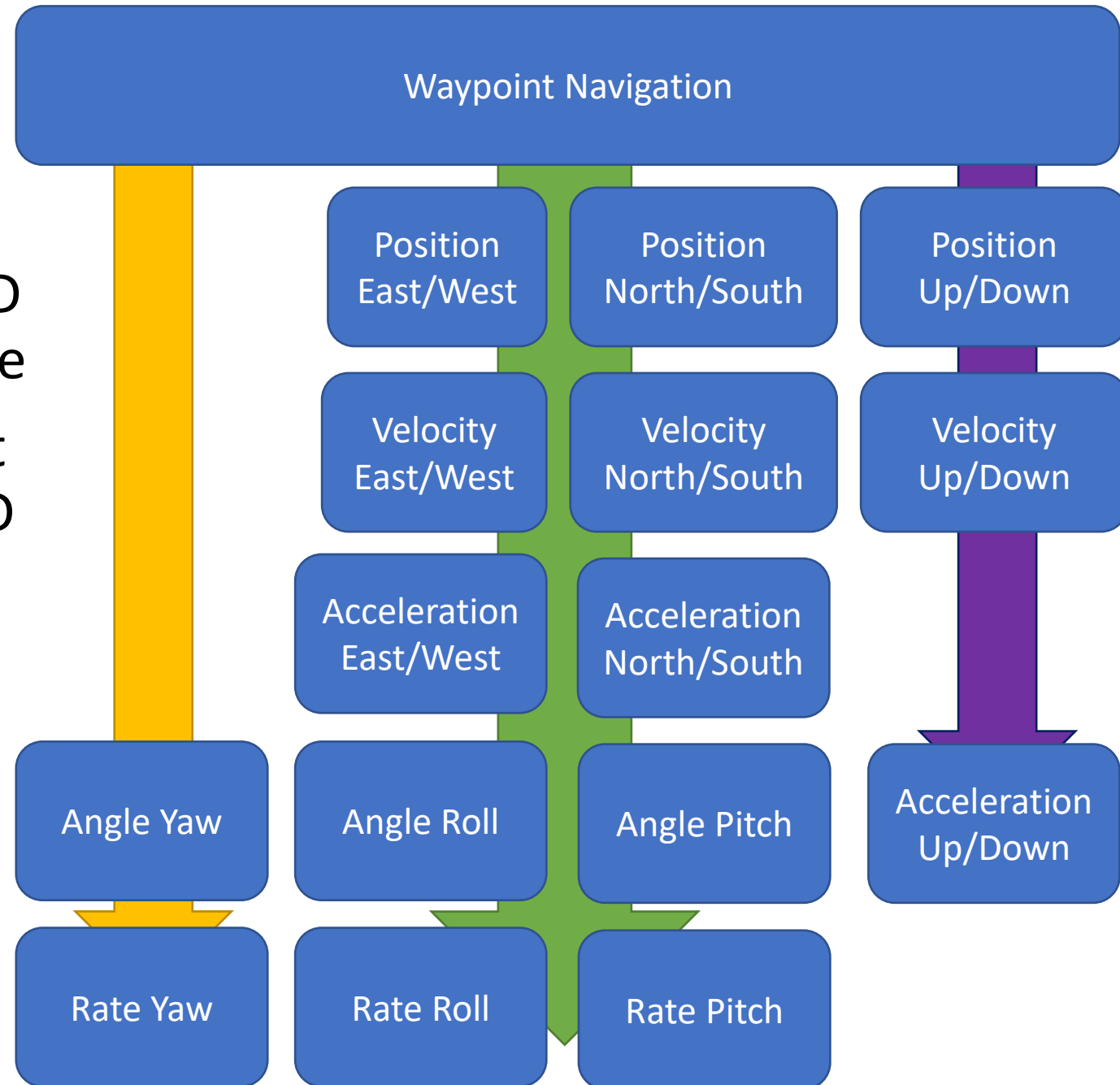
- When raising **INS_GYRO_FILTER** listen for any oscillations
- Also check the motor temperature after a short hover
- Audible oscillations or hot motors *may* indicate insufficient filtering
- They may also be due to a poor PID tune
- Check logs to identify the source



PID Tuning

Background

- Ardupilot uses a cascade of PID controllers to control the drone
- To get good autonomous flight performance each of these PID loops needs to be tuned
- We will start from the bottom and work our way up



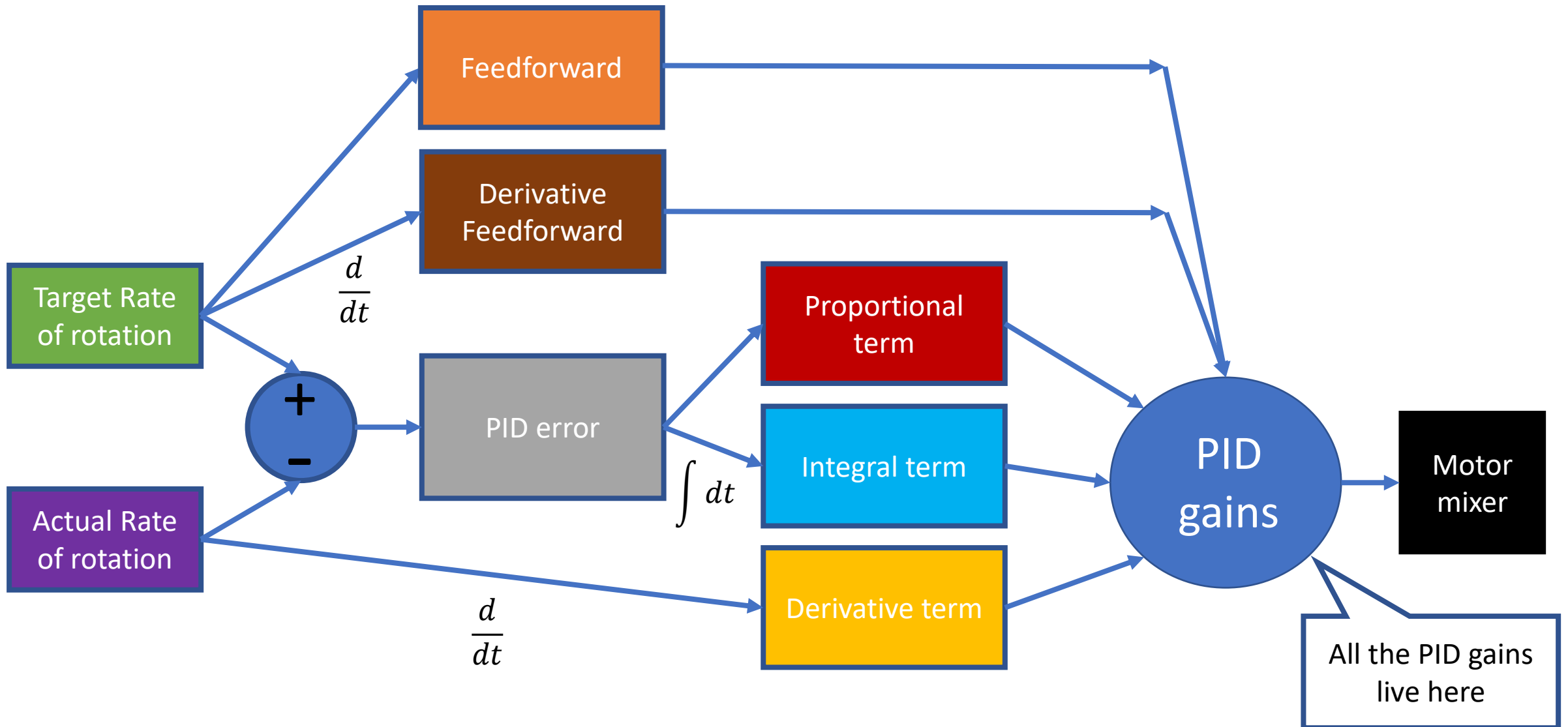
Ardupilot Autotune

- Ardupilot has a couple of Auto Tuning functions which try to find good PID values for the Rate and Angle Controllers
- These tools can produce tunes suitable for hobby use on small drones
- They will struggle on larger drones and produce suboptimal tunes which can be dangerously unflyable!
- A methodical manual tuning approach will produce better results more safely
- This is what we will cover in this guide

The PID-FF-DFF controller

- Ardupilot's PID-FF-DFF controller consists of five main parts
- P is the proportional term
- I is the integral term
- D is the derivative term
- FF is the Feedforward term
- DFF is the Derivative Feedforward term

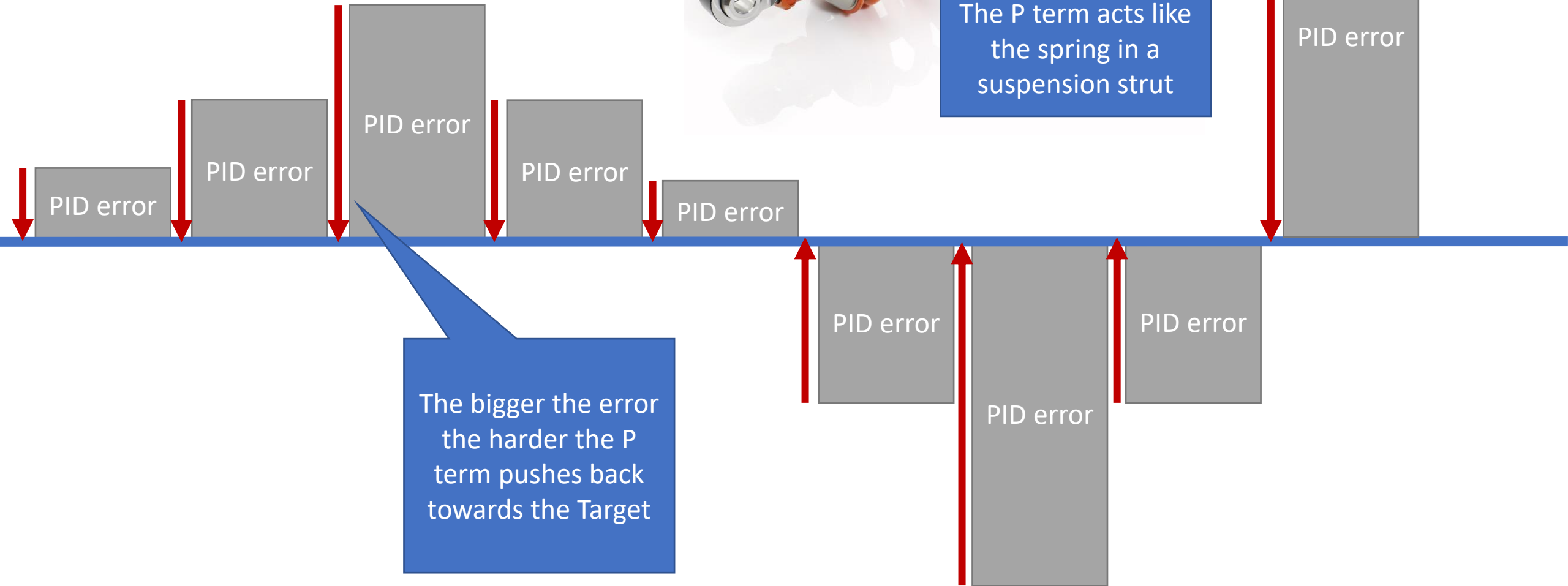
The Ardupilot Rate PID-FF-DFF Controller



Proportional term



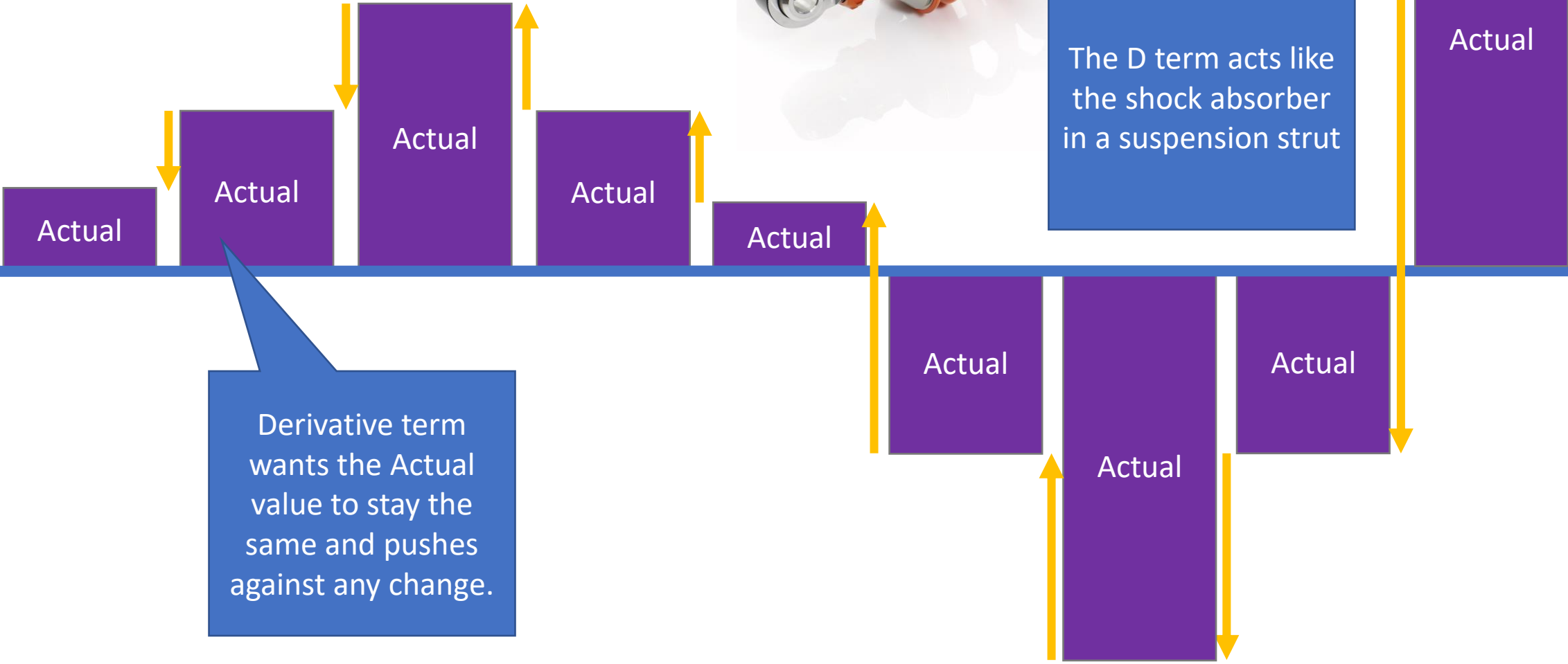
The P term acts like the spring in a suspension strut



Derivative term



The D term acts like the shock absorber in a suspension strut

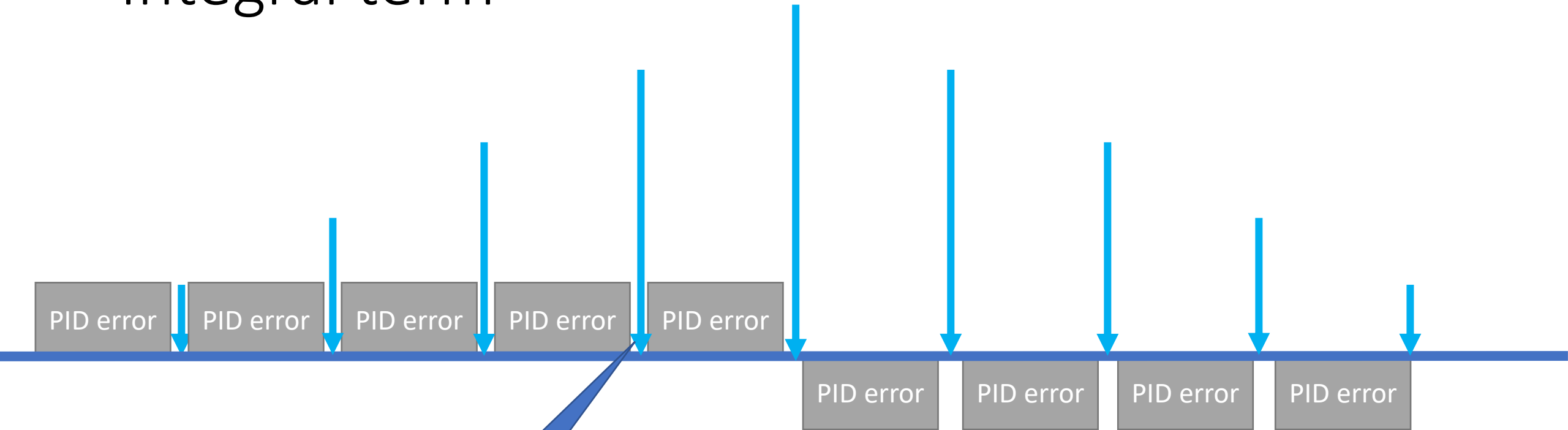


P:D balance

- Just like in a suspension strut the balance between the spring strength (P term) and the size of the shock absorber (D term) is very important
- The Ardupilot default P:D balance is usually a suitable starting point but not always!
- The right balance between P and D terms is the first step of a good PID tune



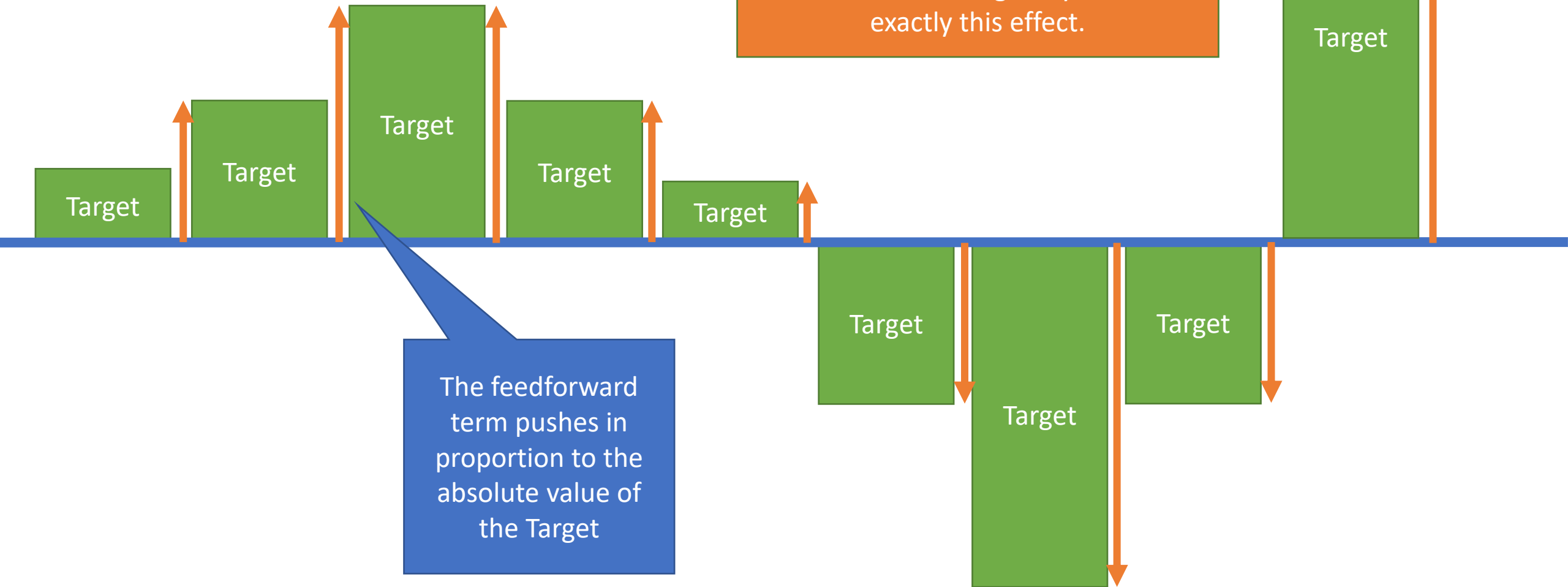
Integral term



Integral term adds up the error over time and pushes back harder and harder the longer the error persists

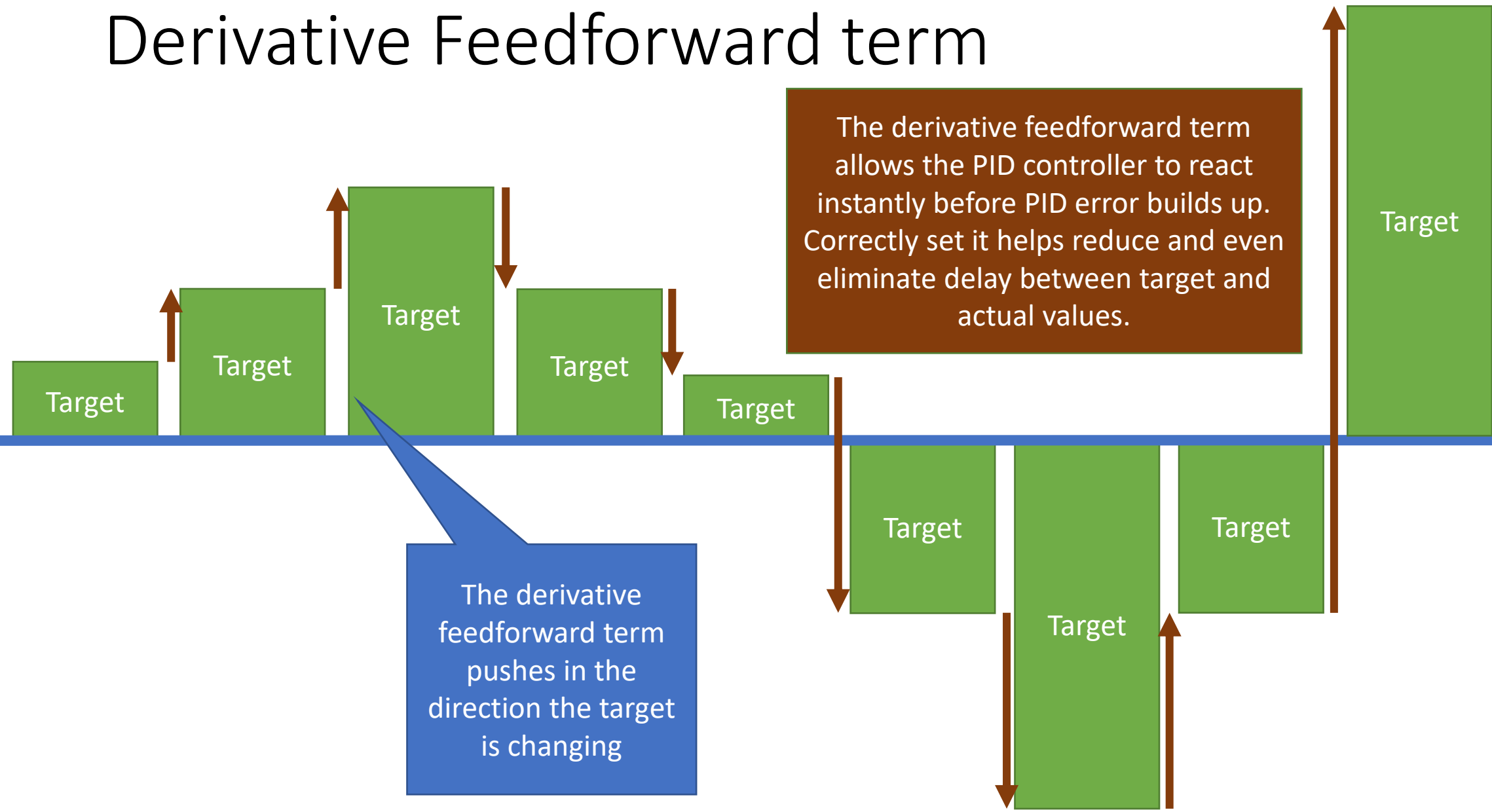
Feedforward term

The feedforward term helps overcome resistance that increases in proportion to the target value. It's very useful for the vertical velocity controller where gravity creates exactly this effect.



The feedforward term pushes in proportion to the absolute value of the Target

Derivative Feedforward term



P:I balance and D->P->I->DFF->FF tuning approach

- In the same way as the D term prevents the P term oscillating the P term prevents the I term oscillating
- As a result there is an ideal P:I ratio for a controller that allows the maximum I term without oscillations
- This gives us the relationship D->P->I->DFF->FF which guides the tuning process: D term first, then P term, I term, DFF and finally FF



There are 3 Rate Controllers in Ardupilot

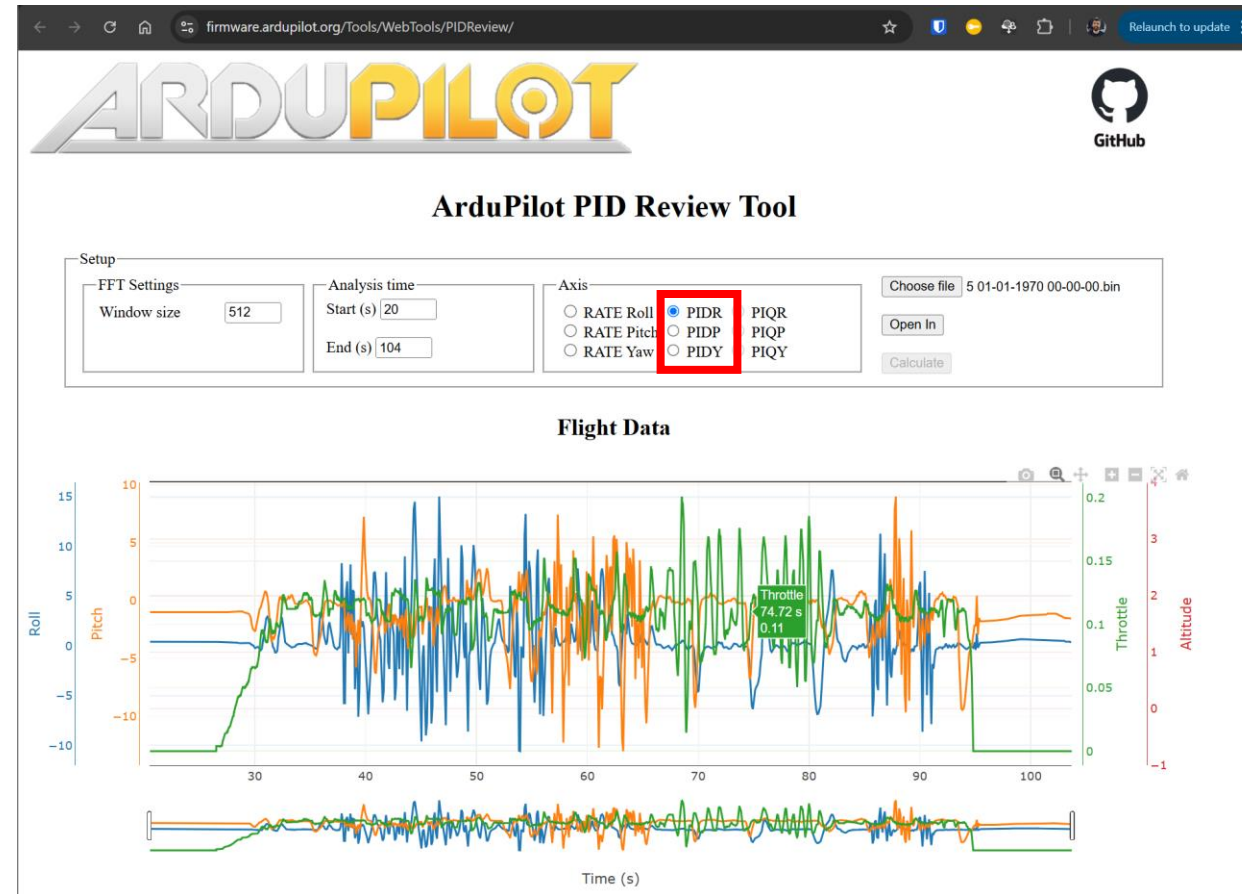
- One each for roll, pitch and yaw
- They all work the same way
- However, the derivative term on the yaw axis is usually set to 0 because the lack of authority on the yaw axis means it is usually over damped and does not require an additional derivative term

Tuning flight tips

- PID tuning flights consist of sharp wobbles on all 3 axis
- When you do sharp moves make sure that you keep hold of the stick as it returns to centre
- If you release the sticks, they can bounce around the centre as they spring back which will make the quad oscillate (and might make you think you have too much P gain when you don't)
- You can do these sharp moves in Stabilize or Altitude Hold mode (but **not** Loiter)

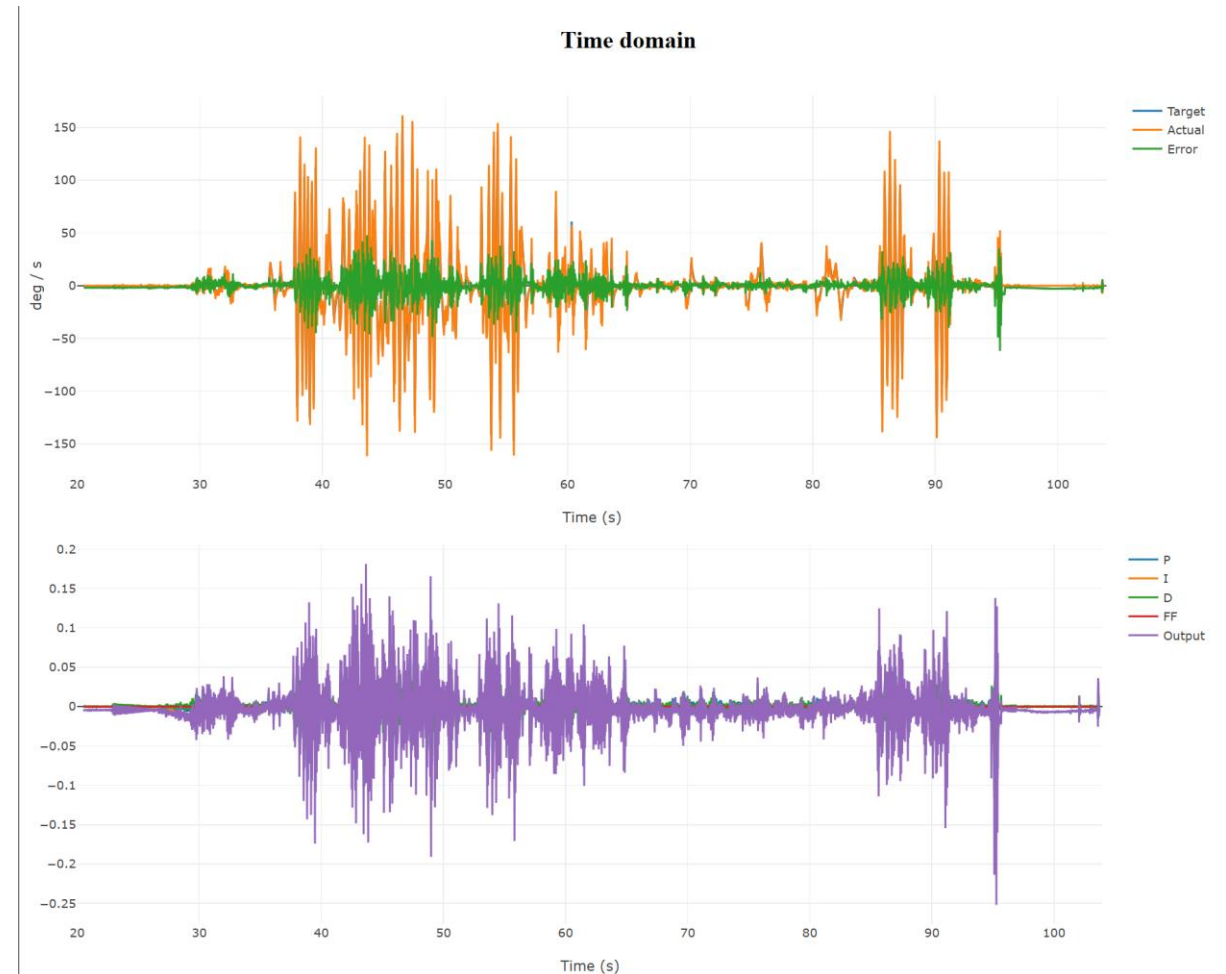
PID Review – Load Log

- Open your log in ArduPilot WebTools PID Review:
<https://firmware.ardupilot.org/Tools/WebTools/PIDReview/>
- Check that the Flight Data Graph looks correct and there are no gaps (logging drop outs)
- Select PID ROLL, PITCH or YAW to look at



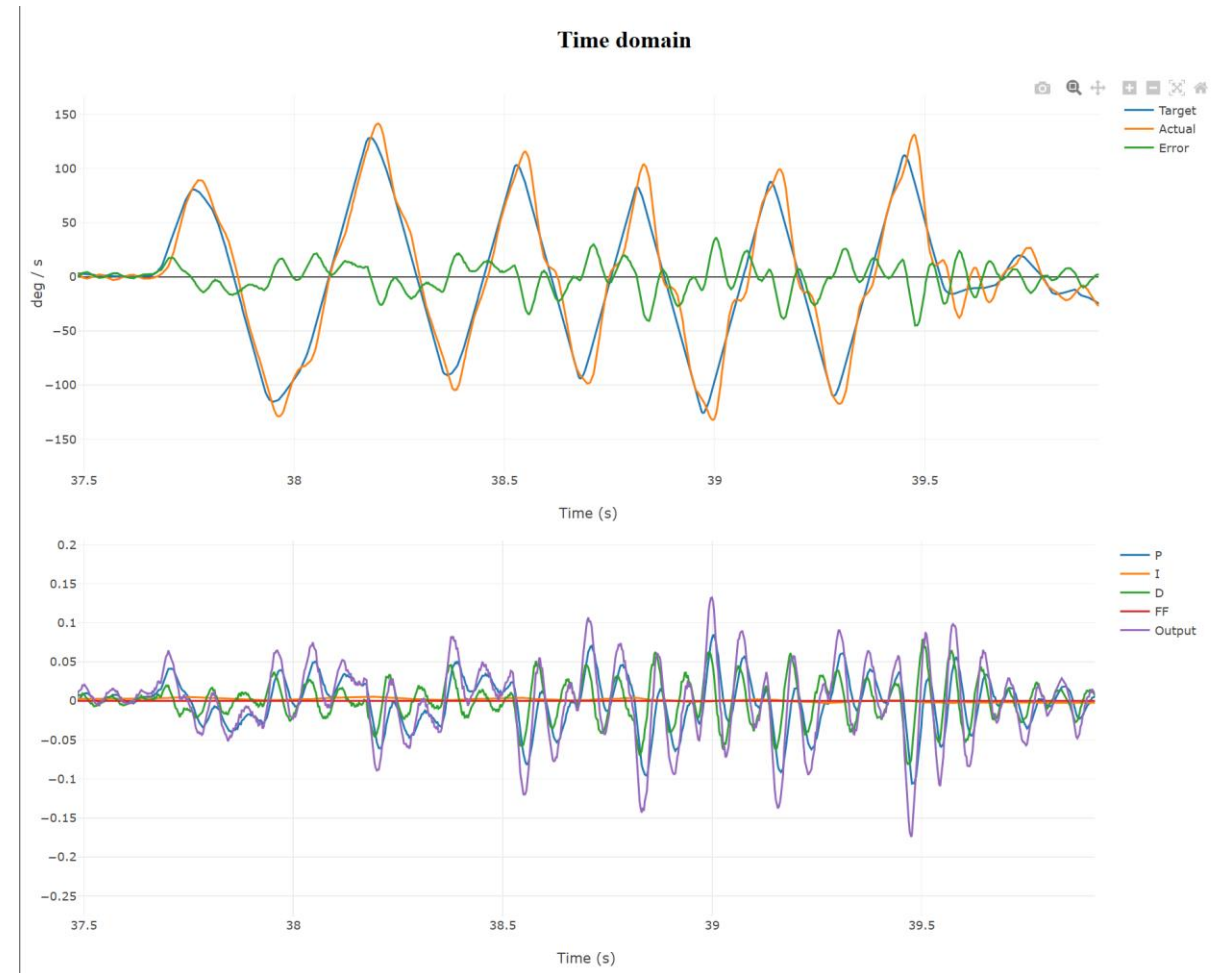
PID Review – Reading time series data

- Time domain data is unreadable at the default zoom level
- Zoom into the parts of the log where you wobbled the drone on the selected axis



PID Review – Reading time series data

- At this zoom level we can see the individual movements
- The goal is to get the Actual and Target lines to sit perfectly on top of each other
- It is possible to tune P:D balance only using time series data
- This is useful as for some controllers time series is all we have easy access to



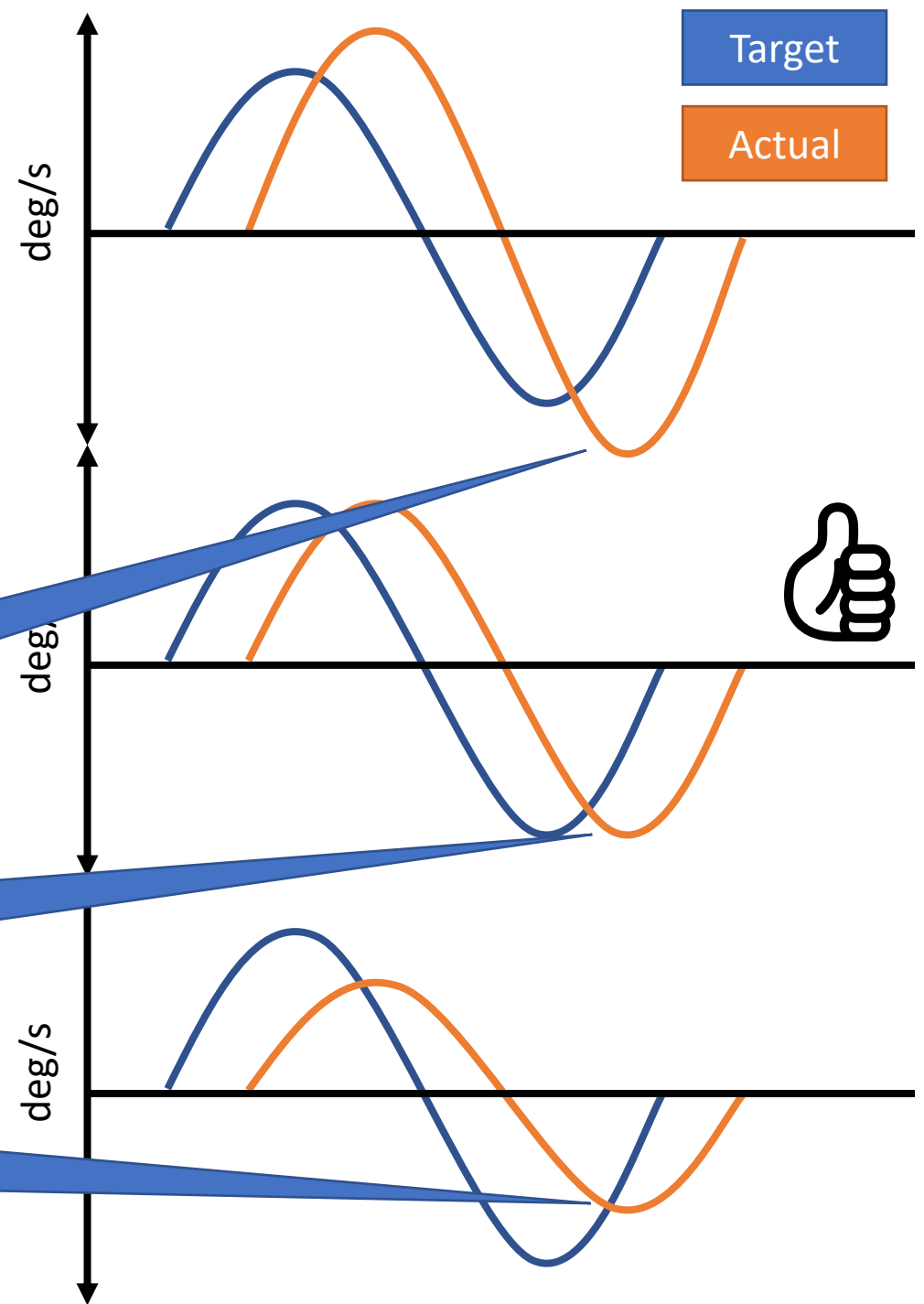
Tuning P:D balance

- Without DFF the Actual will always lag the target, that's OK for now

Actual peak value > Target peak value
Too much P term relative to D term

Actual peak value = Target peak value
P:D balance is correct

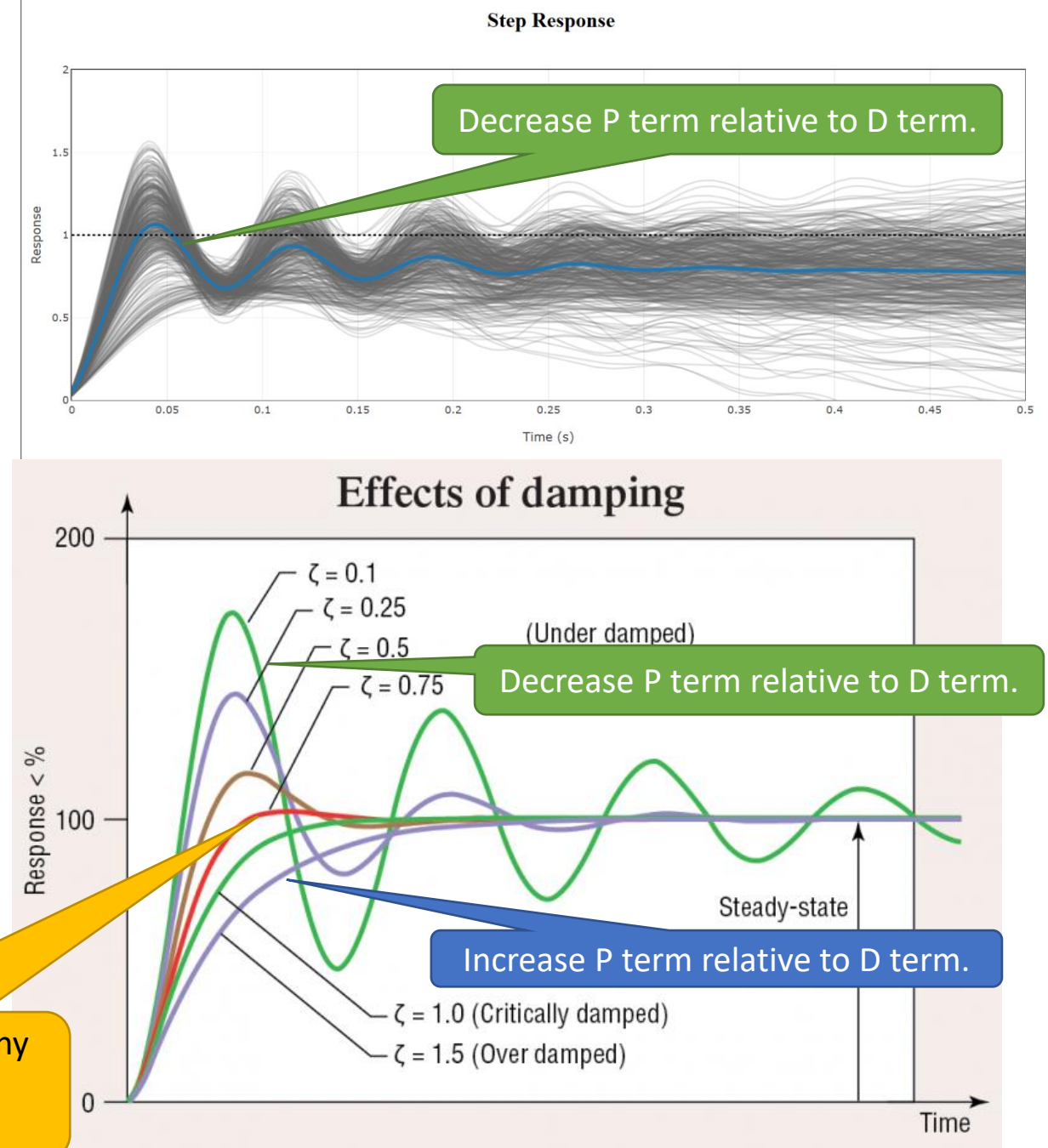
Actual peak value < Target peak value
Not enough P term relative to D term



Tuning P:D balance

- It's also possible to do this analysis using the step response in PIDReview
- You may find this view easier but the information is the same

The red line is the goal! A tiny bit of overshoot is OK but absolutely no oscillation.



Tuning P:D balance

- What is important is the P:D ratio not the individual values
- I would suggest only changing the P term during this stage of P:D balance tuning to keep things simple
- You can do this in Mission Planner > Config > Extended Tuning
- Unless you have a symmetric drone unlock Pitch and Roll Values and tune each axis separately

Mission Planner 1.3.82 build 1.3.9169.6147 ArduCopter V4.6.0-beta3 (110acc96)

DATA PLAN SETUP CONFIG SIMULATION HELP

GeoFence

Basic Tuning

Extended Tuning

Onboard OSD

MAVftp

User Params

Full Parameter List

Planner

CubeLan 8 port Switch

Stabilize Roll (Error to Rate)
P 4.500
ACCEL MA 135700

Stabilize Pitch (Error to Rate)
P 4.500
ACCEL MA 135700

Stabilize Yaw (Error to Rate)
P 4.500
ACCEL MA 28800

Position XY (Dist to Speed)
P 1.000
INPUT TC 0.150

Lock Pitch and Roll Values

-Rate Roll
P 0.135
I 0.135
D 0.002
IMAX 0.500
FLTE 0
FLTD 25.5
FLTT 25.5

Rate Pitch
P 0.135
I 0.135
D 0.002
IMAX 0.500
FLTE 0
FLTD 25.5
FLTT 25.5

Rate Yaw
P 0.180
I 0.018
D 0.000
IMAX 0.500
FLTE 2
FLTD 0
FLTT 25.5

Velocity XY (Vel to Accel)
P 2.0
I 1.000
D 0.500
IMAX 100

Basic Filters
Gyro 80
Accel 10

Throttle Accel (Accel to motor)
P 0.50
I 1.000
D 0.000
IMAX 80

Throttle Rate (VSpd to accel)
P 5.000
Tune None
Min 0.000 0.000

Altitude Hold (Alt to climb rate)
P 1.000

WPNV (cm/s)
Speed 1000
Radius 200
Speed Up 250
Speed Dn 150
Loiter Speed 1250

RC6 Opt Do Nothing
RC7 Opt Do Nothing
RC8 Opt Do Nothing
RC9 Opt Do Nothing
RC10 Opt Do Nothing

Filter Logs
Mask Options 5

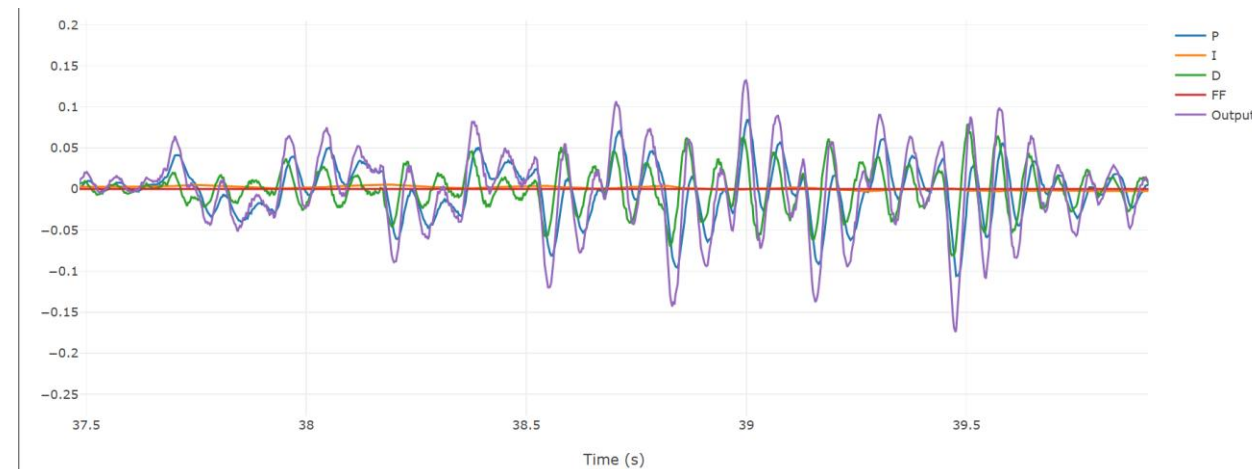
Static Notch Filter
Enabled
Frequency 10
Bandwidth 5
Attenuation 5

Harmonic Notch Filter
Enabled Enabled
Mode 3
Reference 1
Frequency 80
Attenuation 40
Bandwidth 15
Options 6
Harmonics 7

Write Params Refresh Screen


Troubleshooting Oscillation

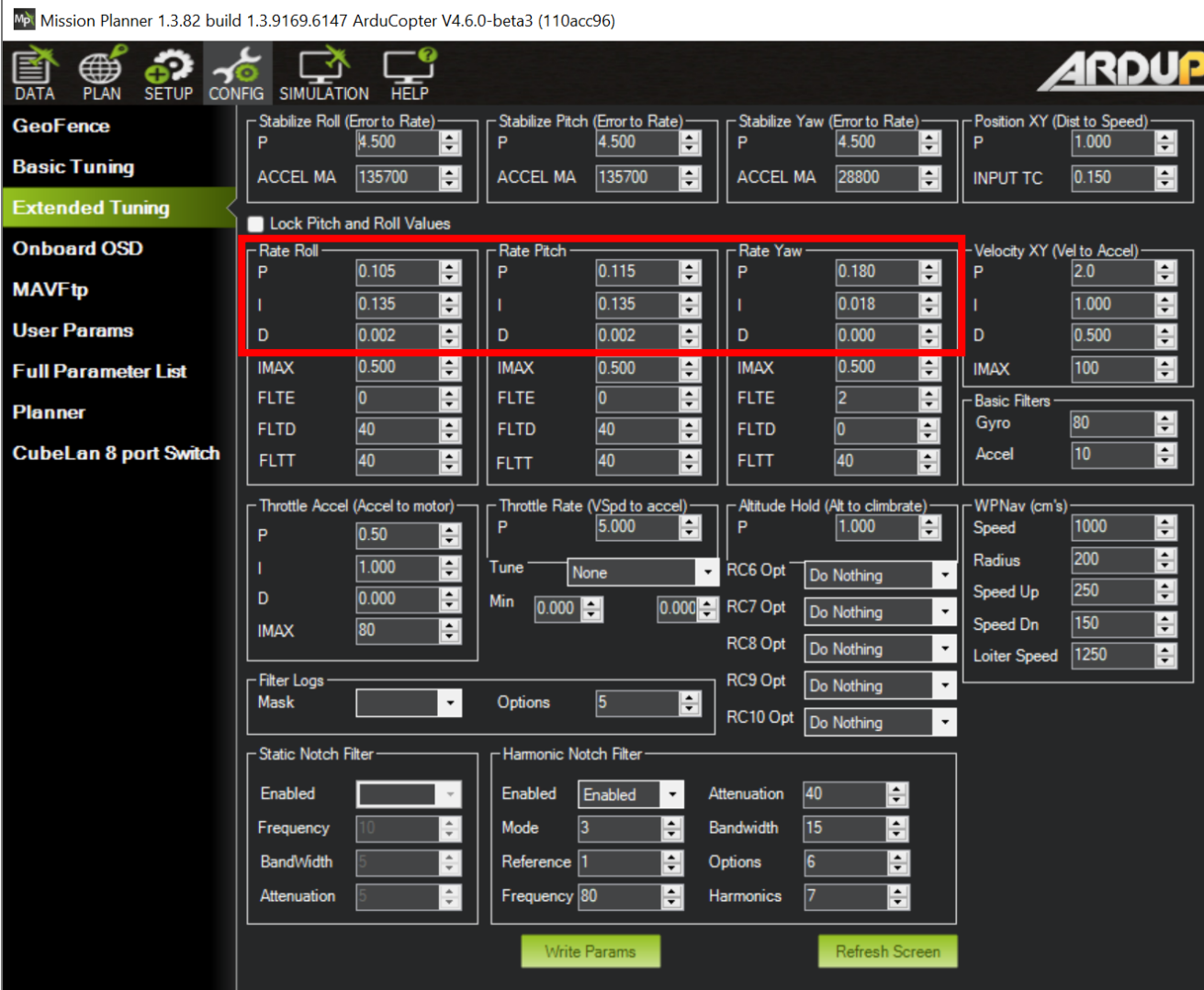
- If you are suffering from oscillations that don't improve when you reduce the P term this could be 2 things:
- D term oscillation: High D gains can self-oscillate independent of the P term, to fix this reduce both the D and P terms in steps of 10%
- Excessive filter delay can also cause oscillations, double check that you cannot improve your gyro filter settings



Absolute PID Gain Tuning

PID Gain Tuning

- Once the P:D Balance of the drone has been found we want to increase the overall PID gain to reduce PID error
- The way to do this is to increase P, I and D by the same multiple
 - $P_{\text{new}} = P_{\text{old}} * 1.1$
 - $I_{\text{new}} = I_{\text{old}} * 1.1$
 - $D_{\text{new}} = D_{\text{old}} * 1.1$
- This keeps P:D and P:I ratios the same 
- Keep increasing until you start to see oscillations in the logs then back down 10-20%
- Each axis should be adjusted separately



Mission Planner 1.3.82 build 1.3.9169.6147 ArduCopter V4.6.0-beta3 (110acc96)

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P 4.500

ACCEL MA 135700

Stabilize Pitch (Error to Rate)

P 4.500

ACCEL MA 135700

Stabilize Yaw (Error to Rate)

P 4.500

ACCEL MA 28800

Position XY (Dist to Speed)

P 1.000

INPUT TC 0.150

Lock Pitch and Roll Values

Rate Roll

P 0.105

I 0.135

D 0.002

Rate Pitch

P 0.115

I 0.135

D 0.002

Rate Yaw

P 0.180

I 0.018

D 0.000

Velocity XY (Vel to Accel)

P 2.0

I 1.000

D 0.500

IMAX 100

Basic Filters

Gyro 80

Accel 10

Throttle Accel (Accel to motor)

P 0.50

I 1.000

D 0.000

IMAX 80

Throttle Rate (VSpd to accel)

P 5.000

Tune None

Min 0.000 0.000

Altitude Hold (Alt to climbrate)

P 1.000

RC6 Opt Do Nothing

RC7 Opt Do Nothing

RC8 Opt Do Nothing

RC9 Opt Do Nothing

RC10 Opt Do Nothing

WPNV (cm/s)

Speed 1000

Radius 200

Speed Up 250

Speed Dn 150

Loiter Speed 1250

Filter Logs

Mask Options 5

Static Notch Filter

Enabled

Frequency 10

BandWidth 5

Attenuation 5

Harmonic Notch Filter

Enabled Enabled

Mode 3

Reference 1

Frequency 80

Attenuation 40

Bandwidth 15

Options 6

Harmonics 7

Write Params

Refresh Screen

PID Gain Tuning

- In many cases you will see a drastic improvement in flight performance from increasing overall PID gains 😊

Mission Planner 1.3.82 build 1.3.9169.6147 ArduCopter V4.6.0-beta3 (110acc96)

DATA PLAN SETUP CONFIG SIMULATION HELP

GeoFence

Basic Tuning

Extended Tuning

Lock Pitch and Roll Values

Rate Roll

P	0.105
I	0.135
D	0.002

Rate Pitch

P	0.115
I	0.135
D	0.002

Rate Yaw

P	0.180
I	0.018
D	0.000

Velocity XY (Vel to Accel)

P	2.0
I	1.000
D	0.500
IMAX	100

Basic Filters

Gyro	80
Accel	10

Throttle Accel (Accel to motor)

P	0.50
I	1.000
D	0.000
IMAX	80

Throttle Rate (VSpd to accel)

P	5.000
Tune	None
Min	0.000

Altitude Hold (Alt to climbrate)

P	1.000
---	-------

WPNV (cm/s)

Speed	1000
Radius	200
Speed Up	250
Speed Dn	150
Loiter Speed	1250

Filter Logs

Mask	
Options	5

Static Notch Filter

Enabled	
Frequency	10
BandWidth	5
Attenuation	5

Harmonic Notch Filter

Enabled	Enabled
Mode	3
Reference	1
Frequency	80
Attenuation	40
Bandwidth	15
Options	6
Harmonics	7

Write Params Refresh Screen

P:I Balance Tuning

- I term typically has a wide tuning window
- It is not always necessary to directly tune the I term (except as part of overall PID gain tuning)
- However, theoretically increasing the I term can give target tracking improvements
- I term should be increased until there is evidence of I term oscillations in the logs then backed down 10-20%
- Each axis should be adjusted separately

Mission Planner 1.3.82 build 1.3.9169.6147 ArduCopter V4.6.0-beta3 (110acc96)

DATA PLAN SETUP CONFIG SIMULATION HELP

GeoFence

Basic Tuning

Extended Tuning

Onboard OSD

MAVftp

User Params

Full Parameter List

Planner

CubeLan 8 port Switch

Parameter	Value
Stabilize Roll (Error to Rate) P	4.500
Stabilize Roll (Error to Rate) ACCEL MA	135700
Stabilize Pitch (Error to Rate) P	4.500
Stabilize Pitch (Error to Rate) ACCEL MA	135700
Stabilize Yaw (Error to Rate) P	4.500
Stabilize Yaw (Error to Rate) ACCEL MA	28800
Position XY (Dist to Speed) P	1.000
Position XY (Dist to Speed) INPUT TC	0.150
Rate Roll P	0.105
Rate Roll I	0.135
Rate Roll D	0.002
Rate Roll IMAX	0.500
Rate Roll FLTE	0
Rate Roll FLTD	40
Rate Roll FLTT	40
Rate Pitch P	0.115
Rate Pitch I	0.135
Rate Pitch D	0.002
Rate Pitch IMAX	0.500
Rate Pitch FLTE	0
Rate Pitch FLTD	40
Rate Pitch FLTT	40
Rate Yaw P	0.180
Rate Yaw I	0.018
Rate Yaw D	0.000
Rate Yaw IMAX	0.500
Rate Yaw FLTE	2
Rate Yaw FLTD	0
Rate Yaw FLTT	40
Velocity XY (Vel to Accel) P	2.0
Velocity XY (Vel to Accel) I	1.000
Velocity XY (Vel to Accel) D	0.500
Velocity XY (Vel to Accel) IMAX	100
Basic Filters Gyro	80
Basic Filters Accel	10
Throttle Accel (Accel to motor) P	0.50
Throttle Accel (Accel to motor) I	1.000
Throttle Accel (Accel to motor) D	0.000
Throttle Accel (Accel to motor) IMAX	80
Throttle Rate (VSpd to accel) P	5.000
Throttle Rate (VSpd to accel) Tune	None
Throttle Rate (VSpd to accel) Min	0.000
Altitude Hold (Alt to climbrate) P	1.000
RC6 Opt	Do Nothing
RC7 Opt	Do Nothing
RC8 Opt	Do Nothing
RC9 Opt	Do Nothing
RC10 Opt	Do Nothing
Filter Logs Mask	
Filter Logs Options	5
Static Notch Filter Enabled	
Static Notch Filter Frequency	10
Static Notch Filter BandWidth	5
Static Notch Filter Attenuation	5
Harmonic Notch Filter Enabled	Enabled
Harmonic Notch Filter Mode	3
Harmonic Notch Filter Reference	1
Harmonic Notch Filter Frequency	80
Harmonic Notch Filter Attenuation	40
Harmonic Notch Filter Bandwidth	15
Harmonic Notch Filter Options	6
Harmonic Notch Filter Harmonics	7

Write Params Refresh Screen

Yaw Axis

- The Yaw axis doesn't usually need a D term for typical Multicopters
- This means that only the P:I balance and overall gains need to be tuned
- Before increasing P and I gains consider reducing the Yaw Error filtering for smaller quads

Mission Planner 1.3.82 build 1.3.9169.6147 ArduCopter V4.6.0-beta3 (110acc96)

DATA PLAN SETUP CONFIG SIMULATION HELP

GeoFence

Basic Tuning

Extended Tuning

Onboard OSD

MAVftp

User Params

Full Parameter List

Planner

CubeLan 8 port Switch

Stabilize Roll (Error to Rate)
P 4.500
ACCEL MA 135700

Stabilize Pitch (Error to Rate)
P 4.500
ACCEL MA 135700

Stabilize Yaw (Error to Rate)
P 4.500
ACCEL MA 28800

Position XY (Dist to Speed)
P 1.000
INPUT TC 0.150

Lock Pitch and Roll Values

Rate Roll
P 0.105
I 0.135
D 0.002
IMAX 0.500
FLTE 0
FLTD 40
FLTT 40

Rate Pitch
P 0.115
I 0.135
D 0.002
IMAX 0.500
FLTE 0
FLTD 40
FLTT 40

Rate Yaw
P 0.180
I 0.018
D 0.000
IMAX 0.500
FLTE 2
FLTD 0
FLTT 40

Velocity XY (Vel to Accel)
P 2.0
I 1.000
D 0.500
IMAX 100

Basic Filters
Gyro 80
Accel 10

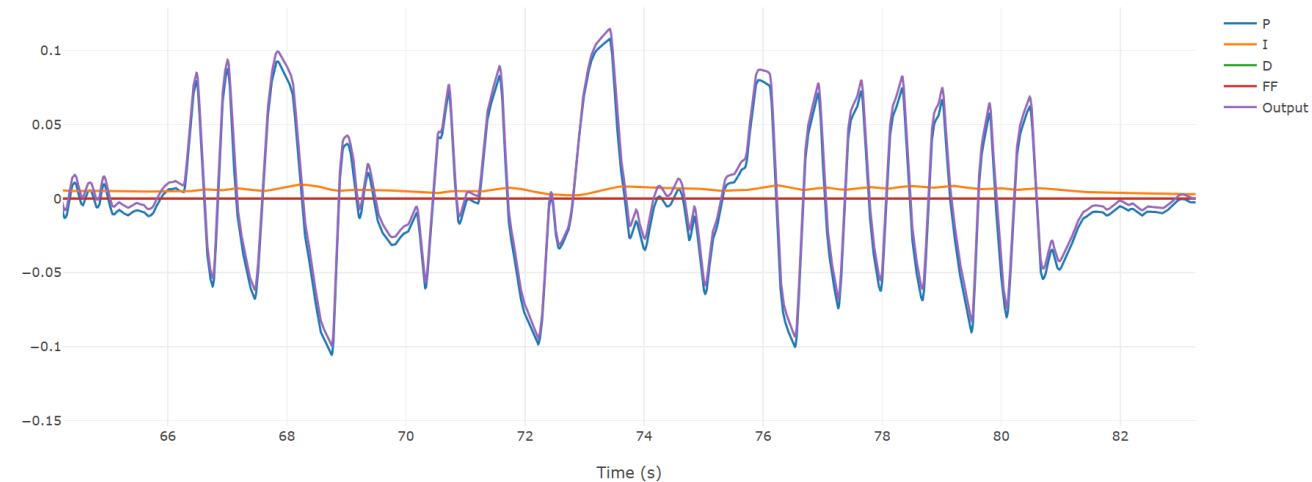
Throttle Accel (Accel to motor)
P 0.50
I 1.000
D 0.000
IMAX 80

Throttle Rate (VSpd to accel)
P 5.000
Tune None
Min 0.000 0.000

Altitude Hold (Alt to climbrate)
P 1.000
RC6 Opt Do Nothing
RC7 Opt Do Nothing
RC8 Opt Do Nothing
RC9 Opt Do Nothing
RC10 Opt Do Nothing

WPNV (cm/s)
Speed 1000
Radius 200
Speed Up 250
Speed Dn 150
Loiter Speed 1250

Filter Logs Mask Options 5



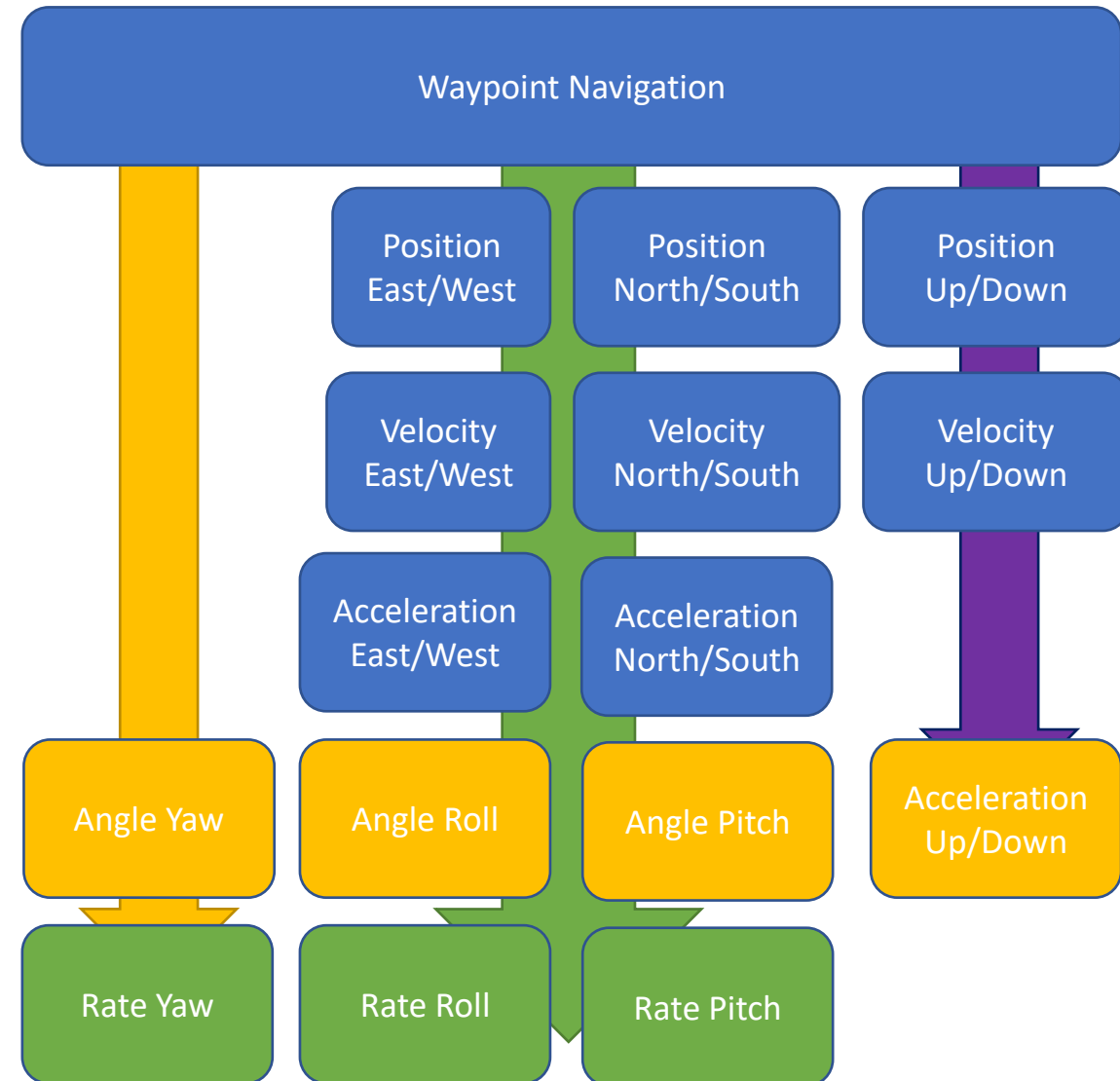
Rate PID Tuning

- At this stage you should have an excellent Rate PID tune on your drone
- If the Rate tune is good then tuning the higher level controllers will be straightforward
- Hopefully you are already seeing a big improvement in the flight behaviour in all modes

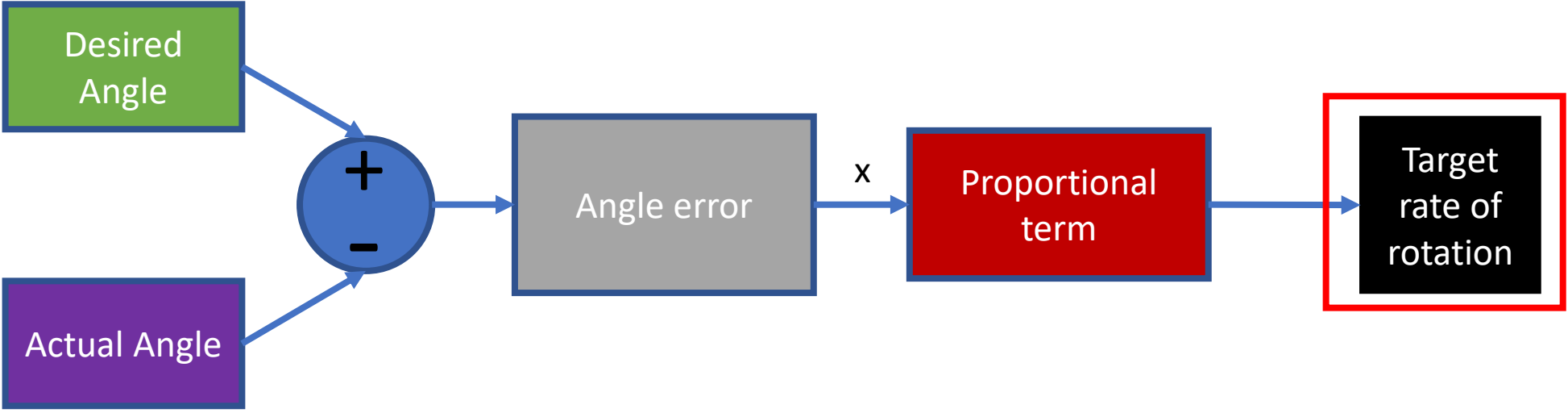
Attitude (Stabilize) Control Tuning

Attitude Controller Background

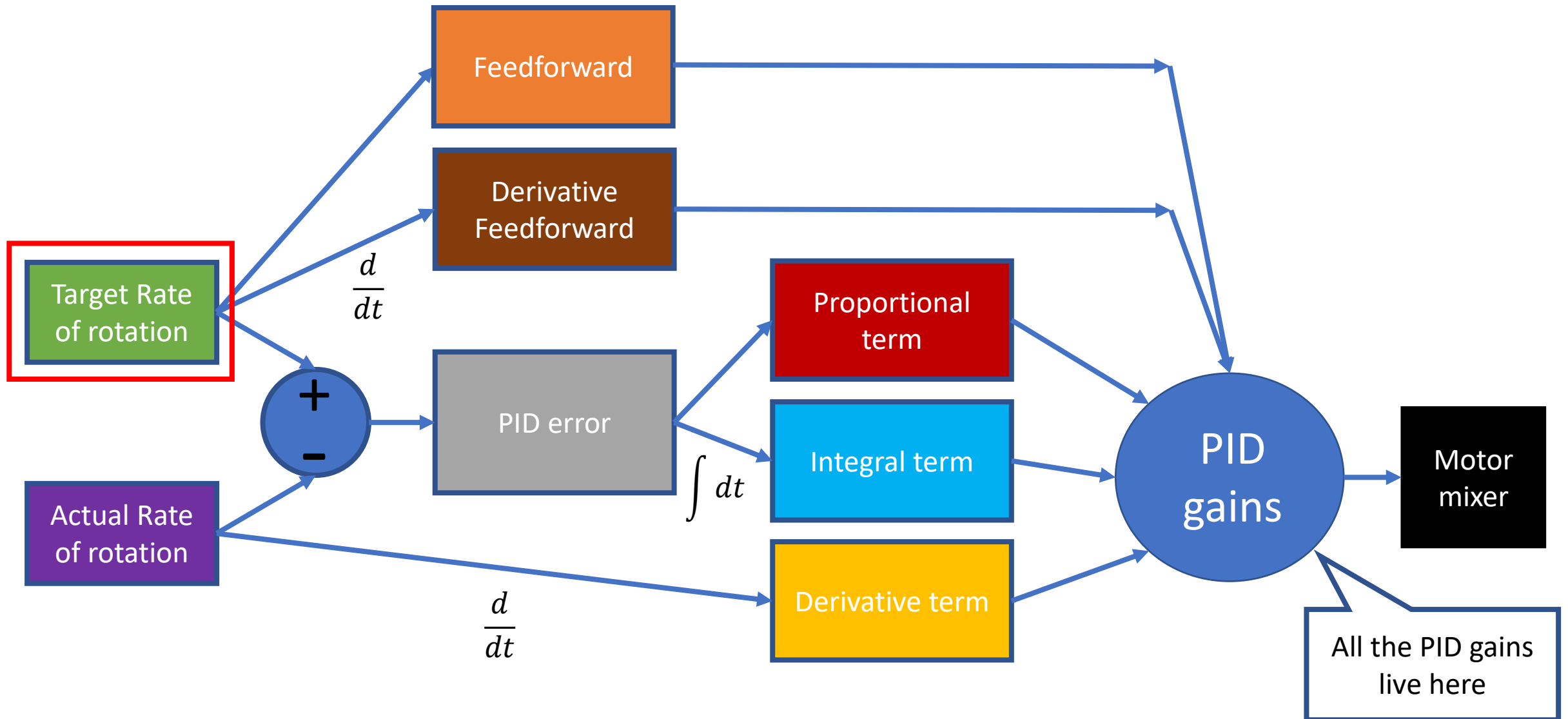
- The Attitude Controller controls the Angle of the drone relative to the ground for the Pitch and Roll axes and North for the Yaw axis
- These are simple proportional controllers
- The difference between Desired and Actual Angle is multiplied by a factor to give the target rate of rotation



The Ardupilot Angle PID Controller



The Ardupilot Rate PID-FF-DFF Controller



Attitude Controller Tuning

- You can tune the P terms for these controllers in the Extended Tuning Tab
- A larger value will give a more aggressive response to errors in attitude
- Increase the value gradually until you start to experience oscillations then back down 20% or so to ensure stability

Mission Planner 1.3.82 build 1.3.9169.6147 ArduCopter V4.6.0-beta3 (110acc96)

DATA PLAN SETUP CONFIG SIMULATION HELP

GeoFence

Basic Tuning

Extended Tuning

Onboard OSD

MAVftp

User Params

Full Parameter List

Planner

CubeLan 8 port Switch

Stabilize Roll (Error to Rate)
P 4.500
ACCEL MA 135700

Stabilize Pitch (Error to Rate)
P 4.500
ACCEL MA 135700

Stabilize Yaw (Error to Rate)
P 4.500
ACCEL MA 28800

Position XY (Dist to Speed)
P 1.000
INPUT TC 0.150

Lock Pitch and Roll Values

Rate Roll
P 0.090
I 0.135
D 0.00200
IMAX 0.5
FLTE 0
FLTD 40
FLTT 40

Rate Pitch
P 0.100
I 0.135
D 0.00200
IMAX 0.5
FLTE 0
FLTD 40
FLTT 40

Rate Yaw
P 0.180
I 0.018
D 0.00000
IMAX 0.5
FLTE 2
FLTD 0
FLTT 40

Velocity XY (Vel to Accel)
P 2.000
I 1.000
D 0.500
IMAX 100

Basic Filters
Gyro 80
Accel 10

Throttle Accel (Accel to motor)
P 0.500
I 1.000
D 0.000
IMAX 80

Throttle Rate (VSpd to accel)
P 5.000
Tune None
Min 0.000 0.000

Altitude Hold (Alt to climbrate)
P 1.000

WPNav (cm's)
Speed 1000
Radius 200
Speed Up 250
Speed Dn 150
Loiter Speed 1250

Filter Logs
Mask Options 5

RC6 Opt Do Nothing
RC7 Opt Do Nothing
RC8 Opt Do Nothing
RC9 Opt Do Nothing
RC10 Opt Do Nothing

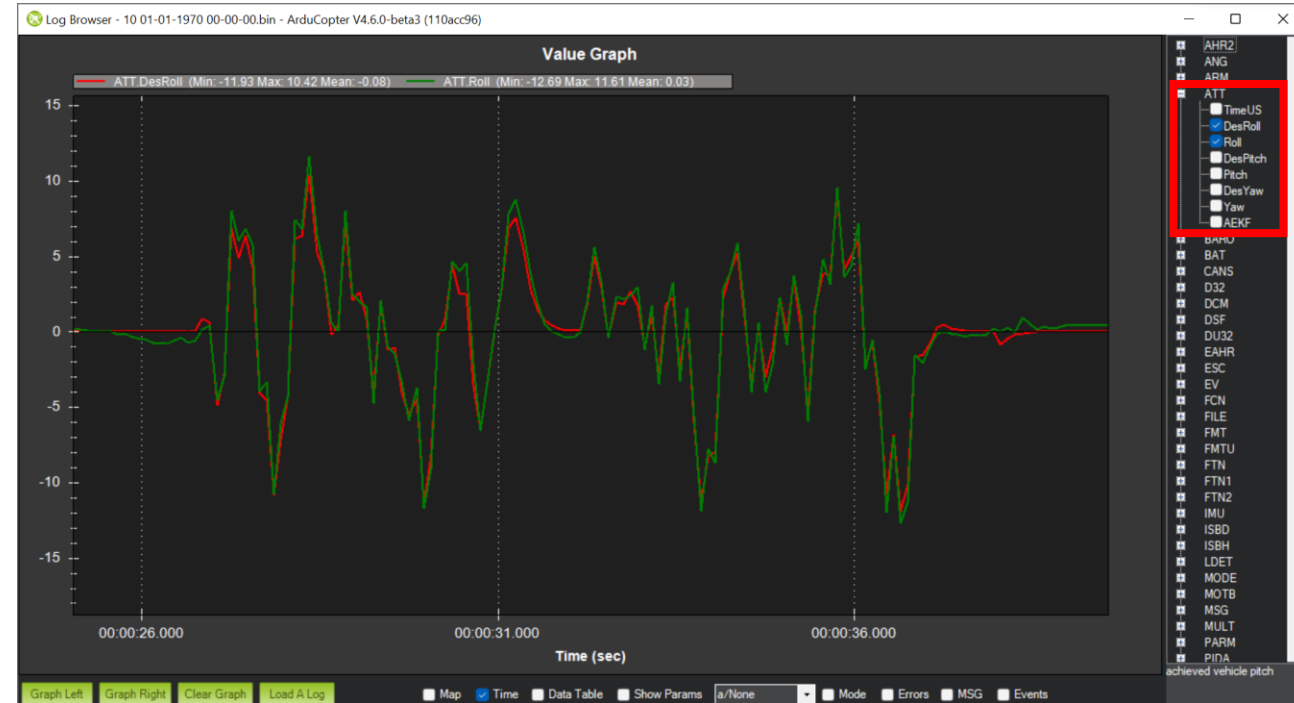
Static Notch Filter
Enabled
Frequency 10
BandWidth 5
Attenuation 5

Harmonic Notch Filter
Enabled Enabled
Mode 3
Reference 1
Frequency 80
Attenuation 40
Bandwidth 15
Options 6
Harmonics 7

Write Params Refresh Screen

Attitude Logging

- You can review the Desired vs Actual angles in the ATT log section
- Here you can check for oscillations or overshoots as you increase the Attitude P gain
- Tune each axis separately



Attitude Max Acceleration

- Ardupilot provides limits for the maximum rate of angular acceleration demanded by the attitude controller
- These should be set according to the capability of the drone

Mission Planner 1.3.82 build 1.3.9169.6147 ArduCopter V4.6.0-beta3 (110acc96)

DATA PLAN SETUP CONFIG SIMULATION HELP

GeoFence

Basic Tuning

Stabilize Roll (Error to Rate) P 4.500
Stabilize Pitch (Error to Rate) P 4.500
Stabilize Yaw (Error to Rate) P 4.500
Position XY (Dist to Speed) P 1.000
ACCEL MA 135700
ACCEL MA 135700
ACCEL MA 28800
INPUT TC 0.150

Extended Tuning

Lock Pitch and Roll Values

Rate Roll P 0.090 I 0.135 D 0.00200 IMAX 0.5 FLTE 0 FLTD 40 FLTT 40
Rate Pitch P 0.100 I 0.135 D 0.00200 IMAX 0.5 FLTE 0 FLTD 40 FLTT 40
Rate Yaw P 0.180 I 0.018 D 0.00000 IMAX 0.5 FLTE 2 FLTD 0 FLTT 40
Velocity XY (Vel to Accel) P 2.000 I 1.000 D 0.500 IMAX 100
Basic Filters Gyro 80 Accel 10
Throttle Accel (Accel to motor) P 0.500 I 1.000 D 0.000 IMAX 80
Throttle Rate (VSpd to accel) P 5.000 Tune None Min 0.000 0.000
Altitude Hold (Alt to climb rate) P 1.000 RC6 Opt Do Nothing RC7 Opt Do Nothing RC8 Opt Do Nothing RC9 Opt Do Nothing RC10 Opt Do Nothing
WPNV (cm/s) Speed 1000 Radius 200 Speed Up 250 Speed Dn 150 Loiter Speed 1250
Filter Logs Mask Options 5
Static Notch Filter Enabled Frequency 10 BandWidth 5 Attenuation 5
Harmonic Notch Filter Enabled Mode 3 Reference 1 Frequency 80 Attenuation 40 Bandwidth 15 Options 6 Harmonics 7

Write Params Refresh Screen

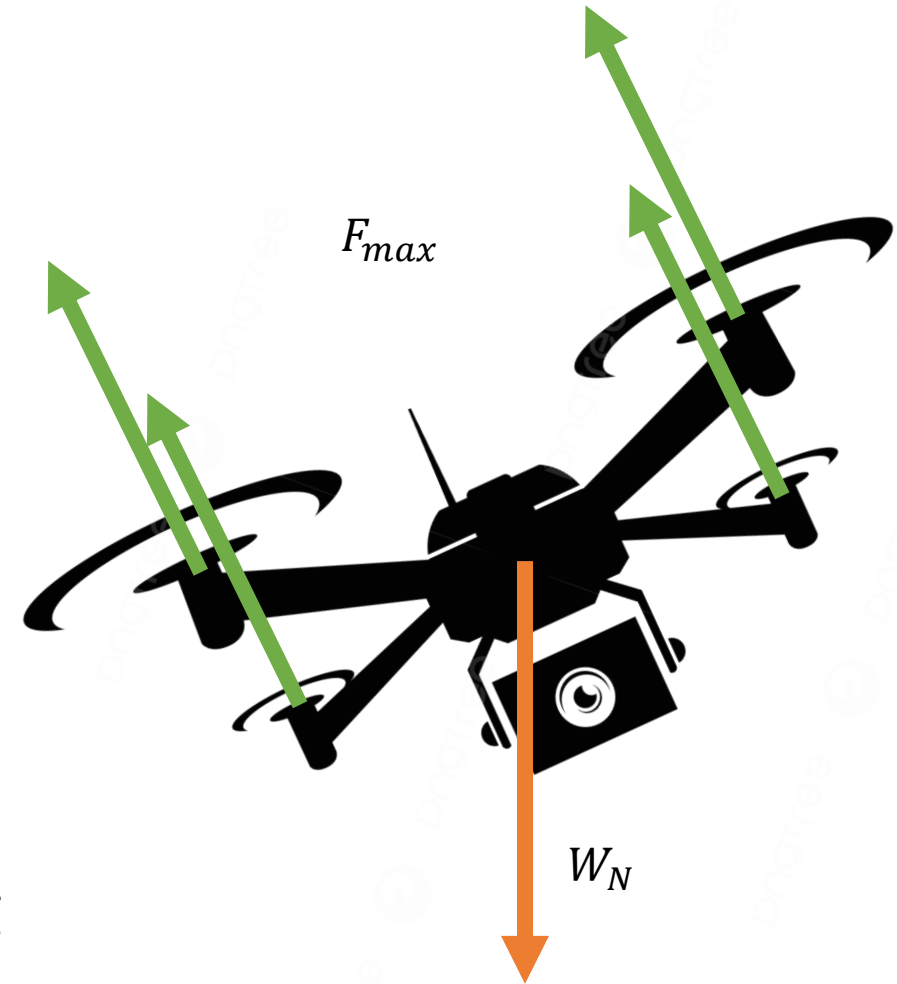
Maximum Lean Angles

Calculating Max Lean Angle

- The maximum lean angle should usually be set to ensure that the drone has enough Thrust to maintain altitude and control even at the maximum lean angle

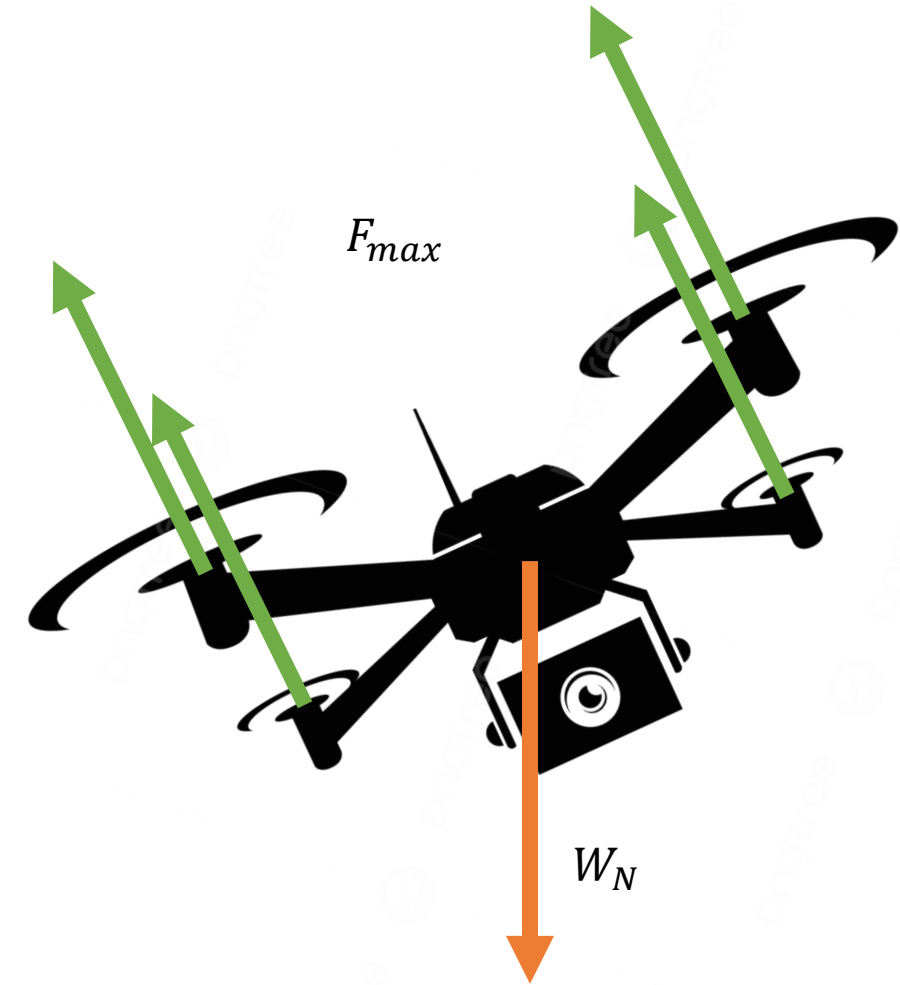
$$\theta_{max} = \cos^{-1}\left(\frac{W_N}{0.8 * F_{max}}\right)$$

- This equation may give large angles of 45° or more
- For most applications a max angle of 30° is sufficient and larger values can be concerning for pilots!



Setting Max Lean Angle

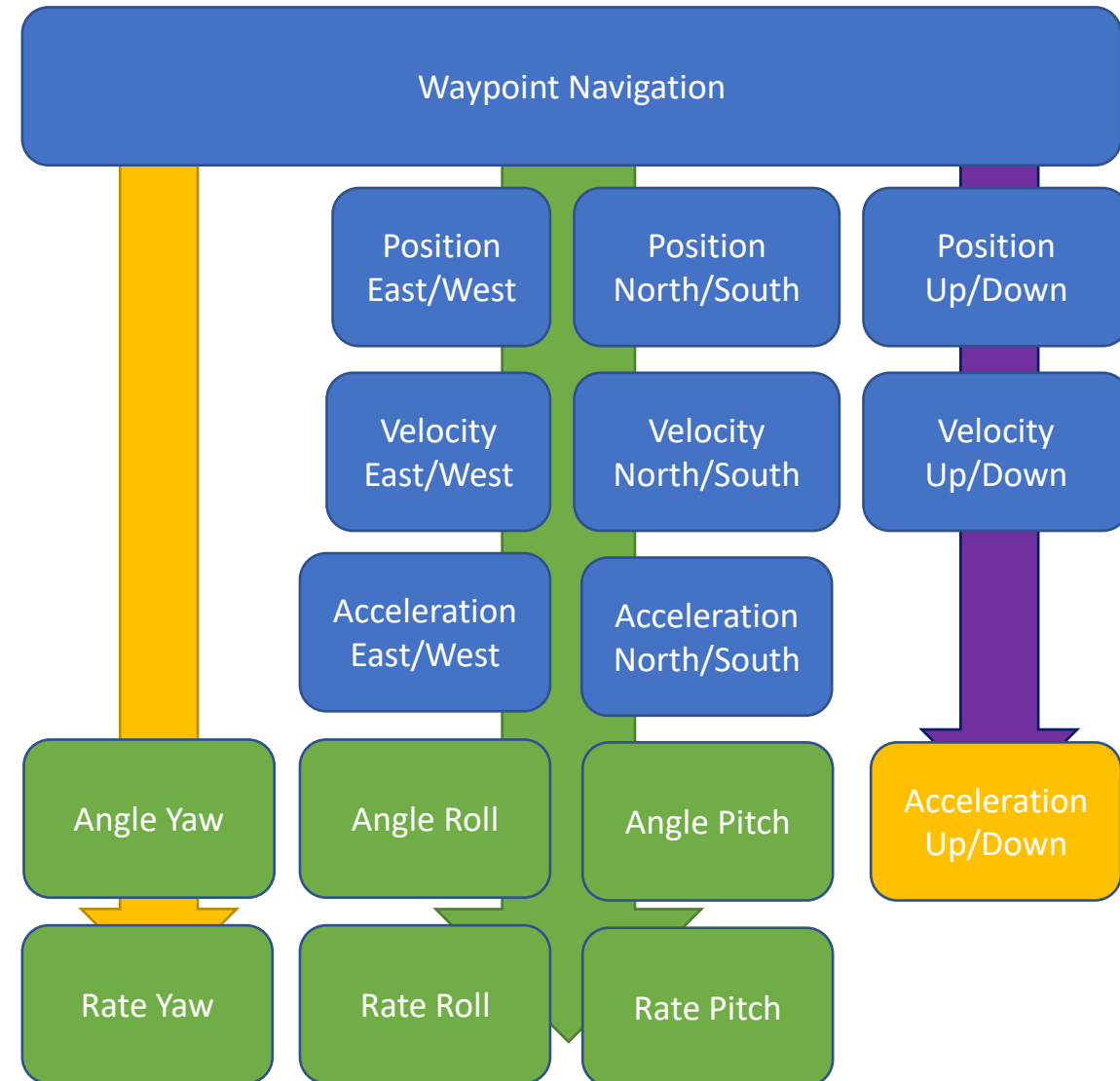
- Once the max lean angle has been decided upon set up the maximum angles:
- **ANGLE_MAX** is the max angle allowed in all modes
- **PSC_ANGLE_MAX** is the max angle allowed in position hold mode (set = 0 to use **ANGLE_MAX**)
- **LOIT_ANGLE_MAX** is the max pilot requested angle allowed in loiter mode (set = 0 to use 2/3 of **ANGLE_MAX**)
- I would generally recommend:
 - **ANGLE_MAX = 30**
 - **PSC_ANGLE_MAX = 0** (same as **ANGLE_MAX**)
 - **LOIT_ANGLE_MAX = 30** (same as **ANGLE_MAX**)



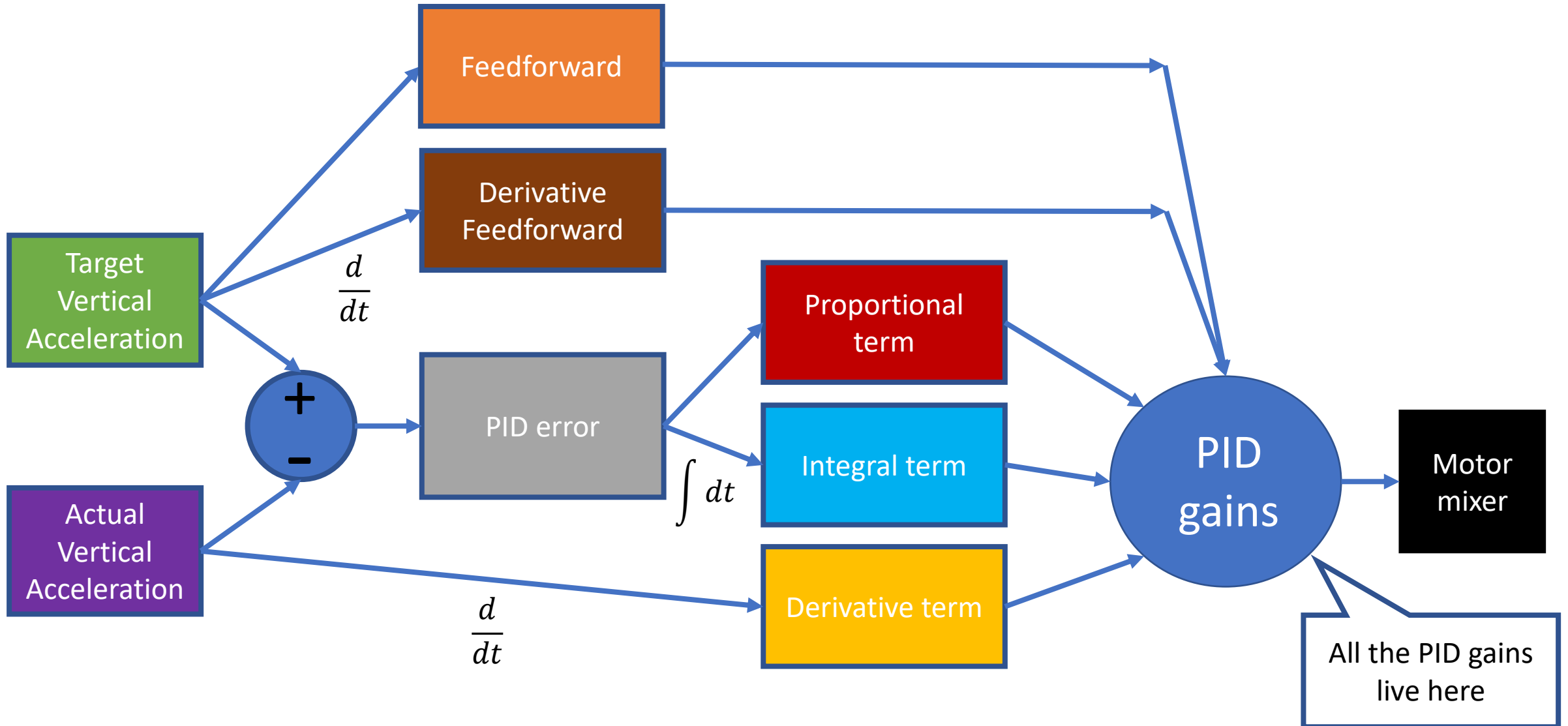
Throttle PID Controller

Throttle Controller Background

- The Throttle Controller controls the Altitude of the drone
- It converts a requested vertical acceleration into a motor output
- It includes P-I-D-FF-DFF terms just like the rate controllers and is tuned in the same way



The Ardupilot Throttle Controller

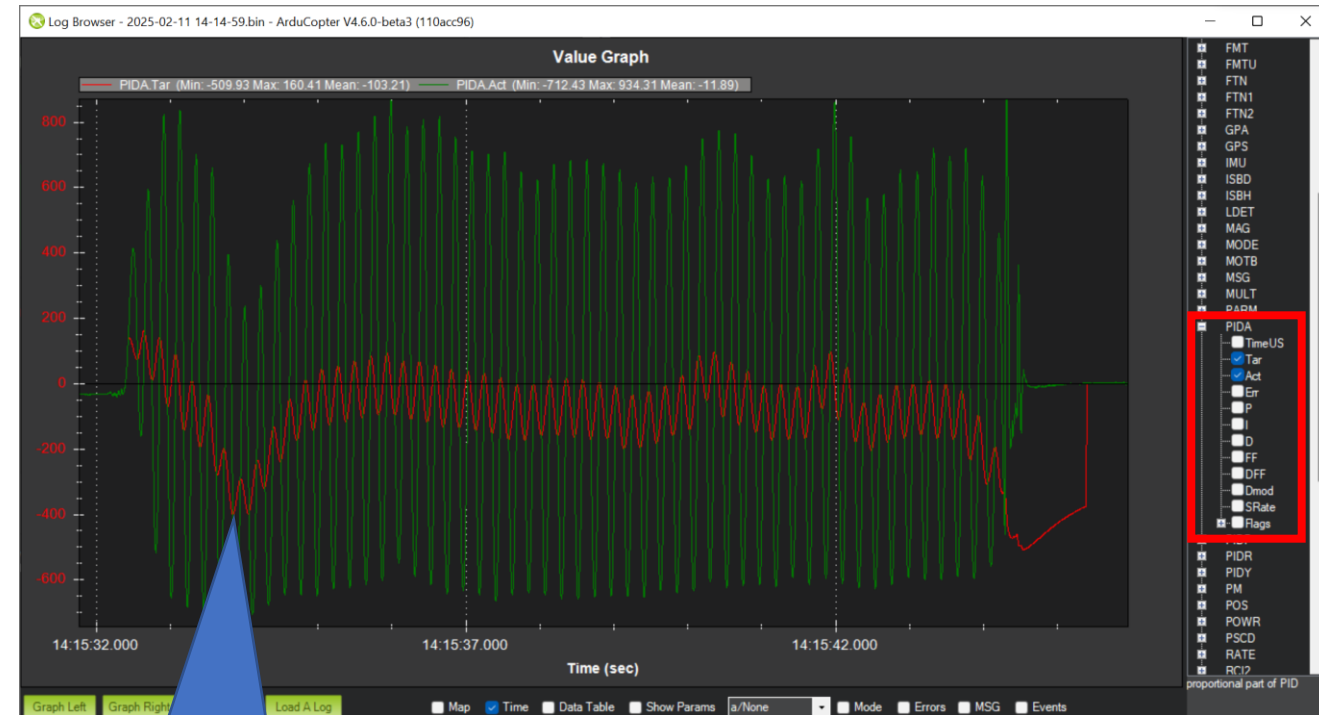


Throttle Controller Tuning Flights

- Tuning flights for the Throttle controller must be done in **Altitude Hold** mode
- They will consist of sharp vertical moves
 - Rapid climb, rapid descent, rapid climb etc.
- Because we are looking at acceleration the drone doesn't have to change altitude very much and the wobbles can be quite quick

Throttle Controller Logging

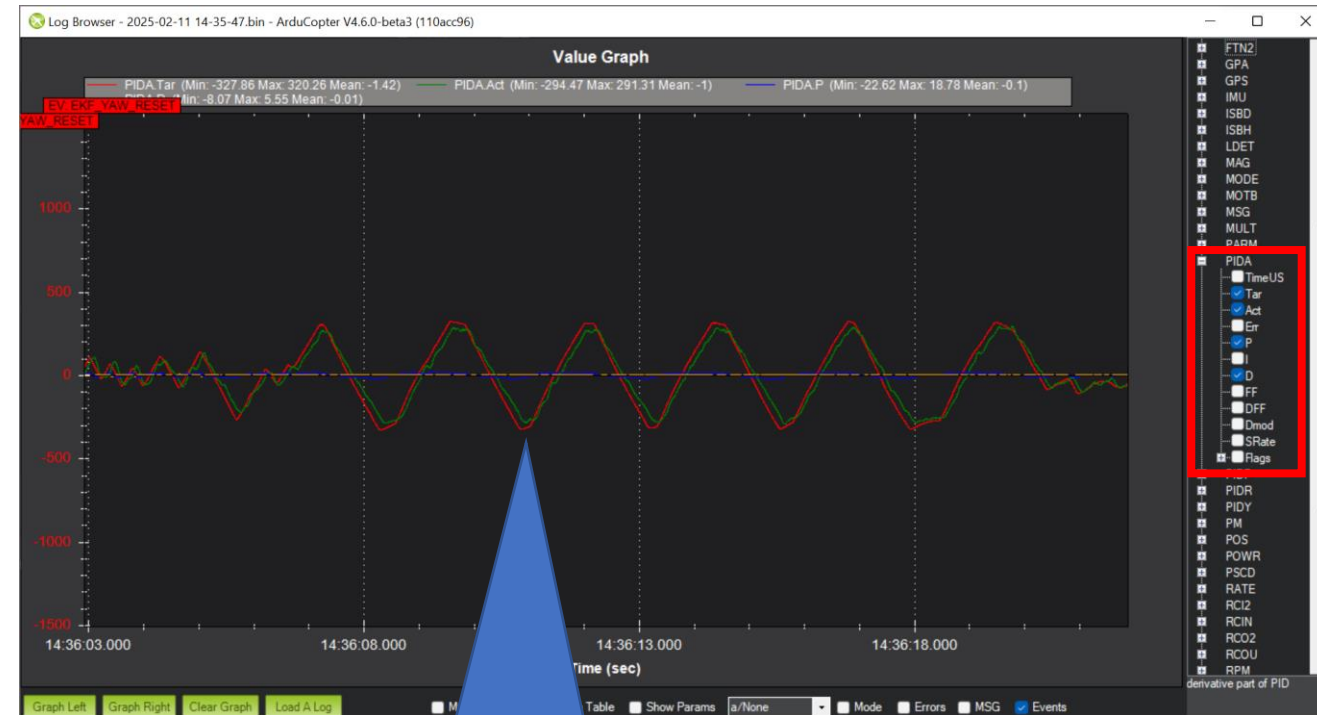
- You can review the Throttle Controller Logs in the PIDA log section
- As you can see the default settings can be very oscillatory as there is no D gain
 - $P = 0.5$
 - $D = 0$



P Term Oscillation due to zero default D gain

Throttle Controller Logging

- Reducing the P gain and adding some D gain will eliminate the oscillations
- In this log (an 8" drone) the P:D balance is around 50:1
 - $P = 0.25$
 - $D = 0.005$



Some delay and undershoot
but oscillations are eliminated

Throttle Controller D-term Noise

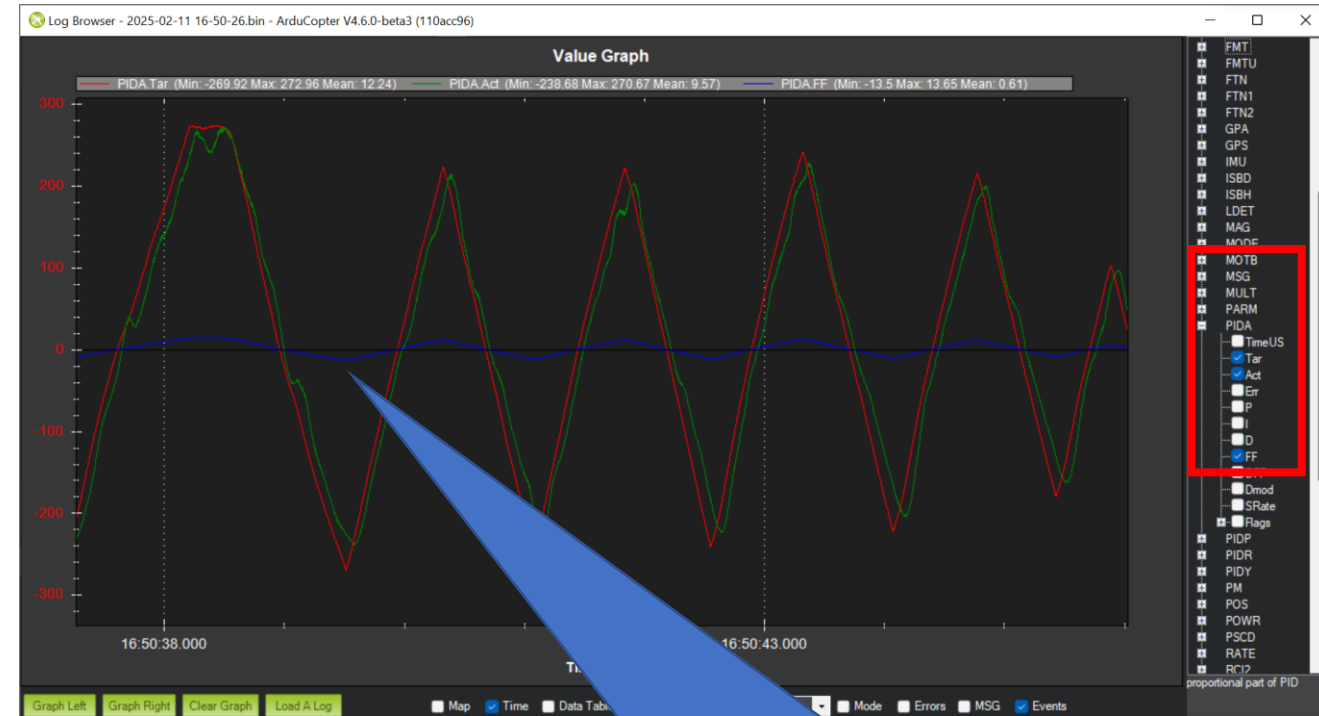
- As with the Rate Controllers it's important to check that the D term is not too noisy
- Excessive D term noise can be addressed by decreasing the **PSC_ACCZ_FLTD** cut-off frequency (0 means disabled)
- If needed start with $\sim 20\text{Hz}$



D term is acceptable here with
 $\text{SNR} \approx 10$ and FLTD disabled

Throttle Controller Feedforward

- Similar to Yaw the Throttle controller can benefit from a positive Feedforward term
- A larger positive vertical acceleration naturally requires a higher throttle setting
- FF provides this without the need for error between the Target and Actual values
- Try **PSC_ACCZ_FF = 0.05** to start with



FF increases motor output when larger vertical acceleration is requested

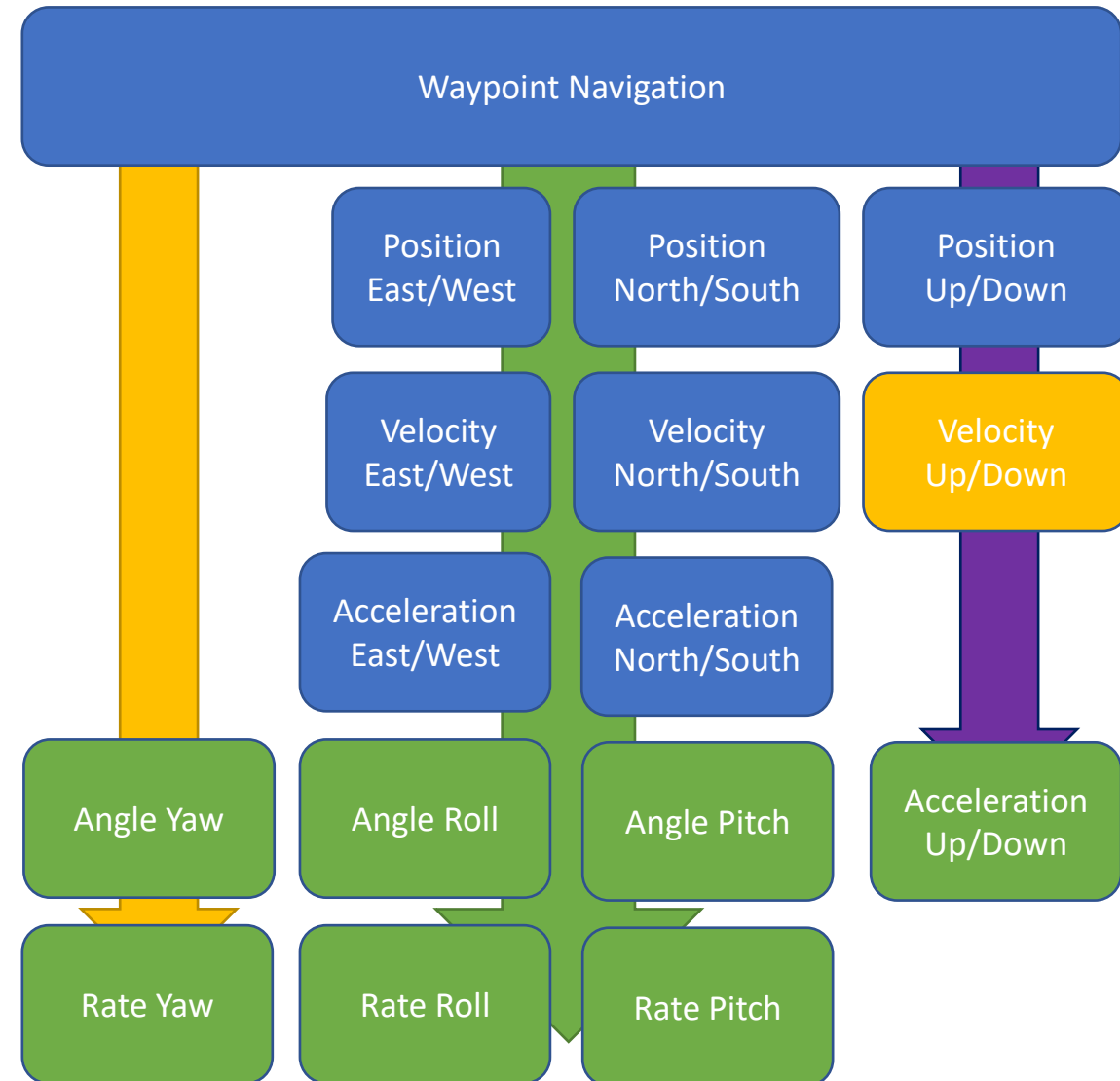
Throttle Controller Derivative Feedforward

- The Throttle controller can benefit from a positive Derivative Feedforward term
- As with the other Rate controllers derivative feedforward helps reduce the delay between the Target and Actual curves
- It is tuned in the same way as for the rate controllers, increase DFF to reduce delay, too much causes Actual to lead Target and overshoot



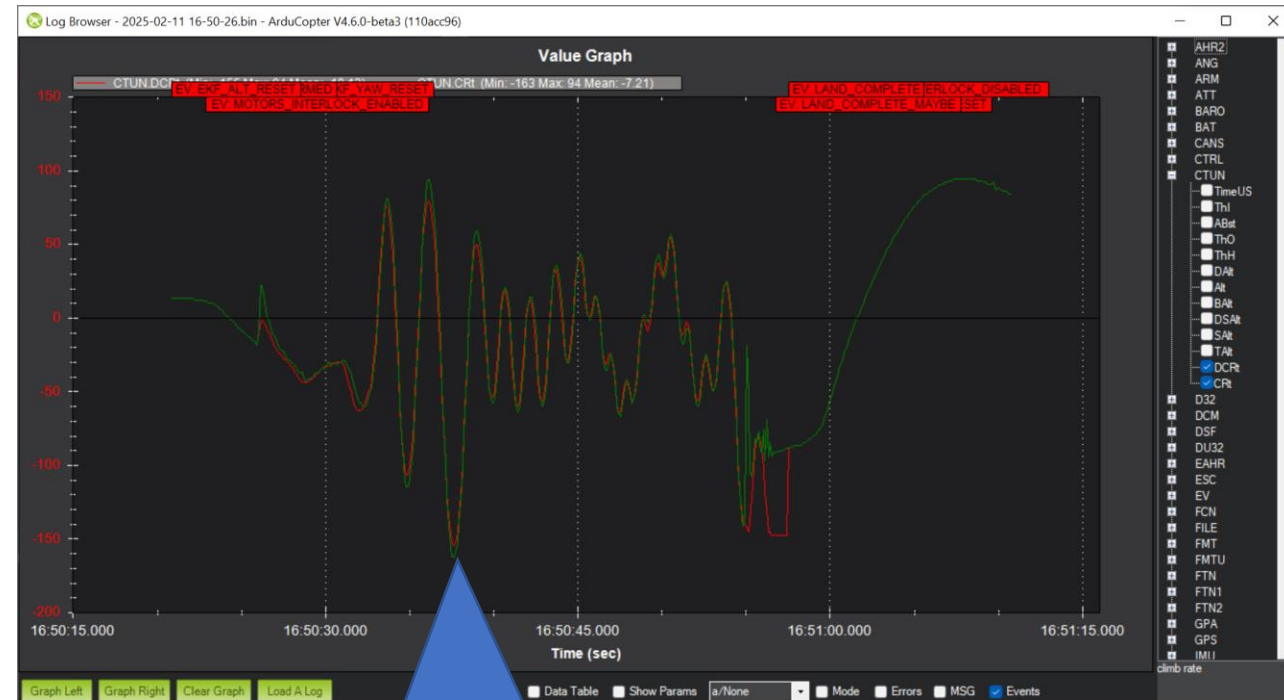
Vertical Velocity Controller

- Sitting above the throttle controller is the vertical velocity controller
- This is another PID controller **PSC_VELZ_P, I, D, FF, FLTE, FLTD**
- There is no derivative feedforward or target filtering in the vertical velocity controller



Vertical Velocity Controller

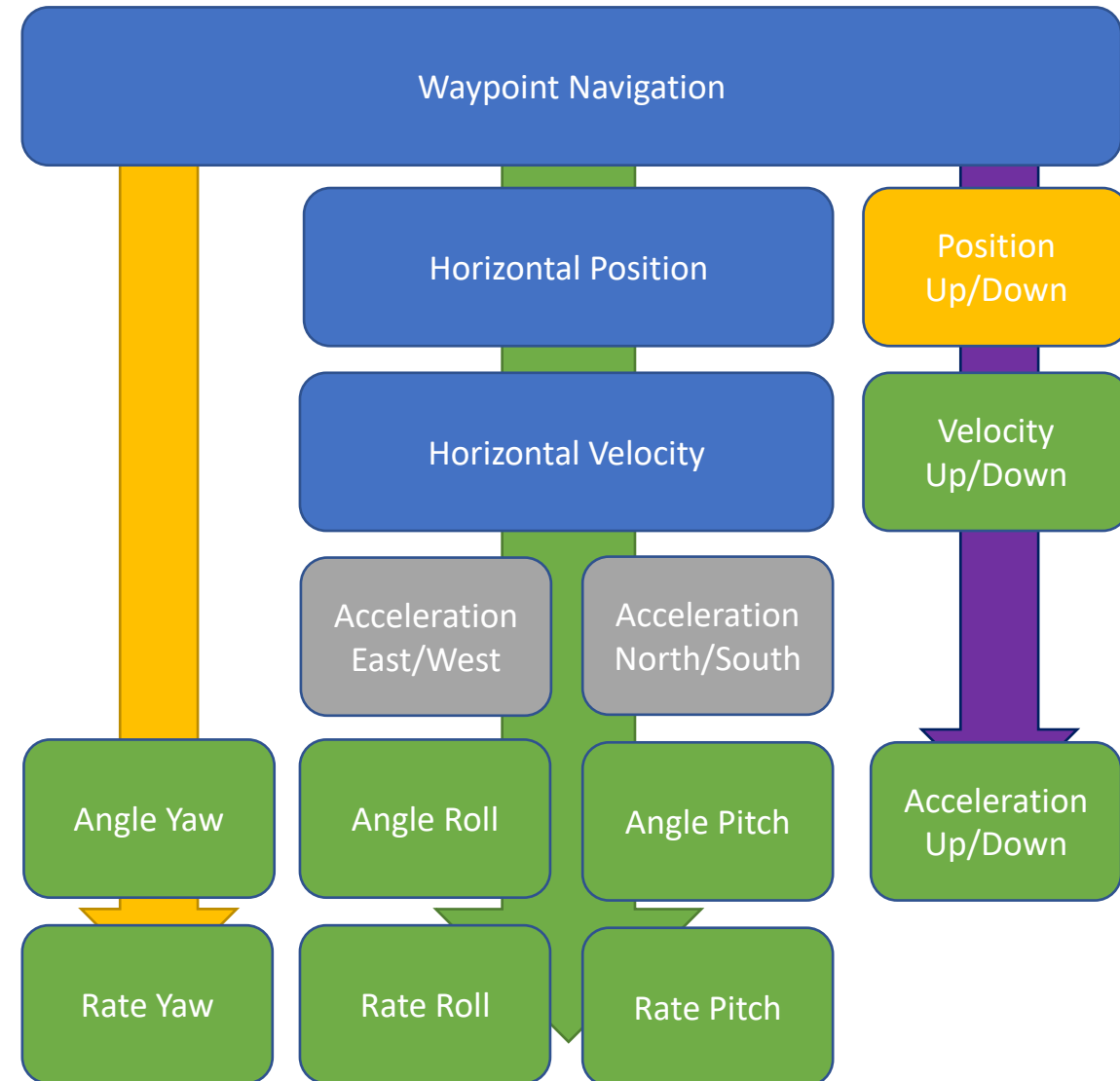
- To Tune the vertical velocity controller you can use the data in
 - $CTUN > DCRt$ (Desired climb rate)
 - $CTUN > CRt$ (Climb Rate)
- If the Throttle Controller is well tuned you may not need to add much D term at all
- You should not typically need to add any Feedforward (FF) or I term into this controller



Here tracking is good and overshoot is minimal, slightly reduce P term

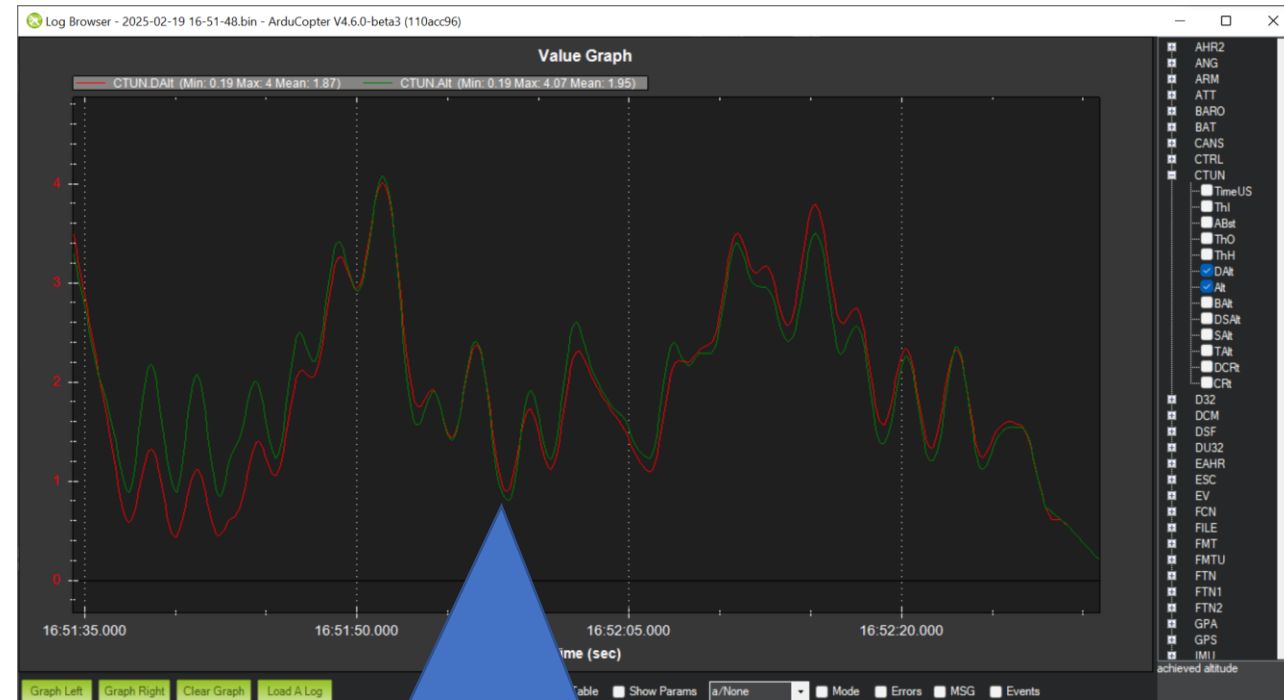
Vertical Position Controller

- Sitting above the vertical velocity controller is the vertical position controller
- This converts an error in the vertical position into a target vertical velocity
- This is simple proportional (P) controller **PSC_POSZ_P**



Vertical Position Controller

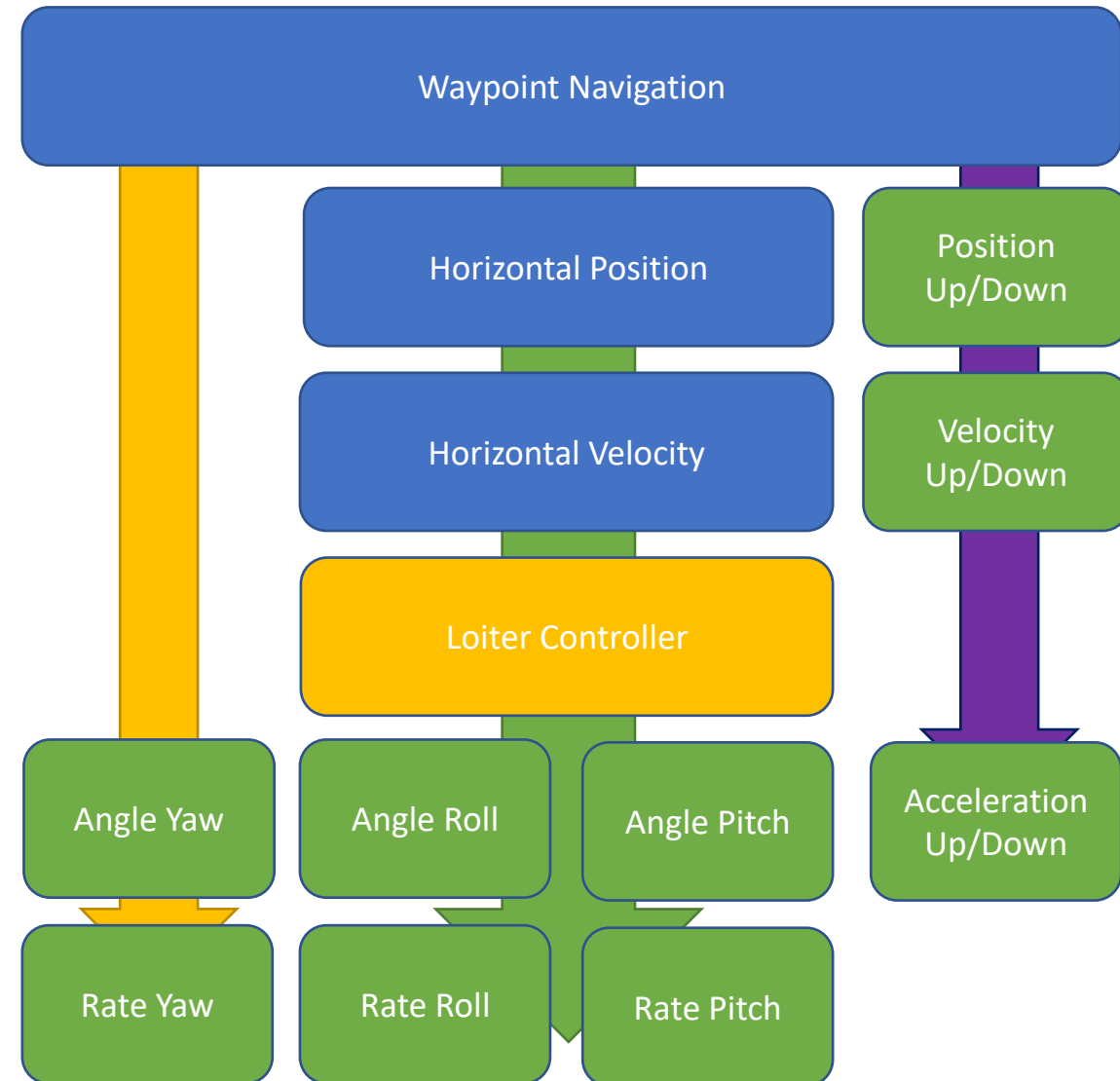
- To Tune the vertical velocity controller you can use the data in
 - $CTUN > DAlt$ (Desired altitude)
 - $CTUN > Alt$ (Altitude)
- The only parameter to adjust is **PSC_POSZ_P** increase it to track the desired altitude more aggressively
- Watch for overshoot/oscillation which indicates **PSC_POSZ_P** is too high



Here tracking is good and overshoot is minimal, P term is appropriate

Loiter Controller

- Sitting above the angle controllers is the loiter controller
- This converts the target horizontal acceleration into pitch and roll angles
- It also contains several parameters which control the drone's movement in loiter mode

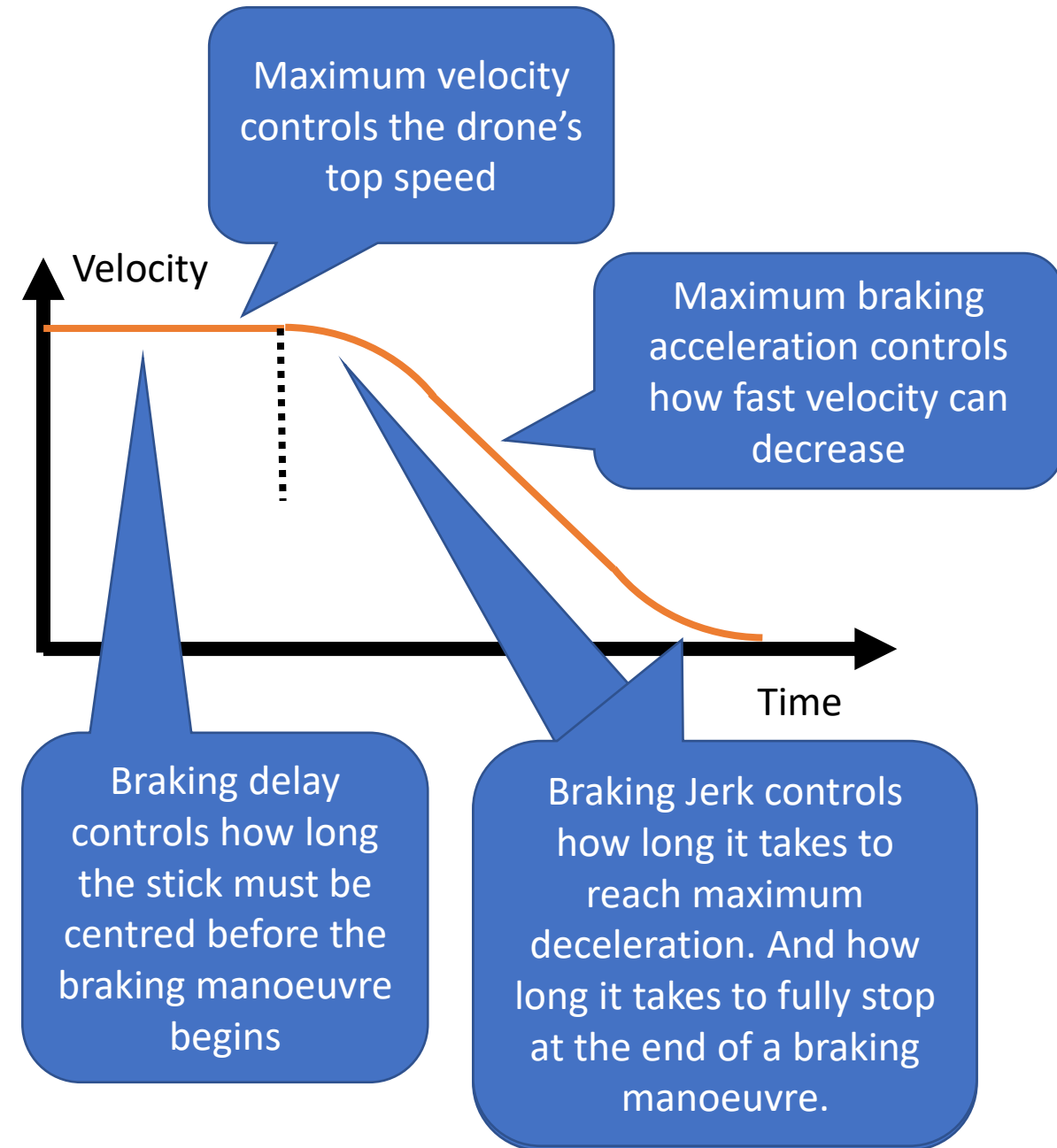


Parameters

- **LOIT_ACC_MAX** the maximum acceleration to correct position errors
- **LOIT_ANG_MAX** the maximum lean angle in position hold mode (usually set equal to **ANGLE_MAX**)
- **LOIT_BRK_ACCEL** the maximum braking acceleration when the stick is centred
- **LOIT_BRK_DELAY** the braking delay when the stick is centred (often best set to 0)
- **LOIT_SPEED** the maximum speed in Loiter Mode
- **LOIT_BRK_JERK** the maximum braking jerk

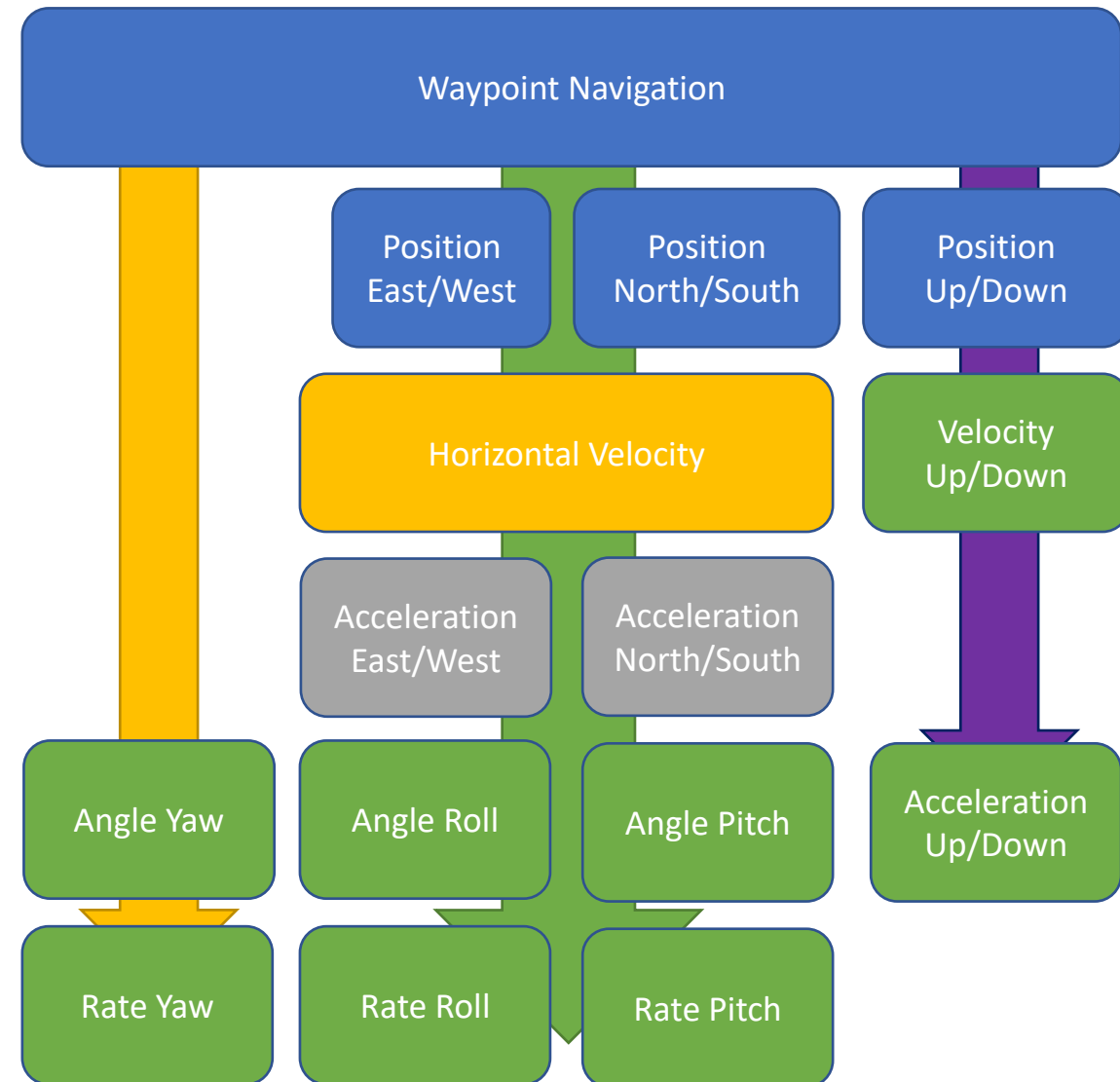
Jerk, Acceleration, Max velocity

- **LOIT_ACC_MAX** the maximum acceleration to correct position errors
- **LOIT_ANG_MAX** the maximum lean angle in position hold mode (usually set equal to **ANGLE_MAX**)
- **LOIT_BRK_ACCEL** the maximum braking acceleration when the stick is centred
- **LOIT_BRK_DELAY** the braking delay when the stick is centred (often best set to 0)
- **LOIT_SPEED** the maximum speed in Loiter Mode
- **LOIT_BRK_JERK** the maximum braking jerk (increasing this reduces drift when stopping)



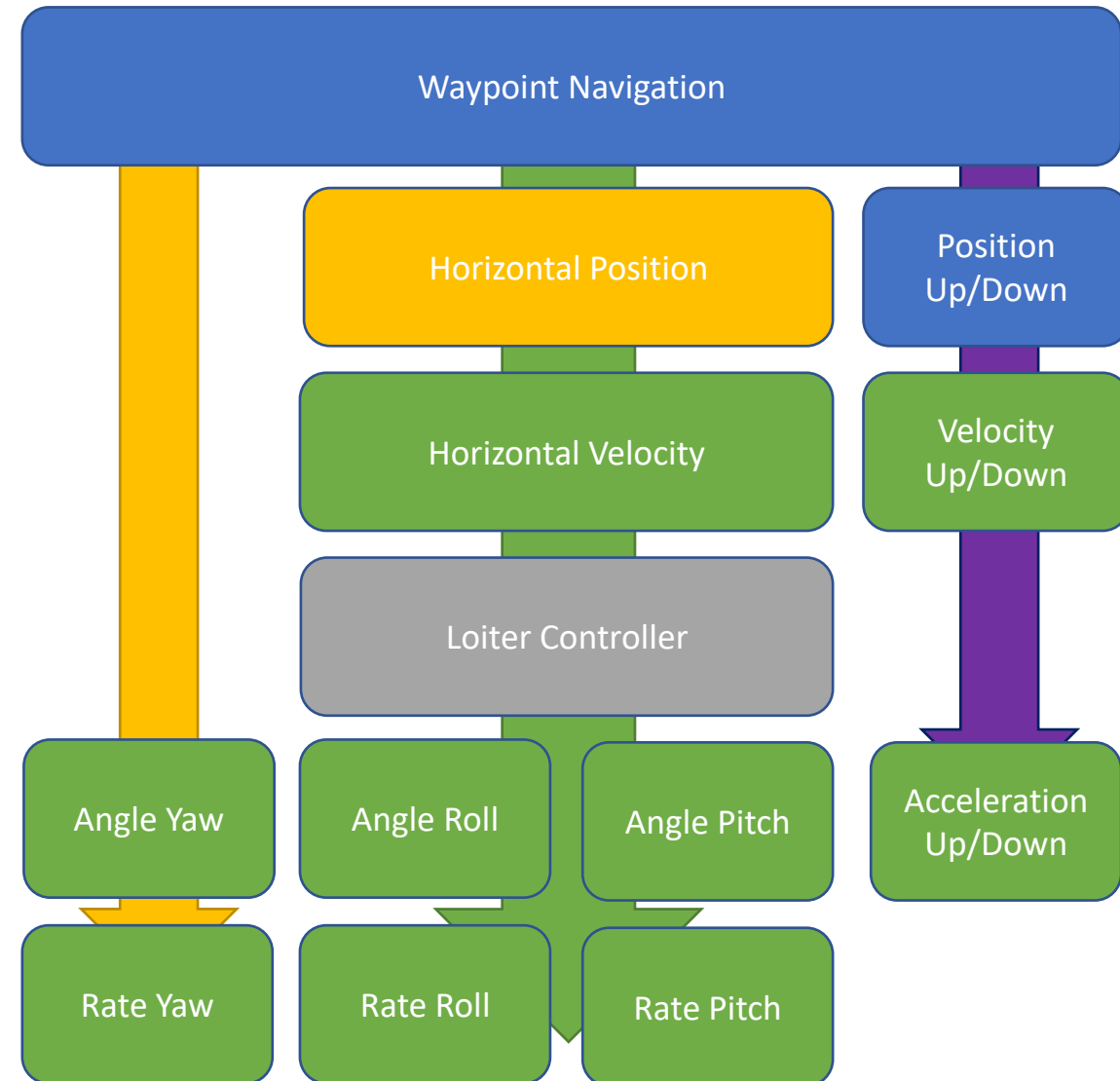
Horizontal Velocity Controller

- Sitting above the angle controllers is the horizontal velocity controller
- This converts a target horizontal velocity into a target acceleration
- This is another PID controller
PSC_VELXY_P, I, D, FF, FLTE, FLTD
- There is no derivative feedforward or target filtering in the horizontal velocity controller



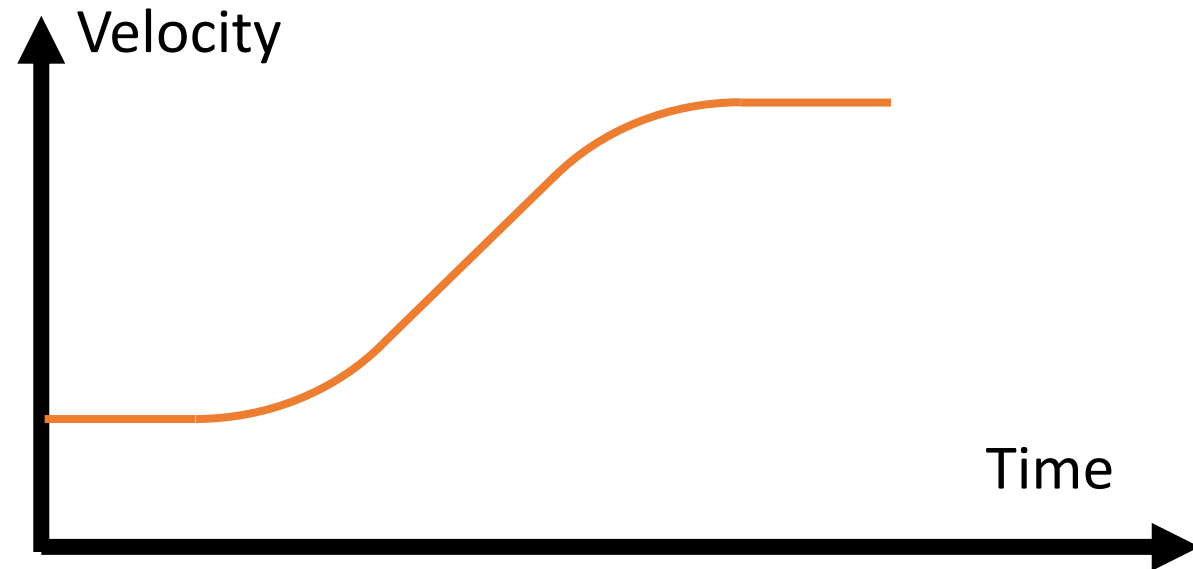
Horizontal Position Controller

- Sitting above the horizontal velocity controller is the horizontal position controller
- This converts an error in the horizontal position into a target horizontal velocity
- This is a simple proportional (P) controller **PSC_PSCXY_P**
- However there are many parameters which limit the velocity and acceleration targets (kinematic path)



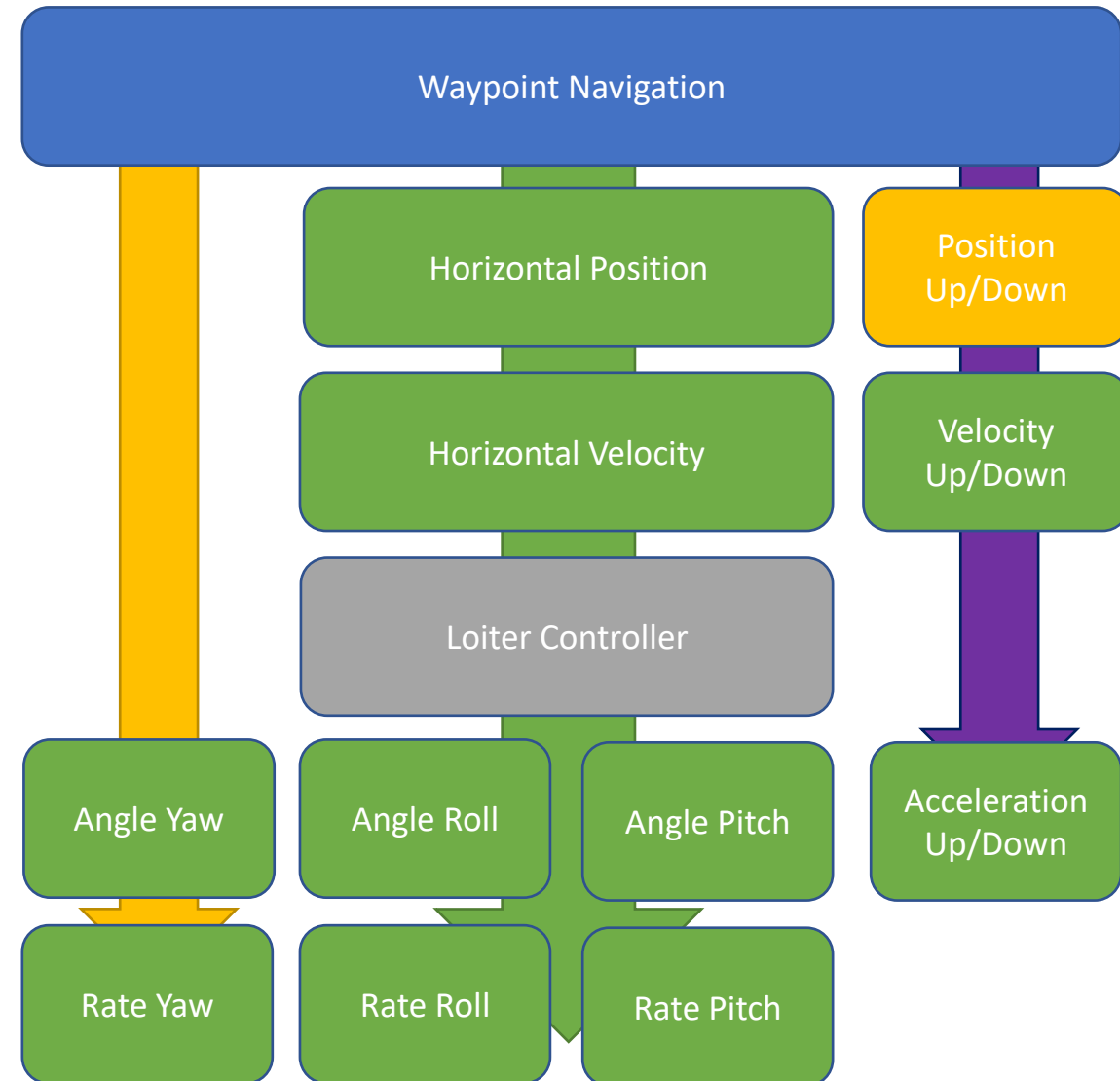
Tuning Horizontal Kinematic Parameters

- The parameters with the biggest effect on the horizontal movement are **LOIT_SPEED** and **PSC_JERK_XY**
- **LOIT_SPEED** is more obvious, set this to a suitable maximum speed
- **PSC_JERK_XY** is more subtle, increase this to give a snappier response to horizontal control inputs in loiter mode
- Setting **PSC_JERK_XY** too high may make the drone feel too aggressive

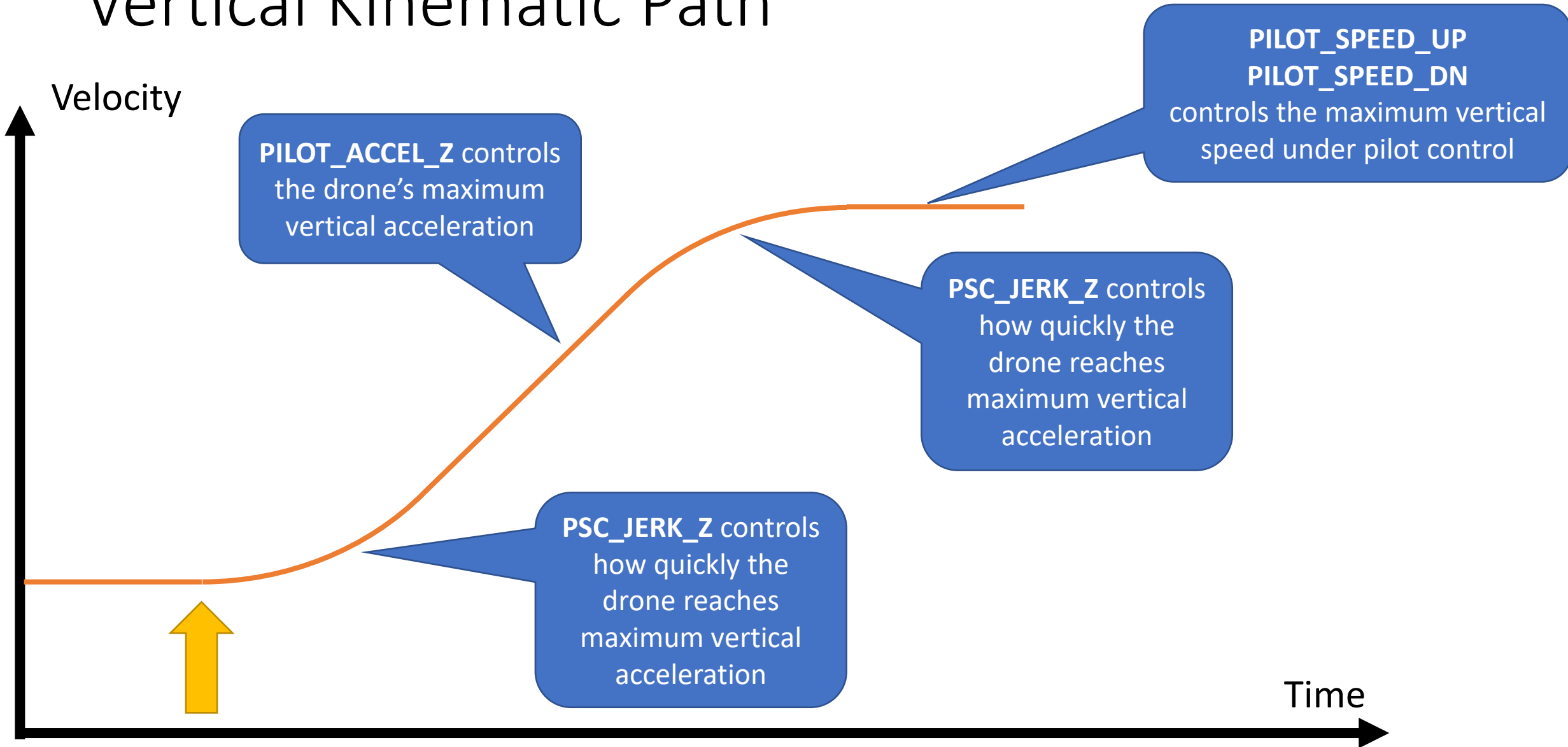


Vertical Position Controller

- Sitting above the vertical velocity controller is the vertical position controller
- This converts an error in the vertical position into a target vertical velocity
- This is a simple proportional (P) controller **PSC_PSCZ_P**
- However there are many parameters which limit the velocity and acceleration targets (kinematic path)

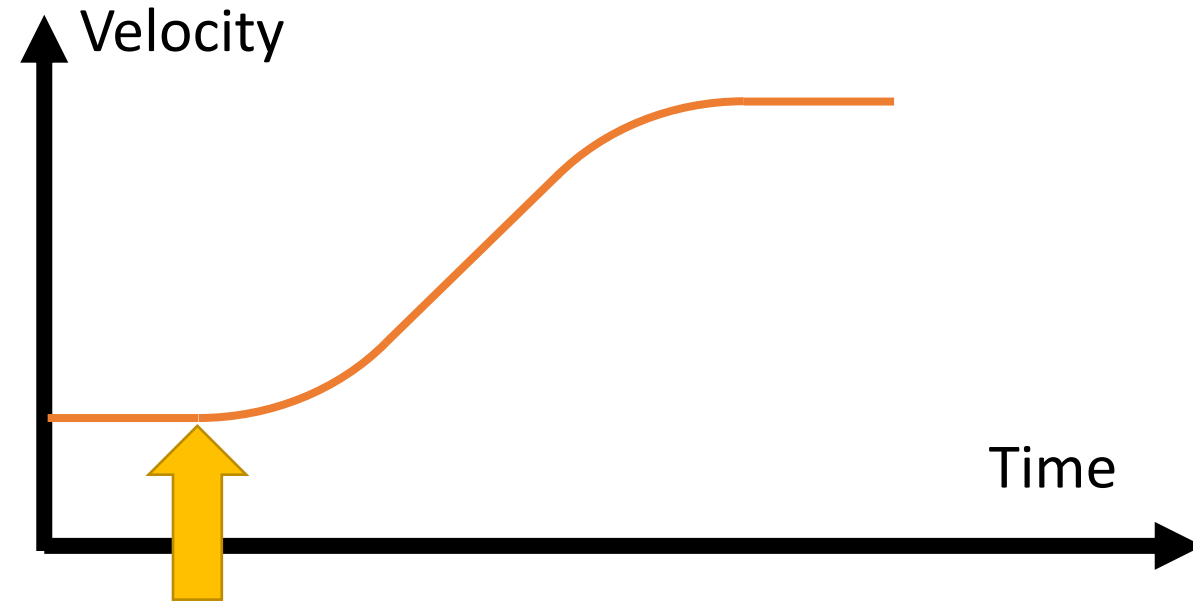


Vertical Kinematic Path



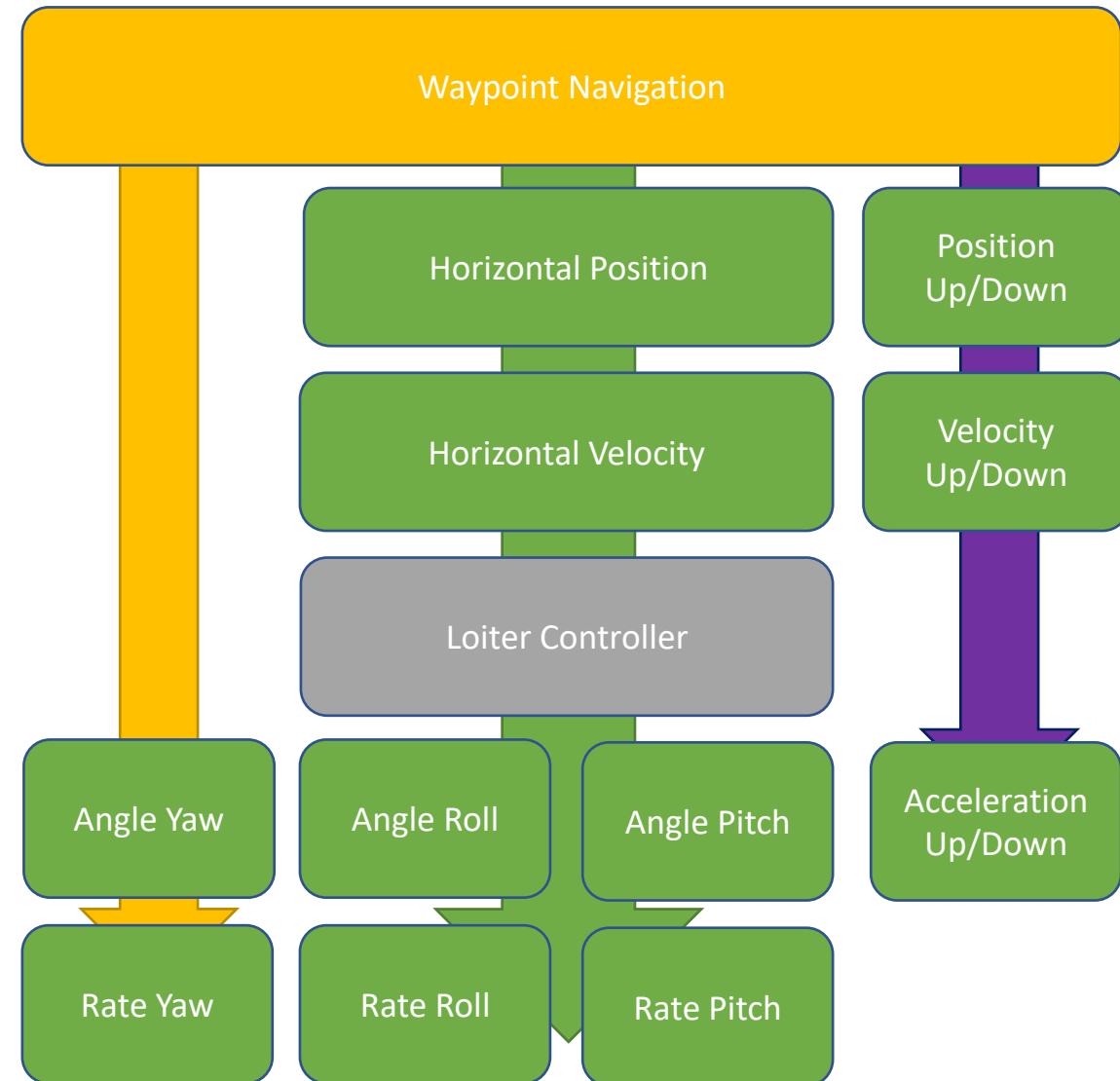
Tuning Vertical Kinematic Parameters

- **PILOT_SPEED_UP, PILOT_SPEED_DN**
typically the max speed when climbing is higher than when descending
- **PILOT_ACCEL_Z** controls the maximum vertical acceleration
- **PSC_JERK_Z** is more subtle, increase this to reduce the delay on vertical stick inputs and get to max vertical acceleration quicker
- Setting **PSC_JERK_Z** too high may make the drone feel too aggressive on sudden vertical moves



Waypoint Navigation Controller

- The waypoint navigation controller sits above all other and controls how the drone behaves when autonomously navigating



Waypoint Navigation Parameters

- The waypoint navigation parameters can be found in
- Mission Planner > Config > Full Parameter List

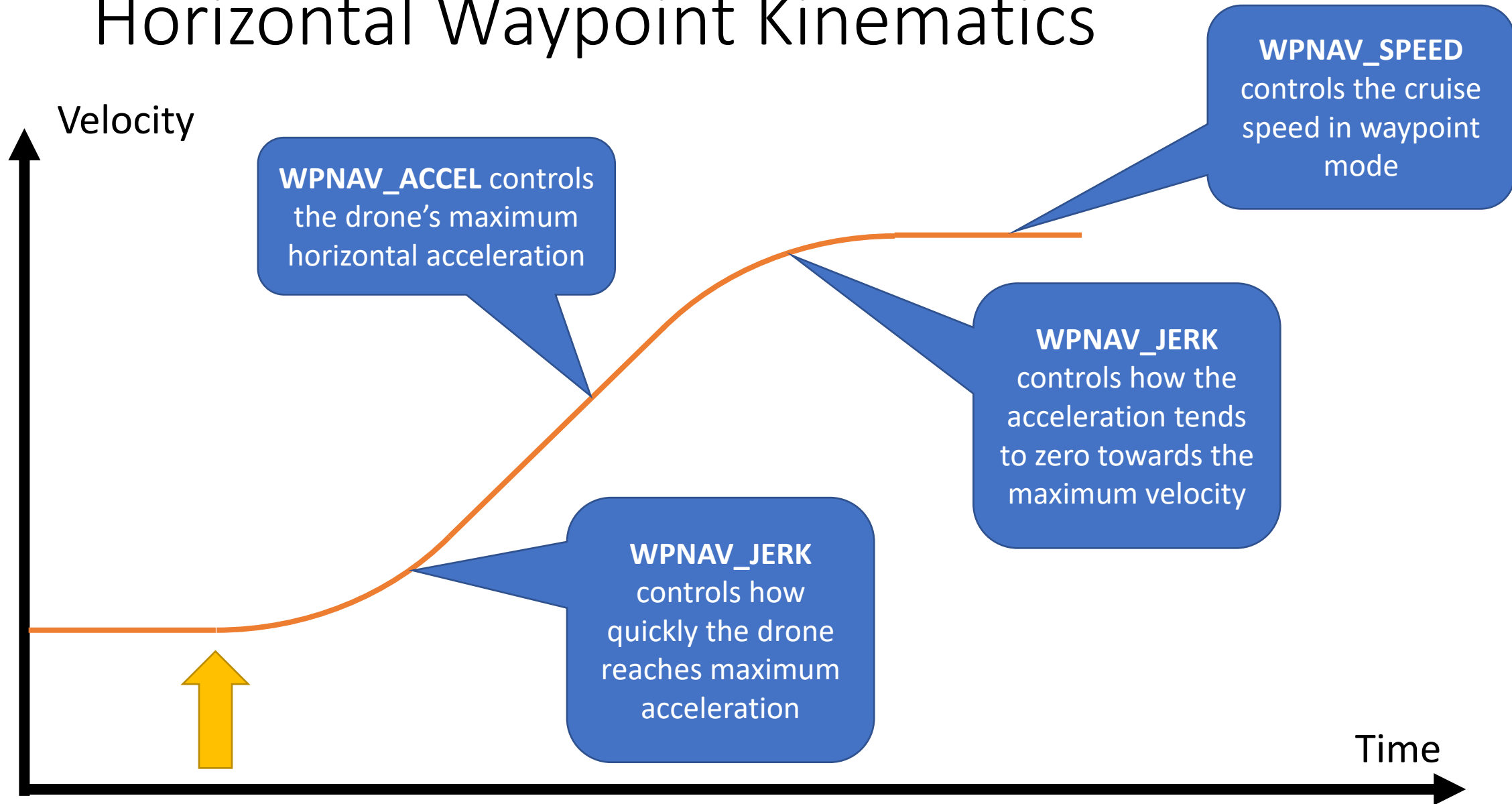
Mission Planner 1.3.82 build 1.3.9169.6147 ArduCopter V4.6.0-beta3 (110acc96)

ARDUPILOT COM21 115200

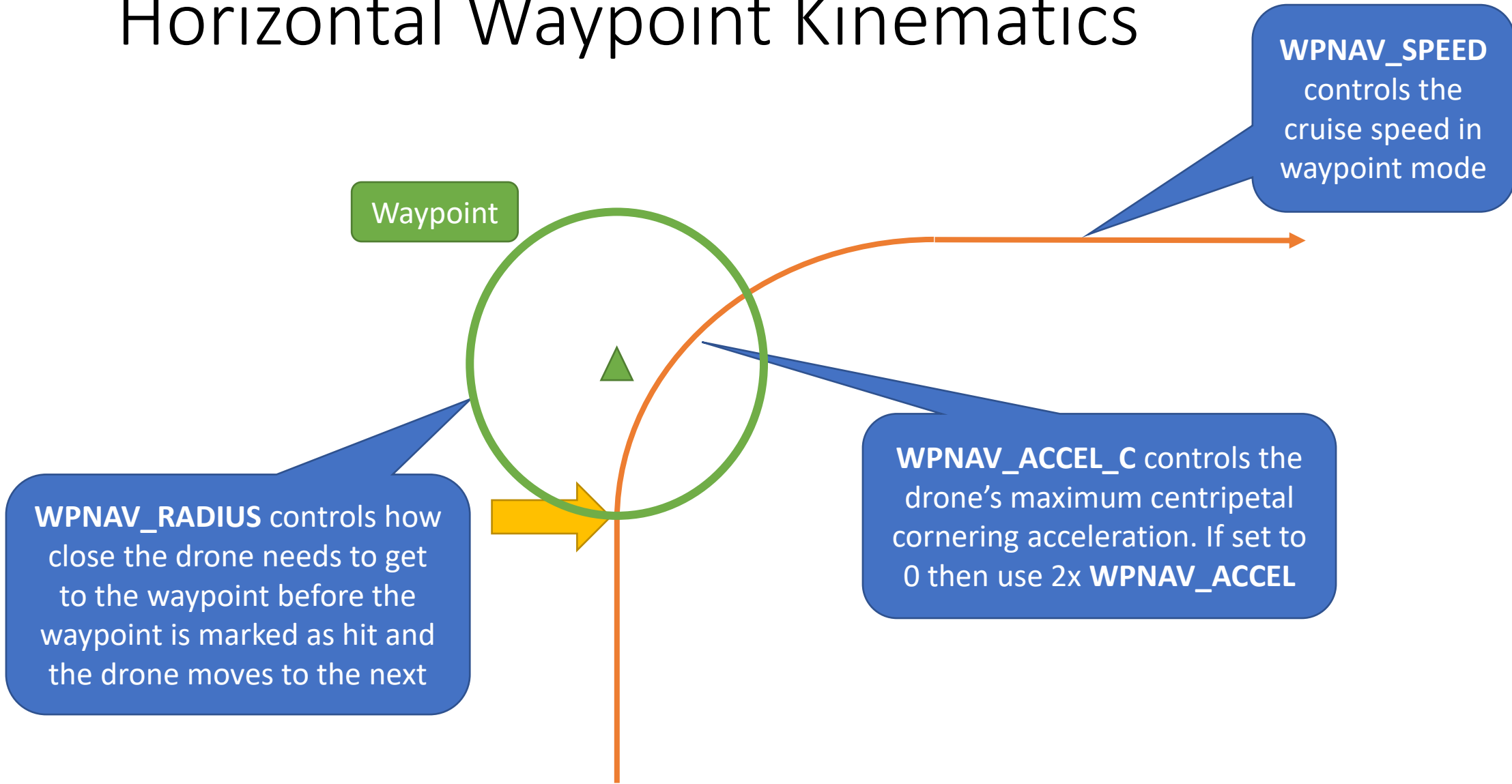
COM21-T-QUADROTO1 DISCONNECT

Name	Value	Default	Units	Options	Desc
LAND_SPEED_HIGH	0	0	cm/s	0 500	The descent speed for the first stage of landing in cm/s. If this is zero then WPNNAV_SPEED_DN is used
RTL_ALT_TYPE	0	0		0:Relative to Home 1:Terrain	RTL altitude type. Set to 1 for Terrain following during RTL and then set WPNNAV_RFND_USE=1 to use terrain following. WPNNAV_SPEED_DN is used instead.
RTL_SPEED	0	0	cm/s	0 2000	Defines the speed in cm/s which the aircraft will attempt to maintain horizontally while flying home. If this is zero then WPNNAV_SPEED will be used instead.
WPNNAV_ACCEL	250	250	cm/s/s	50 500	Defines the horizontal acceleration in cm/s/s used during missions
WPNNAV_ACCEL_C	0	0	cm/s/s	0 500	Defines the maximum cornering acceleration in cm/s/s used during missions. If zero uses 2x accel value.
WPNNAV_ACCEL_Z	100	100	cm/s/s	50 500	Defines the vertical acceleration in cm/s/s used during missions
WPNNAV_IERK	1	1	m/s/s/s	1 20	Defines the horizontal jerk in m/s/s used during missions
WPNNAV_RADIUS	200	200	cm	5 1000	Defines the distance from a waypoint, that when crossed indicates the wp has been hit
WPNNAV_RFND_USE	1	1		0:Disable 1:Enable	This controls if waypoint missions use rangefinder for terrain following
WPNNAV_SPEED	1000	1000	cm/s	10 2000	Defines the speed in cm/s which the aircraft will attempt to maintain horizontally during a WP mission
WPNNAV_SPEED_DN	150	150	cm/s	10 500	Defines the speed in cm/s which the aircraft will attempt to maintain while descending during a WP mission
WPNNAV_SPEED_UP	250	250	cm/s	10 1000	Defines the speed in cm/s which the aircraft will attempt to maintain while climbing during a WP mission
WPNNAV_TER_MARGIN	10	10	m	0.1 100	Waypoint Terrain following altitude margin. Vehicle will stop if distance from target altitude is larger than this margin (in meters)

Horizontal Waypoint Kinematics



Horizontal Waypoint Kinematics



Vertical Waypoint Kinematics

