Guppy LoRaWAN® - Configuration and Usage Guide

Written by Matthew Clark-Massera
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The Guppy LoRaWAN provides a number of configurable parameters, to allow its behavior to be tailored to specific applications. Factors affecting the configuration you might choose include:

- How many messages per day your network will allow
- How often you intend to change the batteries, and the type of batteries in use
- How detailed a bread-crumb trail you require, or the required time between updates

How The Guppy Connects (OTAA)

By default, the Guppy connects to a local LoRaWAN® network using Over The Air Activation. Each Guppy is provisioned with:

- A read-only **DevEUI -** a 16 digit code uniquely identifying the Guppy (printed on the label)
- A configurable **JoinEUI / AppEUI -** a 16 digit code identifying the server the device is registered with
- A configurable **NwkKey (1.1) / AppKey (1.0) -** a 32 digit code that authenticates the Guppy to the network server
- A configurable **AppKey (1.1) -** a 32 digit code that authenticates the Guppy to the application server
    - The default JoinEUI is 70-B3-D5-70-50-00-00-01
    - Each Guppy is provisioned with a random default NwkKey and AppKey (1.1)
- A configurable **Region** and optional **Channel Mask**
    - The channel mask is used in the US915 and AU915 regions, to set the network frequencies
    - Other regions don't need the channel mask, as all their networks use the same OTAA frequencies

Once the region has been configured, the Guppy will attempt to join local networks by transmitting join requests. Any network that hears the join requests and has knowledge of the Guppy's DevEUI, JoinEUI and keys, will allow the Guppy to join the network and transmit data.

The Guppy rejoins the network once a week by default. This renegotiates encryption keys for enhanced security, and ensures continued operation in the event of a network losing the keys (for instance, if the device is mistakenly deleted).

How The Guppy Connects (ABP)

Guppy can also be configured to connect using Activation By Personalization. When using ABP, each Guppy must be configured with some additional numbers:

- A configurable **DevAddr** - an 8 digit code identifying the Guppy to the network
- 32 digit session keys **FNwkSIntKey** (also known as NwkSKey)and **AppSKey**,on LoRaWAN 1.0
- 32 digit session keys **FNwkSIntKey**, **SNwkSIntKey**, **NwkSEncKey**, and **AppSKey**, on LoRaWAN 1.1

ABP allows a LoRaWAN device to connect without exchanging the usual join request and join response, which can save on downlink bandwidth, and allow the device to work when downlink reception is difficult. However, in LoRaWAN 1.0, the ABP mechanism is somewhat problematic. It either suffers from a lack of security (if you configure your device to reset it's uplink frame counts when it resets), or difficulty with configuration (if you don't reset the frame counts, and are in a region requiring dynamic channel configuration). These issues are fixed in the LoRaWAN 1.1 specification, but since the fix negates the chief advantage of ABP by requiring some downlink traffic, we recommend OTAA.

How The Guppy Locates

The Guppy uses an accelerometer to detect movement, allowing it to decide when an asset is in-trip, and when it is stationary. This allows it to schedule the transmissions as infrequently as possible, to maximize battery life. You can configure the Guppy to transmit a status update:

- Periodically (ie. 24-hour heartbeat)
- At configured times of the day
- At the start of a trip
- During the trip
- At the end of the trip
- During after-hours trips
- When the 'Man Down' status changes
- When a Tilt trigger goes off

For longest battery life, the Guppy can be configured to ignore movement and simply transmit a status uplink once per day. If you need lower latency updates, the next step is to enable transmissions at the end of trips. Finally, full tracking is obtained by enabling the in-trip transmissions.

How The Guppy Uses LoRaWAN Airtime

LoRaWAN devices can transmit at various data rates, usually denoted DR0, DR1, DR2, and so forth. The lowest data rate (DR0) takes the longest to transmit, but has the longest range. As the data rate goes up, the range goes down a bit, and the transmission time goes down a lot. Guppies can be configured to use a particular data rate, or a range of data rates (ie. DR2-DR4). Lower data rates will have the longest range, but also use the most battery power and airtime. When configured to use a range of data rates, the Guppy spends an equal amount of airtime using each data rate. The Guppy also has optional Adaptive Data Rate support, which allows the network server to intelligently control the data rate.

There are several factors limiting the maximum transmission rate of a Guppy:

- Radio regulations may limit the transmission time
  - In Europe the law limits you to 36 seconds of transmit time per hour on most frequencies
  - Whereas in Australia there is no legal limit
- Networks may limit the transmission time, to prevent congestion
  - The Things Network for instance limits you to 30 seconds of transmit time **per day**
  - At DR0, this gives you 25 messages with 100% range
  - At DR1, this gives you 45 messages with 75% range

- At DR2, this gives you 90 messages with 50% range
- At DR3, this gives you 181 messages with 37% range
- At DR4, this gives you 323 messages with 28% range
- At DR5, this gives you 647 messages with 21% range
- In America, data rates are all two increments higher, so DR0 corresponds to DR2 in the above list
- Networks may limit the number of messages, for billing purposes
  - Your network might require you to pay more for higher throughput
- Battery life may prove to be a limiting factor
  - A Guppy can only send around 25 thousand messages at DR0 on one set of lithium batteries
  - So for a lifetime of 3 years, the messages per day approximately match the list above

The radio regulations are automatically enforced by inserting delays between messages where required. It is up to the user to configure their Guppy with a low enough transmission rate to meet network and battery life requirements.

How The Guppy is Configured

The Guppy is configurable over-the-air using downlinks. Websites integrating the Guppy can find the complete protocol specification here. Initial configuration of the region and JoinEUI, as well as firmware updates, are performed with a plug-in USB adapter, and a Windows configuration app. An adapter can be obtained from your Guppy distributor. The adapter plugs into the four pin connector below the battery compartment.

To read the available parameters, select your adapter from the drop-down list in the top right, and click *Start*. The configuration tool will read continuously, and display the existing parameters in the center column. To program new parameters and firmware, enter the desired parameters in the right hand column, and check the *Program Parameters* checkbox. To update the firmwares only, check the *Program Firmware* checkbox, and leave the *Program Parameters* checkbox clear.

If you click the *DevEUI List* button, a list of scanned DevEUIs will pop up. You can hot-plug the adapter into many Guppies in sequence to populate the list. Each time a Guppy is programmed the parameter list will flash, the DevEUI list will update, and a chime will sound. The list is in CSV format, so it can be imported into a spreadsheet easily.

The top line in the display shows the DevEUI and version string. In the screenshot above, the DevEUI is 70B3D57050000A09, and the firmware version is 61.2.2.0 (product, hardware revision, major, minor). The configured encryption keys and EUIs can be found in the DevEUI list on the right. Hovering the cursor over a line reveals an action menu ('...') and a help pop-up ('?'), from which you can copy, reset, and inspect parameters and sections. Save and load functions are available in both the File menu and the All Parameters action menu.

Configuration Options

There are many settings, but only a handful require customization. These are highlighted below.

General

Heartbeat Tx (0-7620 mins):

The maximum time between status updates. Setting to 1.00:00 results in at least one status update per day. If movement causes additional updates, the next heartbeat update is scheduled for 24 hours after the last movement update. The default is 24 hours.

In Trip Tx (0-7620 s):

The time between status updates when in-trip. Set to zero to disable these updates entirely. Note that in Europe, radio regulations will prevent the effective time between transmissions from dropping lower than about 140 seconds when using the lowest data rate. The default is 10 minutes, to improve the response time when testing, but a more conservative value on the order of an hour makes more sense in terms of battery life.

+ After Hours:

The time between status updates when in-trip, and after-hours. This allows you to specify different detail levels outside of normal working hours. You can use it to save battery by not tracking non-business trips, or to provide detailed tracking in the event of theft. Set to zero to disable in-trip transmissions when after-hours. The default is 10 minutes.

Trip End Timeout (0-2550 s):

The time required before a trip ends, if no movement is detected. Set to zero to **disable trip tracking entirely**, which saves a small amount of power by disabling the accelerometer. You will still get heartbeat transmissions with the trip tracking disabled. The default is 5 minutes.

Tx On Start:

When set, a status update is scheduled at the start of a trip. The default is true.

+ After Hours:

When set, a status update is scheduled at the start of a trip when the trip is after-hours. You can use this to implement theft alerting. The default is true.

Tx On End:

When set, a status update is scheduled at the end of a trip. This lets you know where the asset is, with one caveat - if the destination is underground parking, it may have no coverage. The default is true.

+ After Hours:

When set, a status update is scheduled at the end of a trip when the trip is after-hours. The default is true.

Disable Statistics:

By default the Guppy will send a statistics message every 3 days. The statistics help keep track of battery usage, and diagnose vibration issues. However, you may wish to disable the statistics to minimize transmissions.

Basic LoRaWAN

Region:

This selects the radio frequencies to use according to your country. Please be sure to select the correct region, to maintain compliance with your country's radio regulations. Guppies leaving the factory are currently pre-configured for either the European 868 MHz band, US915 or AS923 1.0.3, depending on their hardware type. However, this is subject to change, and in the future the region may be left unset. If the region is unset, the Guppy will not transmit until configured. Otherwise, to prevent the Guppy from transmitting before configuration, click the Start button on the tool, and plug the cable into the Guppy, before inserting the batteries. The region cannot be reconfigured over the air.
Next to the region you will see the associated LoRaWAN Regional Parameters revision. Currently only AS923 and AU915 have multiple revisions to choose from:

- In AS923, the 1.0.3 version uses both SF10 and SF9 for join requests, rather than just SF10 in the 1.0.2 version
- In AU915, the 1.0.3 version supports the new 'uplink dwell time' restriction, so it joins at SF10 instead of SF12

Sub-Band / Channel Mask:

In fixed channel regions (US915 and AU915) you can select a sub-band or channel mask, instead of using all 72 channels at startup. Strict compliance with the LoRaWAN standard requires enabling all channels, but if you are confident that your network will not change its operating frequencies, choosing a sub-band speeds up the join process. If you choose a custom channel mask, the hex string you must provide has the lower numbered channels on the right hand side. For instance, 010F in hex is 100001111 in binary, and selects channels 0-3 and 8. On some older network servers, choosing a sub-band might be mandatory to avoid packet loss. The default is 'All'.

Activation:

This chooses between the default (and recommended) Over The Air Activation, and Activation By Personalization. In OTAA, the Guppy and the network server generate the session encryption keys and device address during a join request / join response exchange. In ABP, you have to generate the encryption keys and device address beforehand, and configure them. When choosing ABP, you also have to choose your LoRaWAN version.

Reset FCnts:

This option is available in ABP 1.0 only, and resets the uplink and downlink frame counts whenever the device is reset. This defeats the encryption entirely, but is required by many networks in LoRaWAN 1.0, so that the network server can detect the device reset and reconfigure the device's channels. It is vital that you pick the setting appropriate to your network, or your device may stop connecting after a reset. If you're not sure, you should probably choose 'Yes'. The default however is 'No', for strict compliance and security.

JoinEUI / AppEUI:

In OTAA, this identifies the server your device is registered with. If you don't set a custom JoinEUI, the default for the Guppy LoRaWAN (70-B3-D5-70-50-00-00-01) will be used. In LoRaWAN 1.1, changing the JoinEUI resets the cryptographic counters used by the join server (RJCnt1, DevNonce and JoinNonce). So if you reset the counters on your join server without changing the JoinEUI there, you can reset them on the device by choosing a temporary JoinEUI, writing it to the device, and then configuring it back again.

NwkKey (1.1) / AppKey (1.0):

In OTAA, this 32 character key authenticates the Guppy with the network server. If you don't set a custom key, the Guppy will use a unique random key, which was written to it in the factory. This default key can be read from the DevEUI list dialog, or the label on the box. It is not printed on the Guppy's label. This key cannot be reconfigured over the air. Please note that this key was renamed by the LoRaWAN standard in the 1.0 to 1.1 upgrade, in the most confusing way possible. So the label on your Guppy will either read AppKey (with no version number), or NwkKey.

AppKey (1.1):

In OTAA, this 32 character key authenticates the Guppy with the LoRaWAN 1.1 application server. This key isn't needed in LoRaWAN 1.0. If you don't set a custom key, the Guppy will use a unique random key, which was written to it in the factory. This default key can be read from the DevEUI list dialog. If your Guppy is new enough, it will be written on the label on the box. On older devices, only the AppKey (1.0) is on the label.

Device Address:

This 8 character number identifies the Guppy with the network server. It is only applicable to ABP activation.

FNwkSIntKey / SNwkSIntKey / NwkSEncKey / AppSKey:

These are the 32 character ABP session keys. Only the first and last are required in LoRaWAN 1.0. They may be referred to as the Network Session Key (NwkSKey) and Application Session Key (AppSKey) on your network server.

Advanced LoRaWAN

Adaptive Data Rate:

ADR is a server side mechanism for controlling the data rate, to optimize network capacity and battery life. By default, the Guppy only requests ADR when out-of-trip. When in-trip, it controls its data rate according to the configured range. Once the trip ends, it switches to its lowest configured data rate and maximum power, and begins requesting ADR from the server. Thereafter, the network server will configure it to a lower power mode if appropriate. You may wish to instead force ADR on at all times, in

order to control it using a policy on the network server. It is also possible to force it off at all times, but this can lead to issues on older network servers.

Min / Max Data Rate:

These parameters select the minimum and maximum data rates to transmit at, when ADR is not active. A '0' selects DR0, the lowest data rate with the longest range. If you set both parameters to the same value, the Guppy will always use that rate. If you choose a range, the Guppy will alternate between the allowed data rates in such a way as to spread the transmit time evenly. This means it will use the higher data rates more often. Using a range of data rates allows the network to support more devices per gateway, but reduces your guaranteed range to the range of the highest data rate. Using higher data rates may allow you to send more messages per day. Please see the section *'How The Guppy Uses LoRaWAN Airtime'* above. The default is DR0-DR2.

Roaming Rejoin Uplink Period / Time Period:

This sets the initial maximum number of uplinks / minutes between Rejoin0 Requests in LoRaWAN 1.1. These requests facilitate roaming, and can be reconfigured by the network server at runtime. The default values are the maximums, effectively disabling these requests until the server asks for them.

Rejoin / Reset Time Period:

By default, the Guppy rejoins the network once a week, in case the network server has somehow forgotten the session keys. This period can be extended to up to 255 days, or disabled entirely (0). However, if a device is accidentally deleted on the network server, or the network server suffers a database failure and loses the session keys, the server will be unable to decrypt any device data until it has rejoined. Rejoining weekly generates several extra transmissions, but lowers the time spent out of service in the event of an accident. The exact rejoin behavior depends on the Activation and LoRaWAN version:

- In ABP, the rejoin is equivalent to removing and reinserting the batteries. All protocol state is reset, with the exception of the uplink and downlink counters (unless you have chosen to reset them as well, in LoRaWAN 1.0)
- In OTAA 1.0, the rejoin is also equivalent to removing and reinserting the batteries. A regular Join Request will be sent.
- In OTAA 1.1, a Rejoin1 Request is used to rejoin without resetting any protocol state. Please note that older network servers might not support this mechanism.

ADR Ack Limit / Delay:

This parameter control the number of uplinks between checks that the server can still hear the device when ADR is active. The device starts asking for a response once the *Limit* is reached, and if no response if heard after *Delay* attempts, the device switches to a lower data rate. The default values (64 and 32) are very slow. Please consult your network support before choosing more aggressive settings, as they may have policies forbidding lower values. In LoRaWAN 1.1, these values can also be set dynamically by the network server.

Receive / Join Delay:

These setting control the timing between a request and a response on the network. You shouldn't change them from the defaults unless instructed to by your network. The defaults are 1 and 5 seconds respectively.

Repetitions:

This sets the default number of frame repetitions (called *NbTrans* in the standard). Usually this value is one, until the server requests a higher number. You shouldn't

change this value unless you have special requirements (for instance, a transmit-only ABP configuration).

Tx EIRP Limit:

This setting restricts the transmit power to the given value, in dBm EIRP. This allows you to save a small amount of battery on the transmission, and limit the peak current draw from the batteries. Limiting the current may be useful in extreme cold weather (less than -20°), where lithium batteries begin to struggle. Your network server may require knowledge of the maximum power to correctly operate its ADR algorithm. In this case, be sure to configure the device accordingly on the server. The default is maximum power.

Random Tx Delay:

This parameter allows you to insert a random delay before transmission. This may be useful in applications involving a large number of assets on the same vehicle. The random delay spreads the transmissions out, so they don't interfere with each other.

- The amount of delay required depends on the data rates in use. For a single spreading factor, you need approximately (Number of units) / 1500 * 1.9^SF). For instance, for 100 units at SF10, you'd need 100 / 1500 * 1.9^10) = 613 / 15 = 41 seconds.
- For multiple spreading factors, the formula is (1/DelayA + 1/DelayB + 1/DelayC + ...)^-1, where DelayX is the delay required for one of the spreading factors. So for 100 units at both SF10 (41 seconds) and SF9 (22 seconds), you'd need (1/41 + 1/22)^-1 = 14 seconds.

The default is 8 seconds, appropriate for ~35 units using a mixture of SF10/11/12.

Accelerometer

Wakeup Threshold (0.063-0.5 G):

This sets the amount of force, in increments of 63 mG, that will wake the accelerometer up. Setting it too high might result in trips being missed. Increase this value if you have a problem with small vibrations setting off spurious trips. The default is 0.125 G.

Wakeup Duration (0-960 ms):

This is the required time duration, in increments of 80 ms, of the force that will wake the accelerometer up. Increasing this value will make the accelerometer less sensitive to short, sharp forces, but increases the chances of a trip start being missed. The default is 80 ms.

Disable Wake Filter:

Set to disable the trip-start filtering, that is usually applied in addition to the Wakeup Threshold and Wakeup Count. The wake filter rejects small disturbances, requiring sustained jostling before a trip starts. This is good for battery life, but if you require higher sensitivity, or the filtering is causing too much latency for your application, you can disable it. The filter only starts a trip when it has seen 1 seconds worth of above-threshold movement in a 4 second period, or repeated short movements over several 4 second periods. This setting disables the filter during work hours only. The default is false (not disabled).

+ After Hours:

Set to disable the trip-start filtering after-hours. This can be useful for theft alerting, as it allows you to detect even minor bumps after-hours, without producing many false positives during normal work hours. The default is false (not disabled).

Tilt

Enabled:

This enables reporting of the Guppy's current tilt angles, and arms any tilt triggers configured below. Enabling tilt support has battery implications for two reasons:

- When either tilt or Man Down are enabled, the Guppy must send additional bytes in its status uplink, which uses up to 15% more battery in certain configurations. Whether it uses more power or not depends on the exact Spreading Factor in use.
- The Guppy also spends a minuscule amount of energy sampling the tilt angles, and monitoring for any enabled triggers. Under normal circumstances this doesn't amount to much, but if the Guppy is constantly moving it can add up to 60% of the battery per year. So if constant movement forces you to completely disable the trip tracking to save power, you should also be sure not to configure any tilt triggers (but you may leave tilt reporting enabled).

Tilt is disabled by default.

Retry Trigger Tx:

When a tilt trigger is set off, it triggers a single unconfirmed uplink, if the network is ready (join has been successful). Enabling retries will retry the uplink (with backoff) until the network connection is ready, then transmit once. The default is 'No'.

Trigger Axis / Angle / Type / Min / Max / Hysteresis:

The Guppy allows you to configure up to 3 tilt triggers, which will fire off a transmission whenever the tilt angle passes a threshold. The tilt angle specified in the trigger is the angle of the direction of 'down', relative to the Guppy. There are several different references to choose from, and two types of trigger - a range trigger, and a delta trigger.

- **Axis** chooses one of the device axes to measure against. When the Guppy reports its current tilt, it reports it relative to the Y axis, so this is the natural choice when your mounting options are flexible.
- **Angle** chooses whether to measure the angle between the chosen axis and 'down' (called the *inclination*), or the angle *around* the chosen axis, according to the right-hand grip rule (the *azimuth*). Inclination angles range from 0 to 180 degrees, while azimuthal angles range from 0 to 358.5 degrees, wrapping at 360.
- **Type** chooses between a range trigger, and a delta trigger. A Delta trigger goes off if the angle changes by more than the Min angle, since it was last reported. A range trigger goes off if the angle leaves the range defined by Min, Max, and Hysteresis. The Hysteresis is added to or subtracted from the range boundaries, to prevent chattering of the trigger when the angle is close to the threshold.

For diagrams of the trigger angles, see below. The default configuration for all triggers is disabled.

Timezone

Timezone:

This is the timezone used for after-hours calculations. The default is UTC.

DST Shift:

This is the amount of time that the clock shifts during daylight savings time, if applicable. It applies only to the after-hours and scheduled uploads calculations, and will usually be one hour, or zero to disable daylight savings. The default is disabled.

+ Start / End Nth / Day / Month / Time:

These parameters allow you to specify the start and end times of daylight savings, if DST Shift is nonzero. They only apply to the after-hours calculations.

Most countries use a relative specification such as *'The 1st Sunday of April, at 02:00 local time'*, or *'The Friday before the last Sunday of October, at 2:00 local time'*.

For the first example you would choose '1st', 'Sunday', 'April', '2:00'. For the second, you'd choose 'Last', 'Sunday', 'October', '-2d 02:00'.

You can also choose a fixed date and time using for instance 'Absolute Day', 'Day 28', 'April', '02:00'.

The time is always in the current local time zone, including any daylight savings adjustment.

After Hours

Mon / Tue / ... After Hour Start / End:

These parameters allow you to specify which times are *after-hours*, for the purpose of applying different trip tracking parameters at those times.

Set both the start and end parameters to 00:00 to disable (default).

Set the start to 00:00, and the end to 24:00, to make the entire day after-hours.

Setting a start time to before the end time makes the intervening times after-hours.

Setting the start time to after the end time makes the times between 00:00 and the end time, and between the start time and 24:00, after-hours.

Scheduled Uploads

Scheduled Uploads 1-12:

A heartbeat can be configured, with up to 12 slots, to log a heartbeat at a specific time of the day. This time is set in local time (using the configured timezone and DST) with 7.5 minute intervals. The upload will occur within a variance period of 10 minutes. By default the slots are disabled (00:00:00).

Man Down

Man Down Timeout:

The Man Down indicator is a bit in the Guppy's extended uplink which shows if the device has stopped moving for a configurable time. This can be used to detect if an asset has been idle for a few weeks, a car has been stopped for a few hours, or if livestock have died. The timeout can be set from 10 minutes to 21h10m, in 10 minute increments, or from 1 day to 63 days 12 hours, in 12 hour increments. A value of 0 disables Man Down indication. Note that since the Man Down indicator bit is not present in the standard uplink (port 1), enabling Man Down causes the extended uplink (port 4) to be sent instead. The default is disabled.

+ Fix On Set:

This chooses what action to take when the Man Down indicator bit becomes set. You can choose one of:

- Do nothing - the bit will upload when the next heartbeat is sent (default)
- Transmit once, assuming the network connection is ready (join has been successful)
- Keep retrying (with backoff) until the network connection is ready, then transmit once

The current firmware only supports unconfirmed uplinks, even when retrying.

+ Fix On Clear:

This chooses what action to take when the Man Down indicator bit becomes clear, and is configured as above.

Custom Channels 1-8

Channel Number:

In variable channel regions (everything except AU915 and US915), it is possible to pre-configure some of the channels. Usually, the device joins on one of the two or three fixed join channels specified by the LoRaWAN Regional Parameters. Thereafter, the server configures the additional channels in the join response (with the 'CFList'), or using individual NewChannelReq messages. However, you may wish to pre-configure the additional channels manually, so that the server doesn't have to. In this case the additional channels are filled in this section, with channel numbers that follow on after the default join channels. For instance, if your region specifies two default join channels (channel 0 and channel 1), you will number your first custom channel '2'. The default value is zero, which disables the channel until the server configures it.
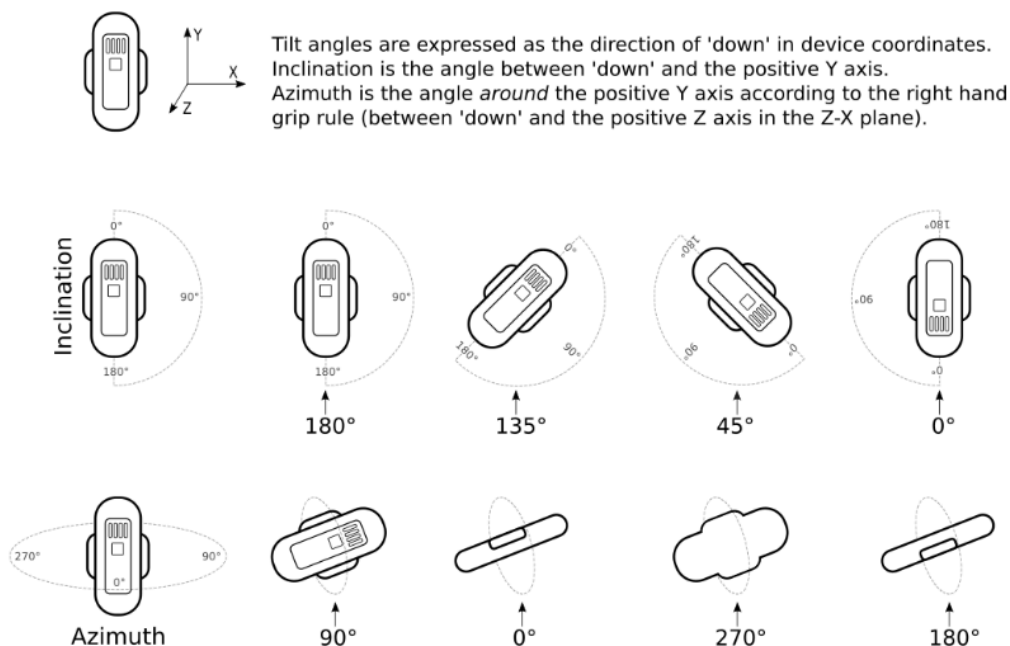
Min / Max Data Rate:

These set the range of data rates supported by the channel. Usually the minimum is zero, and the maximum is between 4 and 7.

Tx / Rx Frequency:

These set the channel center frequencies for uplinks and downlinks respectively. Some networks use two separate frequencies, but most will use the same frequency for both.

How The Guppy Expresses Angles

The Guppy's uplink and triggers express angles in terms of the direction of 'down', in the Guppy's [spherical coordinate system](). The diagram below shows how the inclination and azimuth in the Guppy's status uplink (uplink 1) are calculated. In the diagram, the Guppy is standing upright, with the battery compartment and screws facing away from the viewer. As it is rotated, you can read the angles off from the arrow.

Tilt angles are expressed as the direction of 'down' in device coordinates.
Inclination is the angle between 'down' and the positive Y axis.
Azimuth is the angle *around* the positive Y axis according to the right hand grip rule (between 'down' and the positive Z axis in the Z-X plane).

While the status uplink expresses the azimuth and inclination relative to the Y axis, the triggers may be defined relative to any axis. The diagram below shows how to take the measurements relative to the X axis instead of the Y axis:
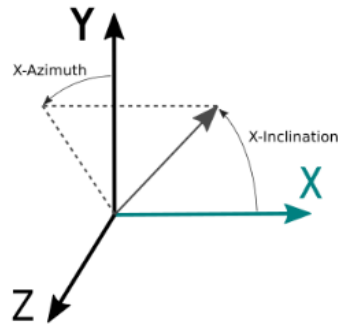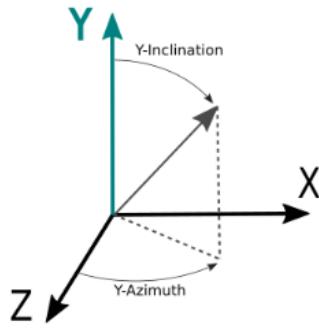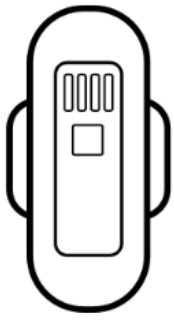
Similarly, the azimuth relative to the Z axis would be measured counter-clockwise from the X axis, in the XY plane. If you stick out the thumb of your right hand in the direction of your chosen axis, your fingers will curl in the direction of the corresponding azimuth.

For some worked examples, see our large and small angle example pages.

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