Application Note: AN1200.80

LoRa® Modem Doppler Immunity

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1 The Doppler Effect

The motion of one radio relative to another will cause a shift in the received frequency due to the Doppler effect. Less apparent than the Doppler shift is another phenomenon, the rate-of-change of the frequency shift: the Doppler *rate*. If the Doppler shift or the Doppler rate exceed the capacity of the receiver to adapt to frequency change, then the communication link will fail. In this Application Note we examine the frequency tracking limits applicable to LoRa radios and how to design a link for robustness to the Doppler effect.

1.1 Doppler Shift

The textbook example of Doppler shift is the sound of a siren passing a stationary observer. The audio wave front is compressed in the direction of travel, creating a high frequency as it travels towards the observer. As the siren passes and recedes into the distance, the wave front expands, lowering the siren's frequency.

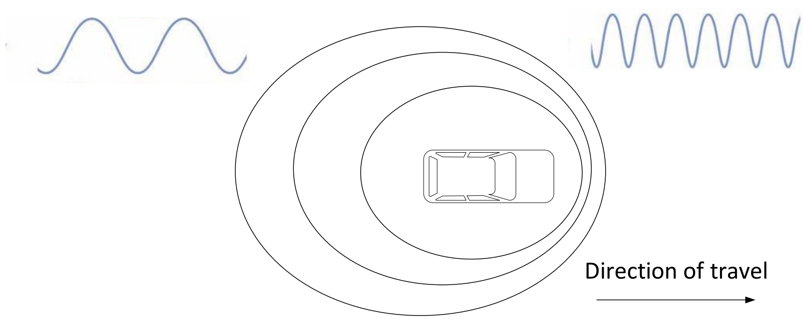

Figure 1. The Doppler Effect

The same phenomenon exists for radio waves, with the Doppler shift, f_D, given by the following equation:

$$f_D = \frac{v}{\lambda} \tag{1}$$

where v is the relative speed between transmitter and receiver and lambda is the wavelength of the propagating wave.

1.2 Doppler Rate

Even if the Doppler shift does not exceed a receiver's limits, it is still possible that the rate-of-change of the frequency could pose a problem for the receiver's frequency tracking loop. The rate of frequency change, or Doppler *rate*, is simply the rate-of-change of the Doppler frequency shift over time and is defined as:

$$\frac{df_D}{dt} \tag{2}$$

Returning to our initial example, if the vehicle was travelling at 50 kmph (30 m/s) and is equipped with a 2.4 GHz transmitter, then the stationary receiver at the roadside would have seen the frequency shift shown by the blue curve in Figure 2:

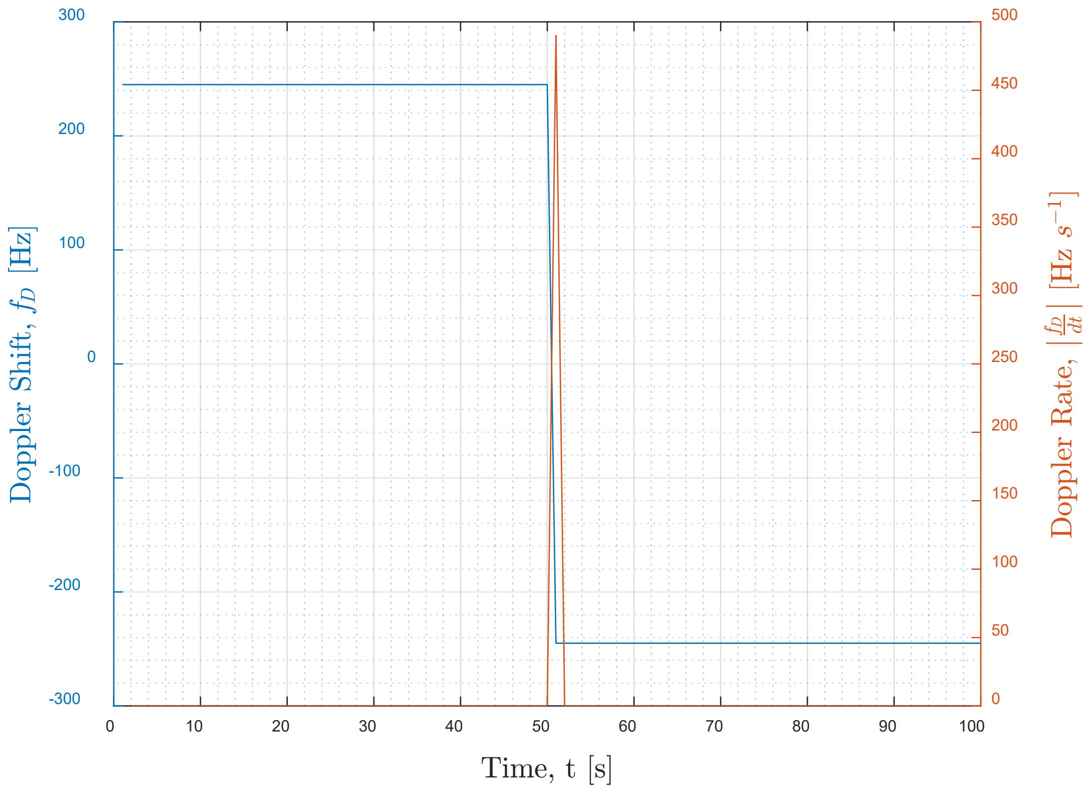

Figure 2. Doppler shift (blue) and Doppler Rate (orange) for a Vehicle Passing a Static Receiver

Prior to passing the observer halfway (at 50 s) the frequency is increased by almost 250 Hz as the vehicle approaches. Upon passing the observer, the frequency drops to approximately -250 Hz. The absolute rate of frequency change is also shown (orange curve). The passage of the vehicle causes a rate-of-change of the frequency peaks of approximately 500 Hz/s as the Doppler shift frequency offset swings between the two extremes.

2 LoRa Doppler Immunity

With an understanding of the two Doppler phenomenon which could compromise radio reception, we define a two-step process to establish the Doppler immunity of a LoRa receiver:

Step 1) To examine the influence of motion on the maximum possible Doppler *shift* including all sources of frequency error.

Step 2) To determine the receiver's ability to track instantaneous Doppler *rate* effects.

In the second step, because the Doppler rate immunity depends upon the receiver hardware implementation, the calculation of the immunity depends upon which generation of LoRa product is being used. For this reason, the guidance on Doppler rate performance is grouped by product family.

2.1 Step 1: Immunity to Doppler Shift

Irrespective of which generation of LoRa modem is used, the maximum frequency error cannot exceed a quarter of the configured LoRa bandwidth. Suppose that we operate at 868 MHz and 125 kHz of LoRa bandwidth. From equation 1, we can see that the product $f_D\,\lambda$ gives the speed at which the radio link will be unable to accommodate the attendant total frequency drift. Note that our calculation must also encompass all sources of frequency error.

For example:

5 ppm crystal error gateway (receiver)	4.34 kHz
25 ppm crystal frequency error (transmitter)	21.7 kHz
Sum of all system drift / error	26.0 kHz
Max drift (¼ of 125 kHz LoRa bandwidth)	31.3 kHz
Remaining frequency drift budget	5.21 kHz

$f_D\,\lambda$ = (3e8/868e6) * 5.21 kHz = 1.8007 kms^{-1} or Mach 5.3! So, we can see that the static component of the frequency error is rarely an issue in terrestrial LoRa links. However, it should be calculated as a precaution - especially for lower LoRa bandwidths or very high, relative-speed links such as satellite LoRa links.

However, the greatest potential source of communication issues caused by Doppler frequency error is the *rate* of frequency change. This immunity depends on the receiver implementation, so guidance is given for the two main groups of LoRa receiver.

2.2 Step 2: Immunity to Doppler Rate for SX12xx and SX1301 Receivers (and earlier)

The first generations of LoRa receiver can receive with a maximum frequency drift of:

$$\Delta f_{packet} = \frac{BW}{3 \times 2^{SF}} \tag{3}$$

Where Δf_{packet} is the maximum frequency drift seen over the duration of the received *packet*.

2.3 Step 2: Immunity to Doppler Rate for LR11xx and SX1302 Receivers (and later)

The latest generation of LoRa receivers feature an improved immunity to Doppler rate transitions with the maximum permissible drift of:

$$\Delta f_{symbol} = \frac{0.1\ BW}{2^{SF}} \tag{4}$$

Where Δf_{symbol} is the maximum drift seen over the duration of a single LoRa *symbol*, this is a much shorter duration than the entire LoRa packet of previous generations of product.

3 Worked Examples

To illustrate the difference in performance between the generations of product, to provide examples of the process of calculating the immunity and to demonstrate the immunity of the LoRa modem, we present three worked theoretical examples for the following applications:

1) High speed railway telemetry at 868 MHz
2) Tire pressure monitoring at 2.4 GHz
3) Satellite communication with uplink at 868 MHz and downlink at 400 MHz

In each case, we will examine how the Doppler effect might influence part selection and modem parameter choices.

3.1 High Speed Railway Telemetry Application

Operating at 868 MHz and using 125 kHz bandwidth LoRa, a high-speed railway needs to collect 35 bytes of data at track-side collection points that cover the extent of the rail network. The trains can travel at a maximum speed of 60 ms^{-1} (216 kmph). The collection points can be located as close as 10 m to the trackside.

For Doppler considerations, the worst-case scenario is depicted in Figure 3, where the train passes the gateway radio mast at the trackside at full speed. Also shown is a scale graduated to distance scales that we will cover in more detail when thinking about Doppler *rate*. The graduations depict the Influence of Symbol Time on Distance Travelled, so the Doppler Rate incurred per Symbol Period.

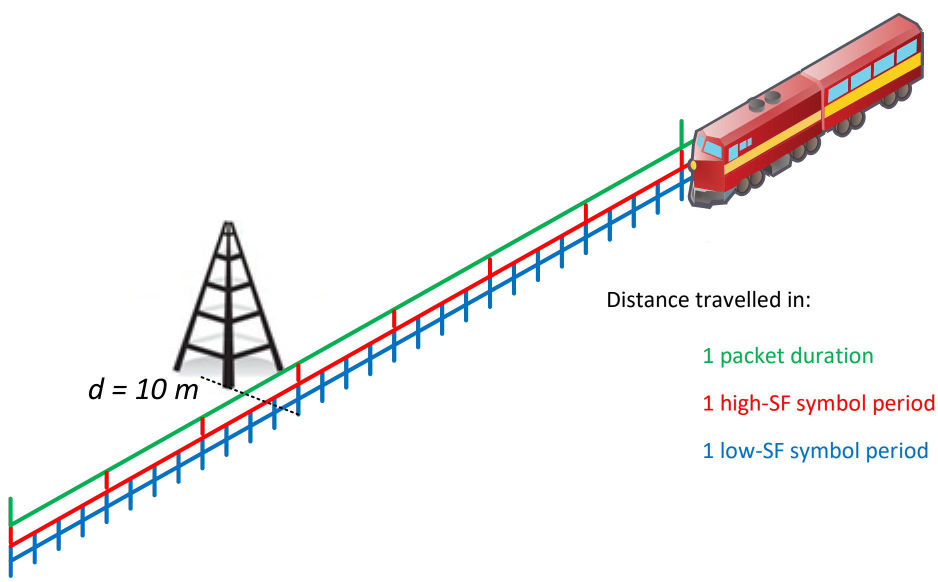

Figure 3. Illustration of the Railway Telemetry Application's Worst-Case Dopler Scenario

Step 1) Doppler Shift

The Doppler shift that the radio link will experience is plotted in Figure 4. It shows a very similar result to that of our first example from Section 1, however in contrast to the 250 Hz shift seen at 2.4 GHz, the high-speed train generates only 173.6 Hz of Doppler shift at 868 MHz albeit at much higher speed.

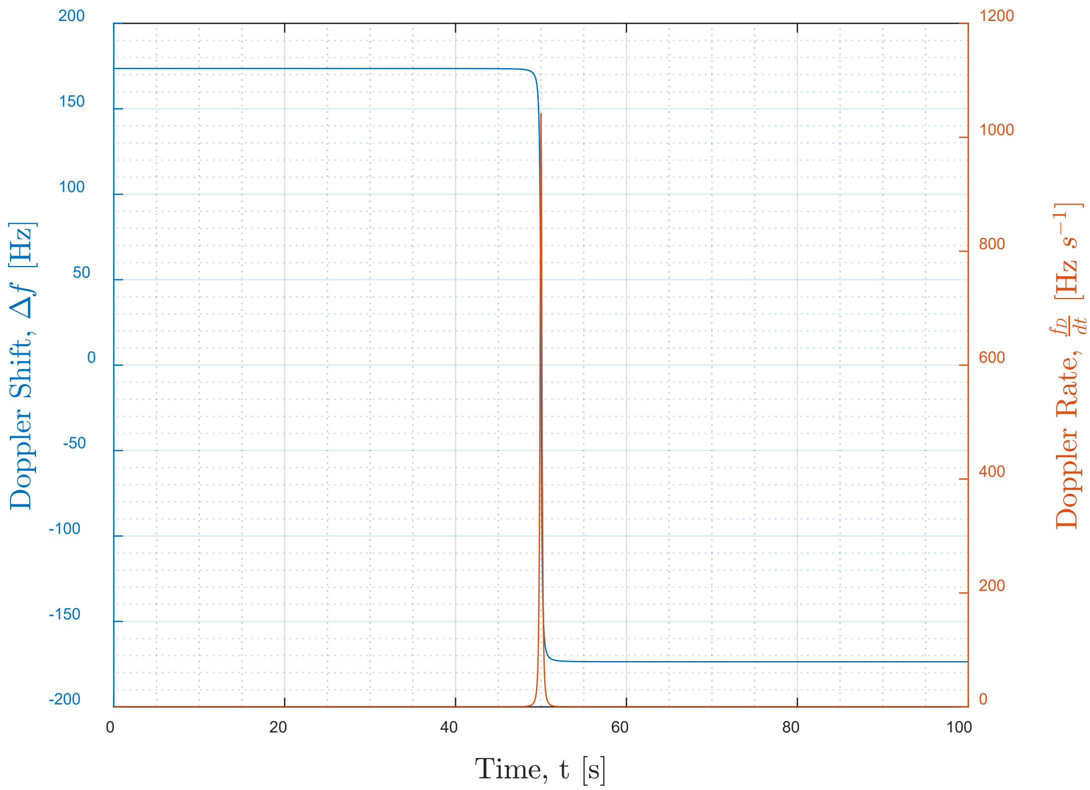

Figure 4. Doppler Effect of a Train Passing a Stationary Receiver at 216 kmph

This is due to the longer wavelength of the 868 MHz signal, meaning that the train travels a shorter fraction of a wavelength at a given speed than for the shorter wavelength of 2.4 GHz. This highlights the potential importance of band selection in engineering a link that is more immune to the Doppler effect.

Lower radio frequencies generate lower Doppler shift at a given speed.

Step 2) Doppler Rate

As was shown in Section 2.2, each family of transceiver requires separate guidance on the Doppler rate immunity.

SX12xx Immunity

The Doppler rate plot of Figure 4 is duplicated below, but instead of considering the Doppler rate seen per second, the plot is normalized to the Doppler rate seen during the entire packet duration.

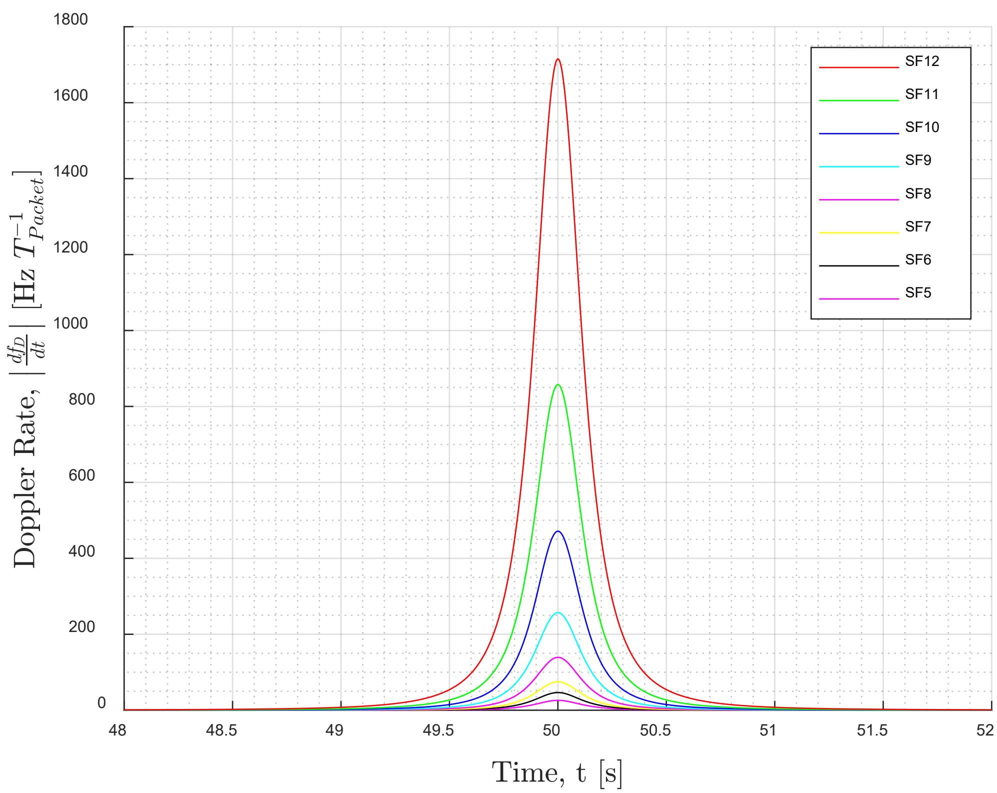

Figure 5. Doppler Rate Normalized to Packet Duration for the Railway Application

By comparing the peak values seen in Figure 5 with the Doppler rate limit of Equation 3, we can determine what range of SF will be compatible with our application. The comparison is tabulated below, from which we see that the application Doppler rate does not exceed the rate limit for SF5 to SF8.

Table 1. Usable SF Values for SX12xx Receivers in the Railway Application

SF	5	6	7	8	9	10	11	12
Packet Duration [ms]	24.9	44.7	71.9	134	245	453	823	1647
Doppler Rate Limit [Hz/pkt]	1302	651	326	163	81.4	40.7	20.3	10.2
Application Doppler Rate [Hz/pkt]	25.9	46.5	74.9	139	257	471	858	1715

LR11xx Doppler Rate

As shown in Section 2.3, later generations of product we benefit from the enhanced Doppler immunity that applies to each LoRa symbol. The LoRa symbol duration is given by equation 5:

$$T_S = \frac{2^{SF}}{BW} \qquad (5)$$

We re-examine the Doppler rate of our scenario in Figure 6. In this plot we do not normalize the drift seen to 1 second (as we did in Figure 4) but instead look at the drift seen over 1 symbol period. Note that lower SF has a higher data rate, so shorter symbol period.

If we increase the SF, the symbol duration increases. This means that the train (travelling at a fixed speed) will travel further during a long symbol (red scale on onset image) than during a short symbol period (blue scale on inset image). The consequence of this is that **for longer symbol periods**, because the train travels further in that time, **we see a greater change in frequency**.

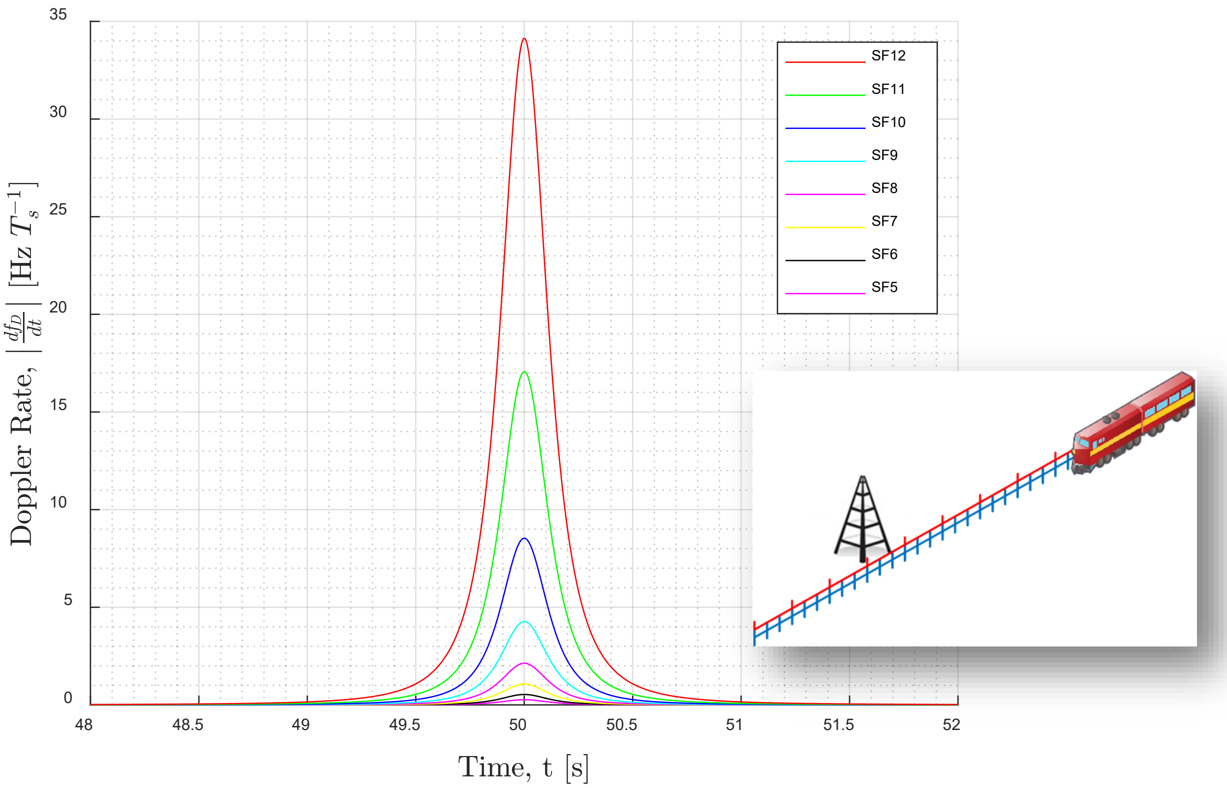

Figure 6. Doppler Rate of the Railway Example. Viewed on the Scale of a Single LoRa Symbol

Comparing the peak frequency drift observed over a single LoRa symbol with the limits given by equation 4, we see a broader range of SF from SF5 to SF10 can be covered by the modem.

Table 2. Usable SF Values for LR11xx Receivers in the Railway Application

SF	5	6	7	8	9	10	11	12
Doppler Rate Limit [Hz/symbol]	391	195	97.7	48.8	24.4	12.2	6.10	3.05
Application Doppler Rate [Hz/symbol]	0.266	0.533	1.07	2.13	4.27	8.52	17.0	33.8

Aside: Application Perspective

Although presented here as an example of how to calculate the susceptibility of the modem to the Doppler Effect in the worst-case scenario, it is worth noting that in the context of a real railway application – passing a trackside gateway is likely to be a very low probability event.

For example, if we pass the gateway once an hour - at SF12 this corresponds to a probability of only 0.046% of passing the gateway at the wrong moment. If this is not an acceptable loss rate, then we could just repeat the packet as a simple means of dealing with the Doppler.

Another important question is whether the link is bidirectional? If not, then only the static gateway must manage Doppler effects. This frees the end device to use the most cost-efficient transmitter and constrains only the gateway.

For a specific application, there are many such questions we can ask. It is hence always useful to bear in mind the broader application picture and evaluating if simple mitigation methods are possible.

3.2 Tire Pressure Monitoring Application

Not all applications involve the passage of one object past another. In tire pressure management systems (TPMS) the wheel mounted sensor is in continuous motion and will always have a Doppler component.

In the example shown below, the wheel rolls in contact with the road surface with a sensor-radio in the wheel and a vehicle chassis-mounted receiver at some distance, *d*. (We keep the problem 2 dimensional for simplicity). The design brief is to:

- Find the LoRa PHY parameters that allow reception of a 10-byte packet, sent at 2.4 GHz with 812 kHz BW.
- Decide on the optimal placement of the receiver distance, *d* up to 2 m.

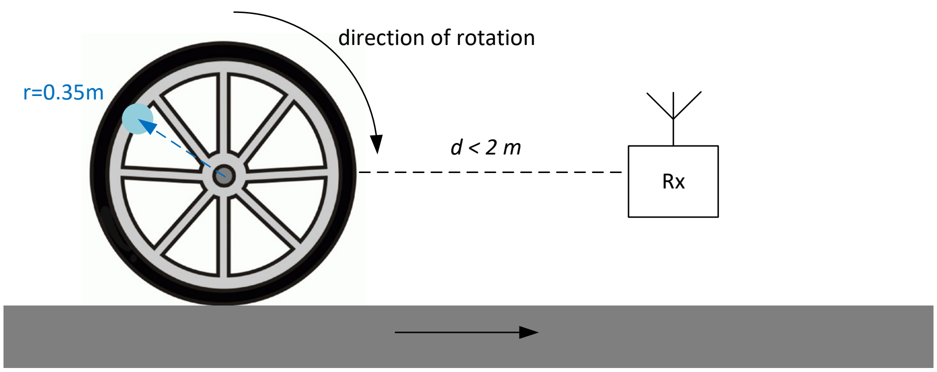

Figure 7. Depiction of Design Constraints of the TPMS System (blue dot denotes sensor location)

We begin by examining the relative speed of the wheel to the receiver, as shown in Figure 8. This does not change as a function of distance, *d*. The speed of the sensor oscillates between two extreme values of +/- 50 m/s, which is the road speed of the wheel, reaching the peak relative-speeds as the sensor reaches the top and bottom of rotation.

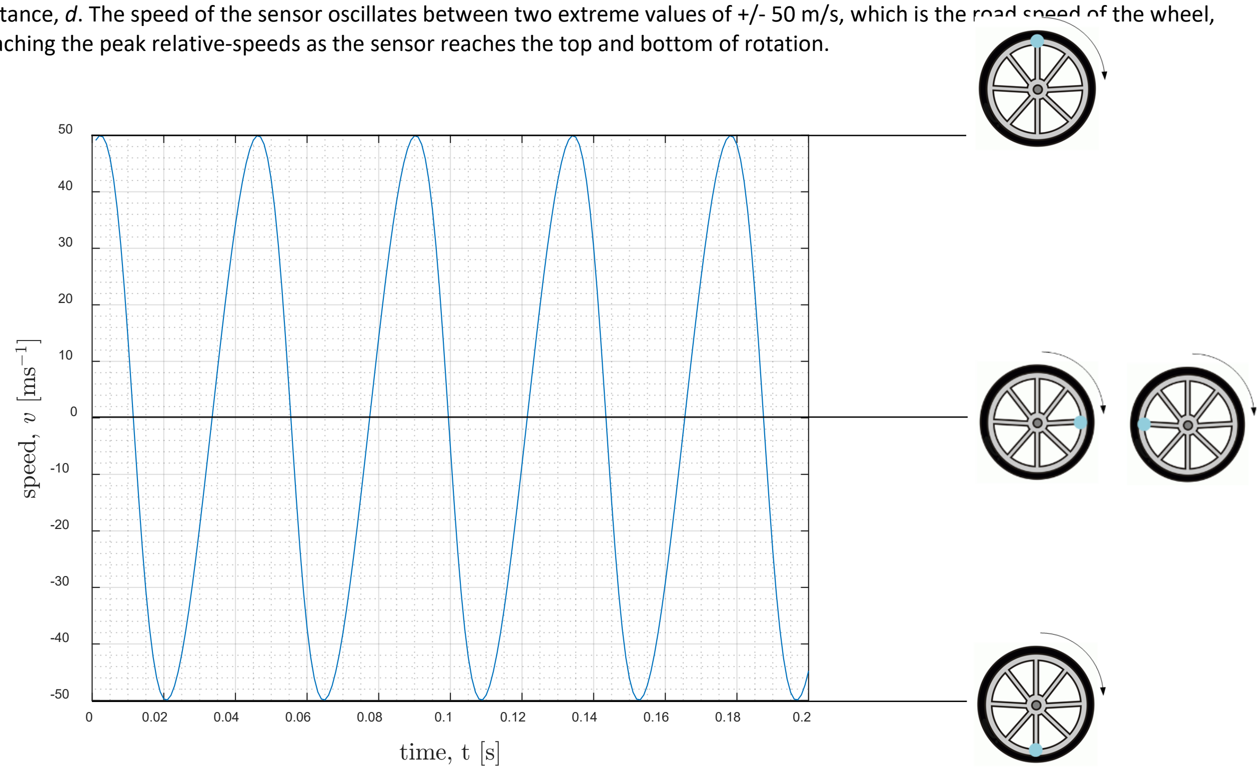

Figure 8. Relative Speed of the Wheel-Sensor to the Vehicle's Receiver

Because the placement of the receiver is a design variable, we first examine how placement will influence the Doppler shift and Doppler rate seen by the radio. To do so we consider two extremes:

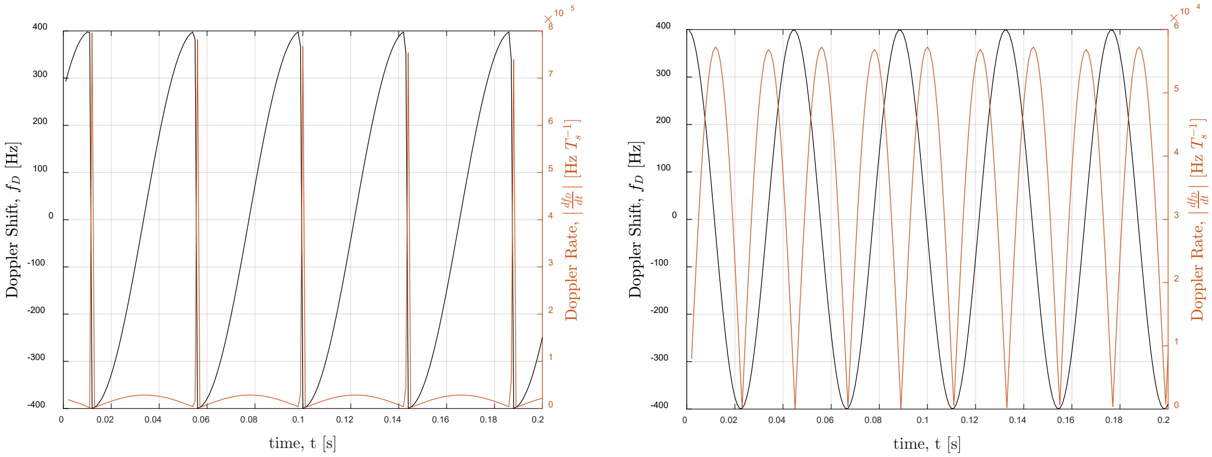

Figure 9. Comparison of Doppler Rate at d = 0 m from the Wheel (left) and d = 100 m (right)

In the left-hand image, the radio is positioned at the wheel edge (d = 0 m) and the rightmost at 100 m (beyond our design specification limit). In both cases we see that the Doppler shift (black curves) swings between two extreme values of ±400 Hz. It is the *rate* of that change (orange curve) which varies with the radio placement. In the case where the radio is close to the wheel the frequency changes at a rate of 753 kHz/s whereas at the more distant spacing, this is reduced to 572 kHz/s.

This finding highlights that increasing separation between transmitter and receiver can help reduce the Doppler Rate.

To minimize the Doppler rate in our application, we therefore elect to place the radio at the maximum possible spacing of 2 m. This reduces the maximum Doppler rate contribution to 669 kHz/s as shown in Figure 10.

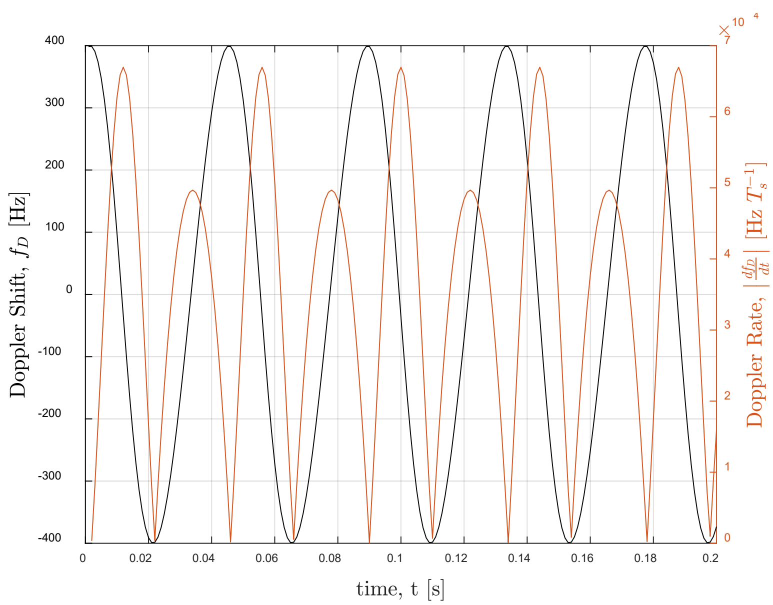

Figure 10. Doppler Shift and Doppler Rate at 2 m Distance from the Wheel

As with previous testing, assume a worst case (highest speed) scenario and follow our two-step process for determining which modem settings are suitable.

Step 1) Doppler Shift

25 ppm crystal error (receiver)	61.3 kHz
25 ppm crystal error (transmitter)	61.3 kHz
Sum of all system drift / error	123 kHz
Max drift (¼ of 812 kHz LoRa bandwidth)	203 kHz
Remaining frequency drift budget	80.5 kHz

With the peak Doppler shift shown in Figure 10 limited to 400 Hz, the absolute Doppler frequency shift will not impact the communication link.

Step 2) Doppler Rate

SX12xx Immunity

Because the time-on-air (ToA) of a 10 Byte packet using the 2.4 GHz LoRa modem bandwidth of 812 kHz is short, we re-plot the Doppler rate - but normalized to a packet duration. This allows us to see the maximum possible Doppler rate over the duration of a packet.

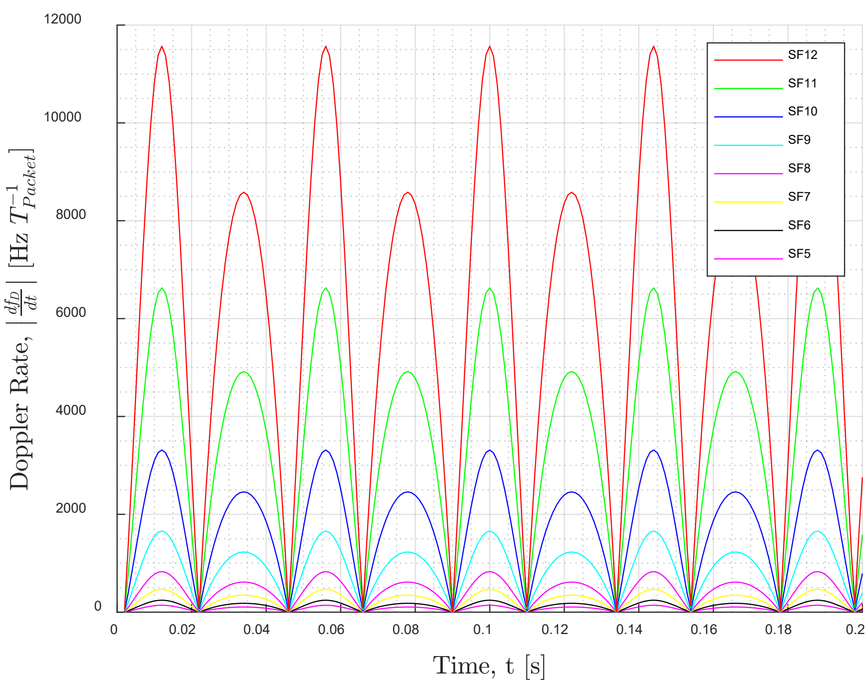

Figure 11. Doppler Rate Normalized to Packet Duration

Table 3 compares the peak values from this plot with the calculated Doppler rate limit of Equation 3.

Table 3. Usable SF Values for SX12xx Receivers in the TPMS Application

SF	5	6	7	8	9	10	11	12
Packet Duration [ms]	2.11	3.65	6.98	12.4	24.8	49.5	98.9	172
Doppler Rate Limit [Hz/pkt]	8458	4229	2114	1057	528	264	132	66.1
Application Doppler Rate [Hz/pkt]	104	181	346	614	1229	2459	4918	8583

From this result, we can see that SF in the range of SF5 to SF8 will be immune to Doppler effects.

LR11xx Doppler Rate

The final step in our investigation is to examine the Doppler rate normalized to the scale of a symbol period, Ts. The results are shown in Figure 12, it shows a marked decrease in the observed Doppler compared with the previous result in Figure 11.

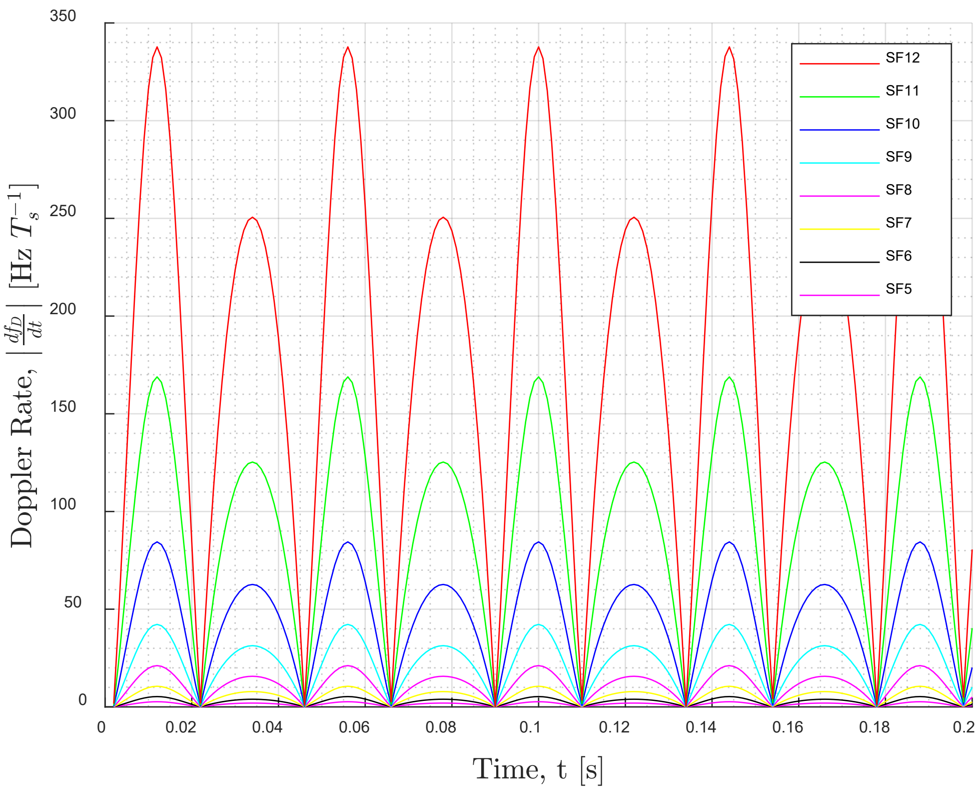

Figure 12. Doppler Rate Normalized to Symbol Period

Taking the peak observed Doppler rate over the scale of a LoRa symbol and comparing it with the limit calculated using Equation 4, gives the results in the following table. This adds SF9 and SF10 to the range of feasible LoRa bandwidths accessible for our application.

Table 4. Usable SF Values for LR11xx Receivers in the TPMS Application

SF	5	6	7	8	9	10	11	12
Doppler Rate Limit [Hz/Ts]	2537	1268	634	317	158	79.3	39.7	19.8
Application Doppler Rate [Hz/pkt]	1.96	3.915	7.83	15.6	31.3	62.7	125	251

3.3 Satellite Application

The high speed of a satellite relative to a ground station means that an analysis of potential Doppler effects is of critical importance. For LoRa based satellite communication, low Earth orbit (LEO) is popular with several satellite operators. To analyze the effects of Doppler on the communication link we need to determine the speed and distance of the satellite relative to the ground station. The orbital speed, v, is given by the following equation, where G is the gravitational constant, R and G are the Earth's radius and mass respectively.

$$v = \sqrt{GM/R} \qquad (5)$$

From this equation we can see that lower orbits generate the highest orbital speeds and is in closest proximity to the surface, thus yielding the most challenging communication environment from a Doppler perspective. (Although reducing link budget requirements and latency – topics beyond the scope of this Note).

In this example, we will examine the feasibility of a LEO satellite at a height of 500 km, but in this case operating in two bands:

- **Downlink:** the radio will operate at 400 MHz and
- **Uplink:** using the 868 MHz ISM band.

Both will operate using 125 kHz LoRa bandwidth and a payload of 102 Bytes. The physical scenario is illustrated below:

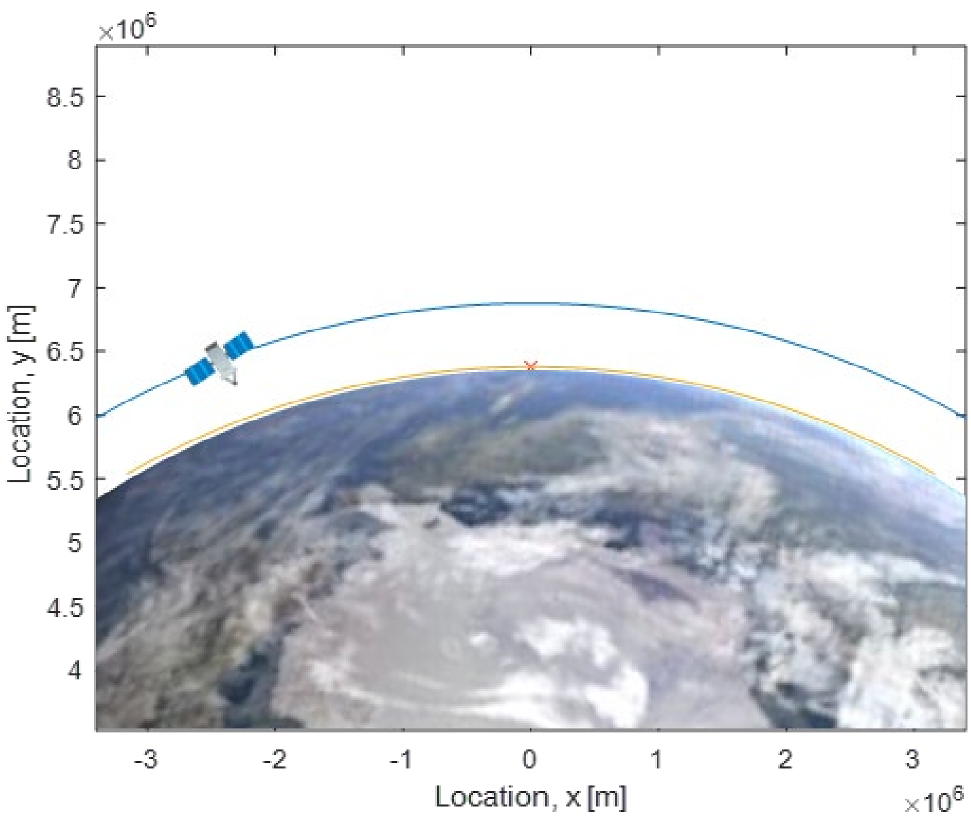

Figure 13. Orbital Path Used in Scenario With Ground Station at Red Cross

We begin by examining the Doppler shift and rate seen at the ground station when receiving from the satellite at this orbital height, using the speed calculated with Equation 5 over a 15-minute window.

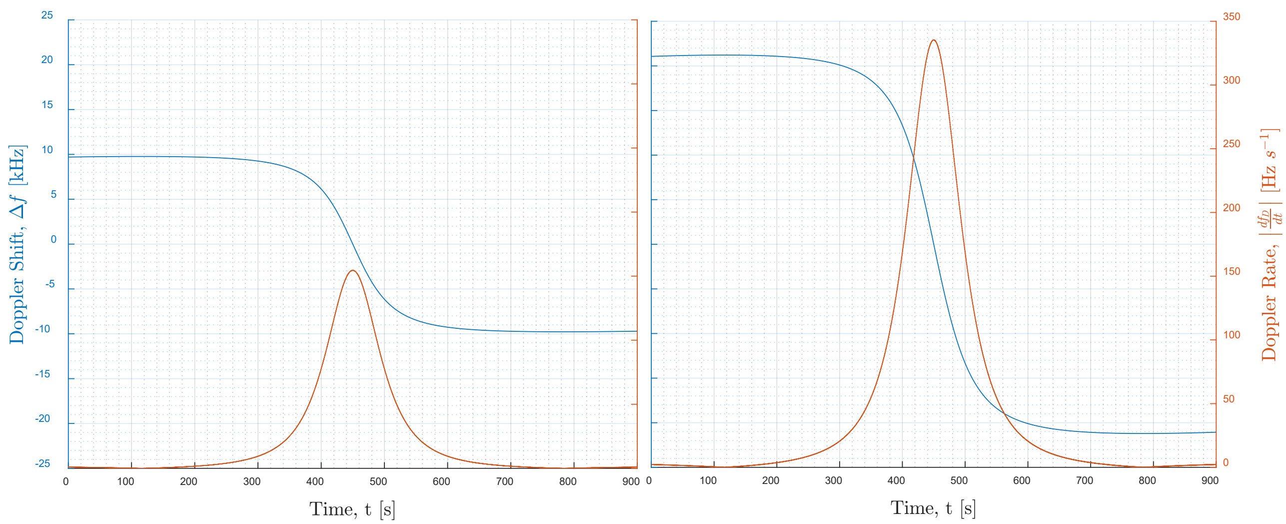

Figure 14. Doppler Shift and Doppler Rate for LEO Orbit of 500 km at 400 MHz (left) and 868 MHz (right)

In this example the performance in both uplink and downlink bands is shown. In the 400 MHz uplink band, the maximum Doppler shift is 9.77 kHz. At 868 MHz, a frequency over double that of the 400 MHz link, we see the Doppler shift increases proportionally to 21.2 kHz.

With this insight, we can examine the frequency error budget of the link, in this example we assume the use of a TCXO with 5 ppm frequency tolerance (with all cases of drift considered) in both the space vehicle and the ground station.

Step 1) Doppler Shift

	400 MHz	868 MHz
5 ppm crystal error (receiver)	2.165 kHz	4.34 kHz
5 ppm crystal error (transmitter)	2.165 kHz	4.34 kHz
Sum of all system drift / error	4.33 kHz	8.68 kHz
Max drift (¼ of 125 kHz LoRa bandwidth)	31.25 kHz	31.25 kHz
Remaining frequency drift budget	26.92 kHz	22.57 kHz

For the 400 MHz downlink band, we can see that the link has a very significant Doppler shift margin, with the capacity to incur up to 26.92 kHz drift, but with only 10.58 kHz experienced. Conversely, in the 868 MHz band, the remaining permissible frequency drift is 22.57 kHz - with the Doppler shift of 21.2 kHz the drift margin is lower, but the full performance of the communication link will be achieved.

Step 2) Doppler Rate

In a second step, we examine the Doppler rate between ground station and satellite, for each generation of receiver.

SX12xx Immunity

In the case of SX12xx family of products we determine the peak Doppler shift seen over the packet duration.

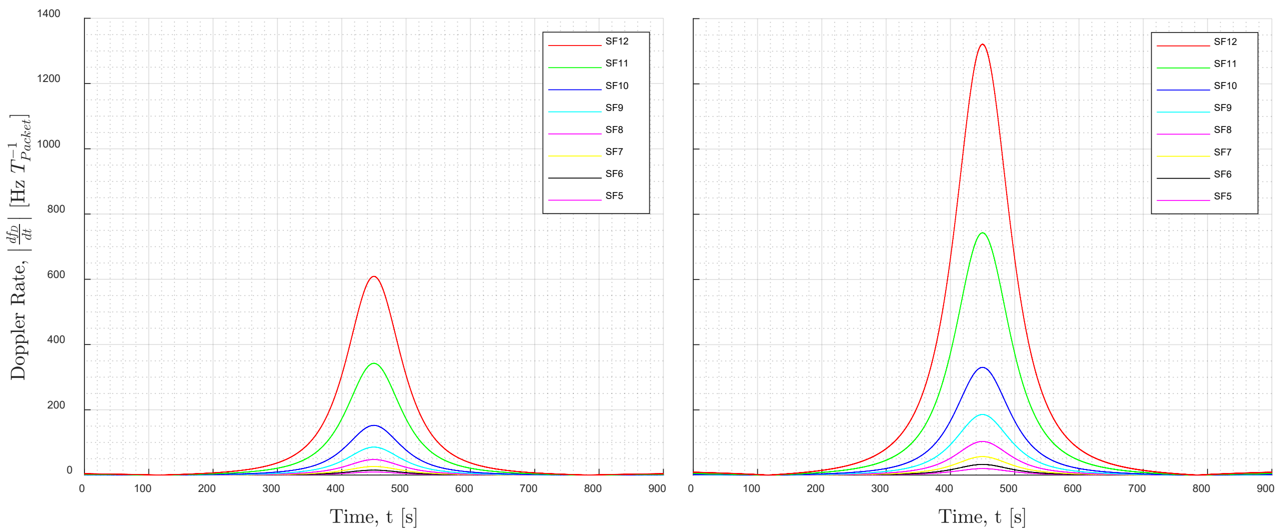

Figure 15. Doppler Rate Normalized to Packet Duration

Comparing this to the Doppler Rate limits given by Equation 3, we see the range of SF compatible with maintaining downlink communication from the orbiting satellite.

Table 5. Usable SF Values for SX12xx Receivers in the Satellite Downlink at 400 MHz

SF	5	6	7	8	9	10	11	12
Packet Duration [s]	0.0594	0.0974	0.169	0.308	0.554	0.985	2.22	3.94
Doppler Rate Limit [Hz/pkt]	1302.1	651.0	325.5	162.8	81.38	40.69	20.34	10.17
Application Doppler Rate [Hz/pkt]	9.19	15.1	26.2	47.6	85.6	152	343	609

Table 6. Usable SF Values for SX12xx Receivers in the Satellite Uplink at 868 MHz

SF	5	6	7	8	9	10	11	12
Packet Duration [s]	0.0594	0.0974	0.169	0.308	0.554	0.985	2.22	3.94
Doppler Rate Limit [Hz/pkt]	1302.1	651.0	325.5	162.8	81.38	40.69	20.34	10.17
Application Doppler Rate [Hz/pkt]	19.9	32.7	56.8	103	185	330	743	1321

In this example, although the Doppler rate that the uplink signal will incur is double at 868 MHz (Table 6) compared with that at 400 MHz (as shown in Table 5), the same range of SF values (highlighted in green) are accessible in both cases.

LR11xx Doppler Rate

Exploring the improved immunity of the later LR11xx generations of product, the Doppler Rate is recalculated on the scale of a LoRa symbol for all SFs and plotted in Figure 16 for the 400 MHz and 868 MHz bands.

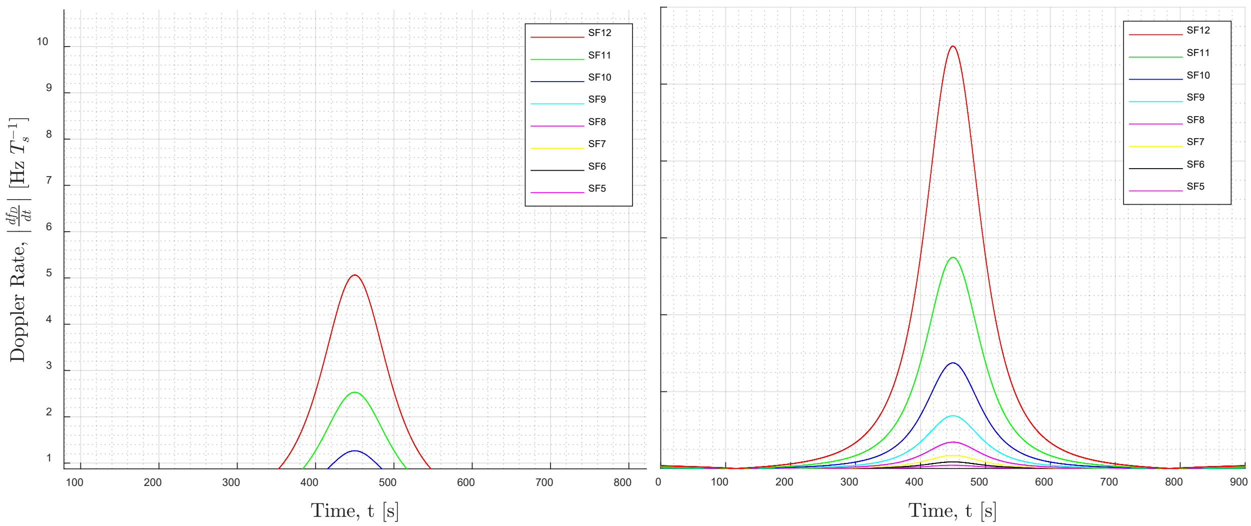

Figure 16. Doppler Rate Normalized to Symbol Period at 400 MHz (left) and 868 MHz (right)

The following tables show the peak Doppler rates from the plots above and contrast them with the frequency tracking limits given by Equation 4.

Table 7. Usable SF Values for LR11xx Receivers in the Satellite Downlink at 400 MHz

SF	5	6	7	8	9	10	11	12
Doppler Rate Limit [Hz/symbol]	390.6	195.3	97.65	48.83	24.41	12.21	6.104	3.052
Application Doppler Rate [Hz/symbol]	0.0395	0.0791	0.158	0.317	0.633	1.27	2.53	5.07

Table 8. Usable SF Values for LR11xx Receivers in the Satellite Uplink at 868 MHz

SF	5	6	7	8	9	10	11	12
Doppler Rate Limit [Hz/symbol]	390.6	195.3	97.65	48.83	24.41	12.21	6.104	3.052
Application Doppler Rate [Hz/symbol]	0.0859	0.172	0.343	0.687	1.37	2.75	5.50	11.0

From the tabulated comparisons above we see that the same range of data rates, up to SF11, is available irrespective of the band selected.

To conclude our satellite example, we will look at what happens if we reduce the payload size from 102 Bytes to 51 Bytes. In the following table we reproduce the result of Table 5, looking at the 400 MHz Doppler rate immunity, but this time with the payload size halved.

Table 9. Usable SF Values for SX12xx Receivers in the Satellite Downlink at 400 MHz (Shorter Payload)

SF	5	6	7	8	9	10	11	12
Packet Duration [s]	0.0594	0.0974	0.169	0.308	0.554	0.985	2.22	3.94
Doppler Rate Limit [Hz/pkt]	1302.1	651.0	325.5	162.8	81.38	40.69	20.34	10.17
Application Doppler Rate [Hz/pkt]	5.23	8.88	15.8	28.6	50.8	95.3	202	382

What this result shows is that the linear decrease in time-on-air has the predictable effect of reducing the Doppler rate seen over the duration of the packet to 50.8 Hz/pkt for SF9, allowing it to become usable.

An interesting observation from this data is that using the latest generation of LoRa modem has a larger influence on the Doppler rate immunity than either reducing time-on-air or reducing the RF operating frequency.

For our satellite application, we can certainly conclude that the latest generation of LoRa modem should be employed in the space vehicle, with the flexibility to use spreading factors up to 11 when communicating with an LR11xx ground station or an SF of up to 9 with the SX12xx generation devices depending upon payload length.

4 Conclusions

In this Application Note we have shown that the Doppler shift is typically easily accommodated by the LoRa modem, and that the Doppler rate typically is the more important design quantity. We have evaluated the Doppler immunity for both SX12xx and LR11xx receiver families and shown the improved robustness of the latter, together with the applicable limits and methodologies for testing a receiver's ability to accommodate Doppler effects. In conclusion, we have shown that there are a number of methods that can be used to improve the Doppler immunity of a LoRa radio link, including:

- Using a lower frequency radio band for communication.
- Increasing the distance between radios to reduce the magnitude of Doppler Rate.
- Reducing the LoRa packet duration in the SX12xx generation of products (by reducing the payload size, reducing the SF or increasing the bandwidth).
- Reducing the LoRa symbol period in the LR11xx generation of products (by reducing the SF or increasing the bandwidth).
- Taking care to look for system-level workarounds such as repeating messages.

5 Revision History

Version	ECO	Date	Changes and/or Modifications
1.0	069006	October 2023	Initial Version

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