VHF/UHF/Microwave: Which JT mode should I choose?

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I. INTRODUCTION

There are 10 Amateur Bands between 50 MHz and 10 GHz inclusive, with widely differing propagation characteristics. There are currently (as of 2-24-19) 5 slow JT QSO modes (FT8, JT4, JT9, JT65, and QRA64) and 3 fast JT modes (ISCAT, JT9-Fast, and MSK144), the latter allowing 15 second or shorter receive cycles. Although the program developers categorize FT8 as a slow mode and I have therefore included it in that category, it also uses 15 second receive cycles just like the fast modes. Many of the modes have multiple sub-modes and if you add up all of those, there are currently 32 modes and sub-modes to choose from[1].

Furthermore, on a given band propagation might be via tropospheric scatter, meteor scatter, rainscatter, aircraft scatter, Aurora, or EME, for example (the possibilities depend on the band). Each of these different propagation modes will have its own path attenuation and frequency dispersion/frequency shift characteristics.

Also, station equipment characteristics need to be considered when deciding on the best mode/sub-mode to use. Some of the characteristics that are important to consider are the frequency stability of the sending and receiving stations, ERP, and the noise figure (sensitivity) of each station's receive system.

So how do you pick the WSJT-X mode/submode to use for a QSO attempt? Although the choice of mode/sub-mode for a given QSO attempt at first glance seems complicated, in fact in order to determine the optimal digital mode to use for a given QSO attempt one just needs to compare a few characteristics of each digital mode/sub-mode with the corresponding characteristics for the path/band/propagation mode to be used, and the likely best match will thereby be selected.

This paper, an update and extension of the report included in the syllabus, will provide a conceptual framework for choosing the "best" JT mode for a given set of conditions. It will not provide a "cookbook" that can be used for mode selection without thoughtful consideration.

The mode/sub-mode characteristics that must be considered in this process are:

1. Sensitivity (i.e., how weak a signal can the mode copy. Conventionally expressed as dB above the noise, or in the case of the WSJT-X modes, in "JT dB")
2. Tolerance of frequency drift, shift, and dispersion
3. Receive cycle time (total time used for signal reception, sandwiched between two transmit sequences)
4. Time required for a single complete message to be received. For the fast modes, this is NOT the same as #3 above, because these modes include multiple sequential transmissions of the complete message in a single receive cycle. For example, for JT9H-Fast the time required to transmit the complete message is 0.425 seconds (even though the receive cycle time for this mode can be set to approximately 5, 10, 15, or 30 seconds). The WSJT-X User Guide calls this transmit interval "**Tx Duration**" and we will use that terminology here.

The band/propagation mode characteristics that need to be considered are:
1. Expected signal-to-noise-ratio at the receiver for the signal in question
2 Frequency dispersion and / or Doppler shift caused by the scattering objects in the case of rainscatter, aircraft scatter, Aurora, EME
3. Time available to complete the QSO. This might be an hour or more for a non-contest experimental session, or as short as a couple of minutes for an aircraft scatter contact with an airplane flying perpendicular to the inter-station path
4. The time available to complete reception of a single complete message element. This ranges from a tiny fraction of a second for a meteor scatter path to the full receive cycle time for a stable tropo path.

The main station characteristics affecting mode/sub-mode selection are:
1. Effective radiated power
2. Receive system sensitivity
3. Frequency stability.

How does all of this come together?
1. The poorer the signal-to-noise ratio of the received signal at the receiving station, the more sensitive must be the chosen mode/sub-mode.
2. The greater the path frequency dispersion/Doppler shift/frequency instability of the transmit and receive stations, the greater the frequency tolerance of the mode will need to be.
3. As the signal-to-noise ratio of the received signal becomes worse and approaches the threshold for detection, the tolerance of each mode/submode for frequency drift/shift/dispersion becomes poorer.
4. Short receive cycle times permit more rapid QSOs, but mode sensitivity may be reduced for shorter cycle times, all other things being equal.
5. With meteor scatter under usual non-shower conditions with only very short meteor pings available, only modes such as MSK144 with very short (0.020-0.072 sec) message completion times are useful. Aircraft scatter has less stringent requirements in this regard, but relatively short message completion times are often needed for successful aircraft scatter contacts on the microwaves, where ISCAT-A, ISCAT-B, and the JT9-Fast modes may therefore be needed.

The slow QSO modes as defined by the WSJT/WSJTX developers are FT8 (which has 15 second receive cycles), JT4, JT9A-H Slow, JT65, and QRA64. Except for FT8, each of these slow modes have one-minute-long (actually ~47-49 second) receive cycle times.

The fast QSO modes as defined by the WSJT/WSJTX developers are ISCAT-A, ISCAT-B, JT9E-Fast, JT9F-Fast, JT9G-Fast, JT9H-Fast, MSK144, and MSK144-sh. These fast modes are less sensitive than the slow modes. In particular, the JT9 fast sub-modes suffer significantly in terms of sensitivity when compared with the corresponding JT9 slow submodes, as you will see below. MSK-144 and MSK144-sh have a niche role for meteor scatter and will not be discussed further here.

II. Specific Mode/Sub-mode Characteristics: Slow Modes

Now we are going to review the specific characteristics of the modes, beginning with the Slow Modes, and limiting the discussion to what is important for operating in the frequency range of 50 MHz through 10 GHz, inclusive, and dropping MSK144 and MSK144-sh from the discussion. If you want more extensive information on the modes/sub-modes, you can start here: **WSJTX Manual: Protocols**

First we will consider mode/submode sensitivity and the relationship between sensitivity and tone spacing. Note in the tables below that for each mode, as sub-mode tone spacing (column 2) **increases** the sub-mode sensitivity (column 4) **decreases**. Moving up the alphabet for each mode, each tone spacing increment doubles the tone spacing (except for the step from JT4C to JT4D). And 1 dB of sensitivity is lost with each such increment upwards in tone spacing for each of the slow modes.

This is shown in the tables for JT4 and JT9-Slow below, taken from the WSJT-X User Guide:

Mode	Tone Spacing (Hz)	BW (Hz)	S/N (dB)
JT4A	4.375	17.5	-23
JT4B	8.75	30.6	-22
JT4C	17.5	56.9	-21
JT4D	39.375	122.5	-20
JT4E	78.75	240.6	-19
JT4F	157.5	476.9	-18
JT4G	315.0	949.4	-17

Mode	Tone Spacing (Hz)	BW (Hz)	S/N (dB)
JT9A	1.736	15.6	-27
JT9B	3.472	29.5	-26
JT9C	6.944	57.3	-25
JT9D	13.889	112.8	-24
JT9E	27.778	224.0	-23
JT9F	55.556	446.2	-22
JT9G	111.111	890.6	-21

And for JT65 and QRA64, taken from the same source:

Mode	Tone Spacing (Hz)	BW (Hz)	S/N (dB)
JT65A	2.692	177.6	-25*
JT65B	5.383	352.6	-24*
JT65C	10.767	702.5	-23*

* table in WSJT-X User Guide shows -25 for all 3 JT65 submodes, but original description in QEX shows above results.

Mode	Tone Spacing (Hz)	BW (Hz)	S/N (dB)
QRA64A	1.736	111.1	-26
QRA64B	3.472	220.5	-25
QRA64C	6.944	439.2	-24
QRA64D	13.889	876.7	-23
QRA64E	27.778	1751.7	-22

Not shown in the tables (because it has only one tone spacing "level") is **FT8**, which has Tone Spacing 6.25 Hz, Bandwidth 50 Hz, and S/N threshold -21 dB.

As noted above, for each mode, the submode with the narrowest tone spacing will have the best sensitivity, and with each step upwards in tone spacing 1 dB of sensitivity will be lost. When just the "best" submode in terms of sensitivity for each slow mode is considered, the modes stack up as shown in the table below. You can see that JT9A is the most sensitive, followed by QRA64A, JT65A, JT4A, with FT8 at the bottom of the heap in terms of sensitivity:

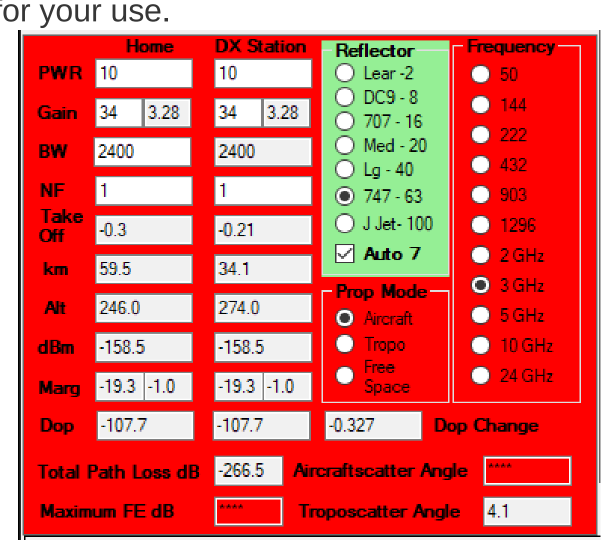
Mode	S/N (dB)
JT9A	-27
QRA64A	-26
JT65A	-25
JT4A	-23
FT8	-21

The fast modes are substantially less sensitive than the slow modes and this will be discussed in more detail later in this paper.

In general it makes sense for a given QSO attempt to choose the mode/submode with the best sensitivity that will also satisfy the other mode/submode performance criteria required for your particular QSO attempt.

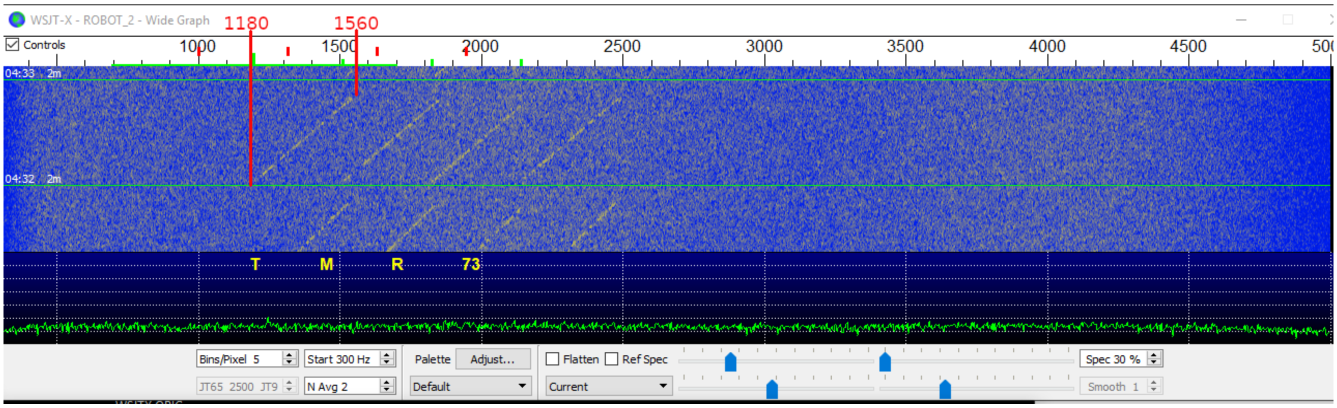
Most of the time you will have only a qualitative sense of what the signal-to-noise ratio will likely be for a given path, unless you have worked that path before, so you won't know exactly what sensitivity you need. If you have worked the path before, you will have a QUANTATIVE idea of what the signal-to-noise ratio is likely to be (for a given frequency, given propagation mode, and given station parameters), and you will know what digital modes have worked for you on that path before. Acquiring this information is a GREAT reason to test things out with other stations "BETWEEN contests", so that you can go right to the mode/sub-mode most likely to succeed for a given path and band when contest time arrives.

If you give it the necessary station parameters, the program AircraftScatterSharp[2] will also give you <u>estimates</u> of the expected quantitative signal-to-noise values for both troposcatter and aircraft scatter propagation, expressed as dB above the noise. This is shown in the image below; the signal strength in dB above the noise is shown in the row labeled "Marg" (short for "Margin"). The first value in the box (-19.3) is the expected signal margin without Forward Scattering Enhancement, and the second value (1.0) includes this effect in the estimated signal margin. If you set your bandwidth ("BW") in AircraftScatterSharp to 2400 Hz for both stations as is shown in the example image, then the signal margins that you get should be in JT dB units, ready for your use.



Frequency Tolerance of the Slow Modes First of all, if you are going to make decisions based on the frequency tolerance of the various modes and submodes, then you need to know the value of the rate of drift for the signal that you are going to try to decode. The best way to determine this is to <u>measure</u> this rate of drift using a signal from your QSO partner transmitted on the frequency that you plan to use. Have your QSO partner transmit a carrier or a JT message in a mode providing traces that are easily seen on the WSJT-X waterfall, and then just measure the drift in Hz observed on the WSJT-X waterfall during the transmit period and divide that by the duration of the transmit period in seconds and you have your rate of drift. The image below is of a JT4G signal that is drifting at a constant rate, as you can see from the 4 traces running from lower left to upper right. The left-most trace drifts from 1180 to 1560 Hz during the transmit cycle interval, which is 47.1 seconds as is shown in the WSJT-X User Guide at the URL given above. So the estimated drift rate taken from the waterfall is 8.07 Hz/Sec, quite close to the actual drift rate known to be exactly 8 Hz/Second. With this method you determine the actual rate of drift for the signal that you are about to attempt to decode, taking into account the characteristics of your station, your QSO partner's station, and the path.

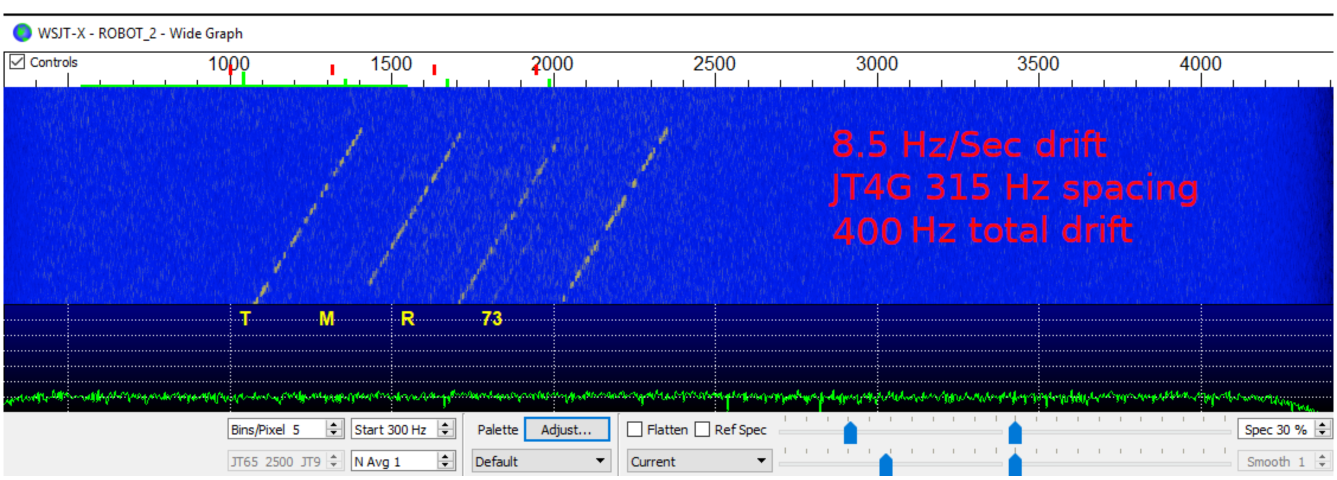
(1560 - 1180) = 380 Hz / 47.1 Sec = 8.07 Hz/Sec (Actual 8 Hz/Sec)



If the rate of frequency drift is too small to measure using the WSJT-X waterfall, then you may choose to use Argo[3], SpectrumLab[4], or Spectran[5] or any number of other programs to make this measurement.

After determining the frequency tolerance requirements by measuring the actual frequency drift, one next needs to consider the frequency tolerance of the various modes/submodes.

The assessment of tolerance of a given mode/submode to frequency dispersion, drift, and Doppler shift has some nuances. At first glance, one might think that the frequency tolerance of a given mode/submode is simply a function of the tone spacing for that mode/submode. The different tone "channels" (4 for JT4, 8 for FT8, 9 for JT9, 64 for QRA64, 65 for JT65) are used to encode the channel symbols that form each message. One might expect that a frequency shift or drift during the Tx Duration (12.6 seconds for FT8, 47.1 seconds for JT4, 49.0 seconds for JT9, 48.4 seconds for QRA64, and 46.8 seconds for JT65) that was greater than the tone spacing would corrupt a message by right- or left-shifting the value of any channel symbol whose tones had crossed the boundary between channels. In the image below, the frequency drift of the JT4G signal is 8.5 Hz/second, giving a total drift of 8.5 * 47.1 = 400 Hz, which is wider than JT4G's tone spacing of 315 Hz(the four channel tone frequencies are marked by the small vertical red bars superimposed on the frequency scale at the top of the watefall). Yet this signal was consistently decoded correctly by WSJT-X.



So choosing a mode based on frequency drift / frequency tolerance is not as simple as just picking a mode with tone spacing at least as great as the frequency shift that you would expect to see during one Tx Duration with your particular path/station. However, there is a relationship between frequency tolerance and tone spacing, and so it is useful to calculate and consider the predicted “maximum permitted drift” for each mode based on tone spacing, which is of course just (tone spacing in Hz) / (Tx Duration in Sec). If things were this simple then we would predict that FT8 with its 12.6 second Tx Duration and its tone spacing of 6.25 Hz, would have a frequency tolerance of 6.25/12.6 = 0.5 Hz/second. And JT4G as in the examples above with its Tx Duration of 47.1 seconds and tone spacing of 315 Hz would have 315/47.1 = 6.7 Hz/second frequency tolerance. The results of similar calculations for the other slow modes/submodes are shown in the following tables:

Mode	Max Drift (Hz/Sec)
JT9A	0.04
JT9B	0.07
JT9C	0.14
JT9D	0.28
JT9E	0.57
JT9F	1.1
JT9G	2.3
JT9H	4.5

Mode	Max Drift (Hz/Sec)
FT8	0.5
JT4A	0.09
JT4B	0.19
JT4C	0.37
JT4D	0.83
JT4E	1.7
JT4F	3.3
JT4G	6.7

Mode	Max Drift (Hz/Sec)
JT65A	0.06
JT65B	0.11
JT65C	0.23
QRA64A	0.04
QRA64B	0.07
QRA64C	0.14
QRA64D	0.29
QRA64E	0.57

Given that the structure of each mode in terms of the number of tone channels, tone channel spacing, sync tone frequency (if present) is known in advance, it would not be surprising to learn that intelligent decoders could make use of this additional information to improve their frequency tolerance over what is predicted in the tables above. Both the JT9 and JT65 modes do in fact have some degree of frequency compensation or “AFC” built in to the decoder. It also would not be surprising to learn that frequency tolerance is dependent on the signal-to-noise ratio of the received signal.

It turns out that the actual frequency tolerance of a given mode/submode IS dependent on tone spacing, but there is also a substantial dependence on signal strength/signal-to-noise ratio. Frequency tolerance is poorest for weaker signal levels near the threshold of signal detection, and improves substantially as signal-to-noise ratio increases.

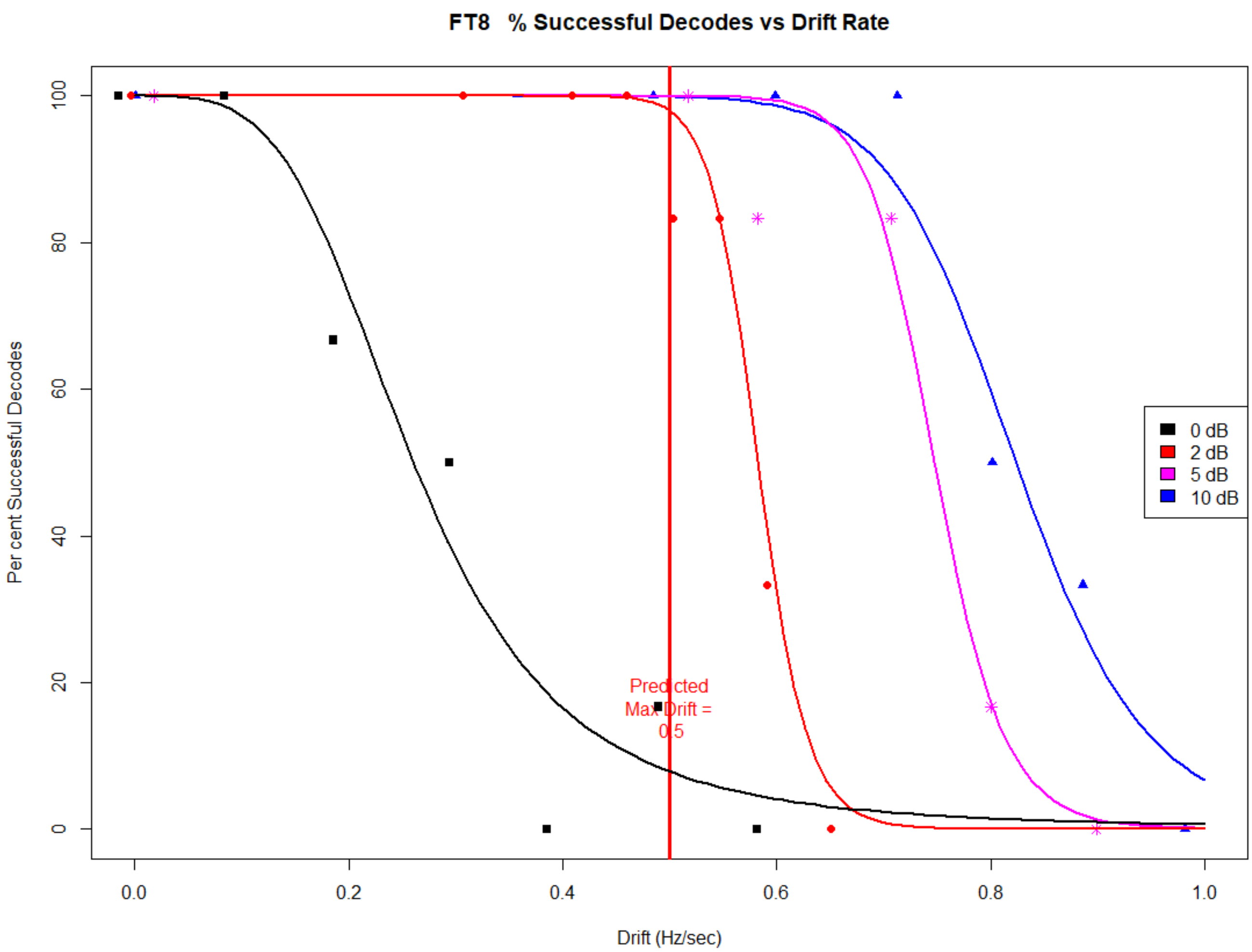
Thus, while the “Max Drift” values given in the tables above provide a rule of thumb for selecting the “best” mode to choose for a given amount of frequency drift, they are not the whole story and in some cases provide inaccurate predictions.

Also, note that the same considerations that apply to frequency drift also apply to Doppler shift, which is an issue with aircraft scatter and also with EME, and to frequency dispersion (spread).

Frequency Tolerance: Slow Modes Let's consider 6 slow modes as examples and look at the frequency tolerance of each at various signal levels. The modes considered will be FT8, JT4G, JT9G, JT9D, JT9A, and JT65C. The frequency tolerance of each mode will be assessed at 4 signal levels: the first level being the lowest signal level which results in 6/6 successful decodes and then signal levels 2 dB, 5 dB, and 10 dB above that. These signal levels will be termed, respectively, the "0 dB", "2 dB", "5 dB" and "10 dB" levels.

Details of the methods are given in the Appendix, but briefly two modified instances of WSJT-X 2.0.0 are used to create and decode a WSJT-X message with the audio tones in the sent message being swept in frequency at the desired "drift rate", and the percentage of successful decodes is determined for each set of conditions.

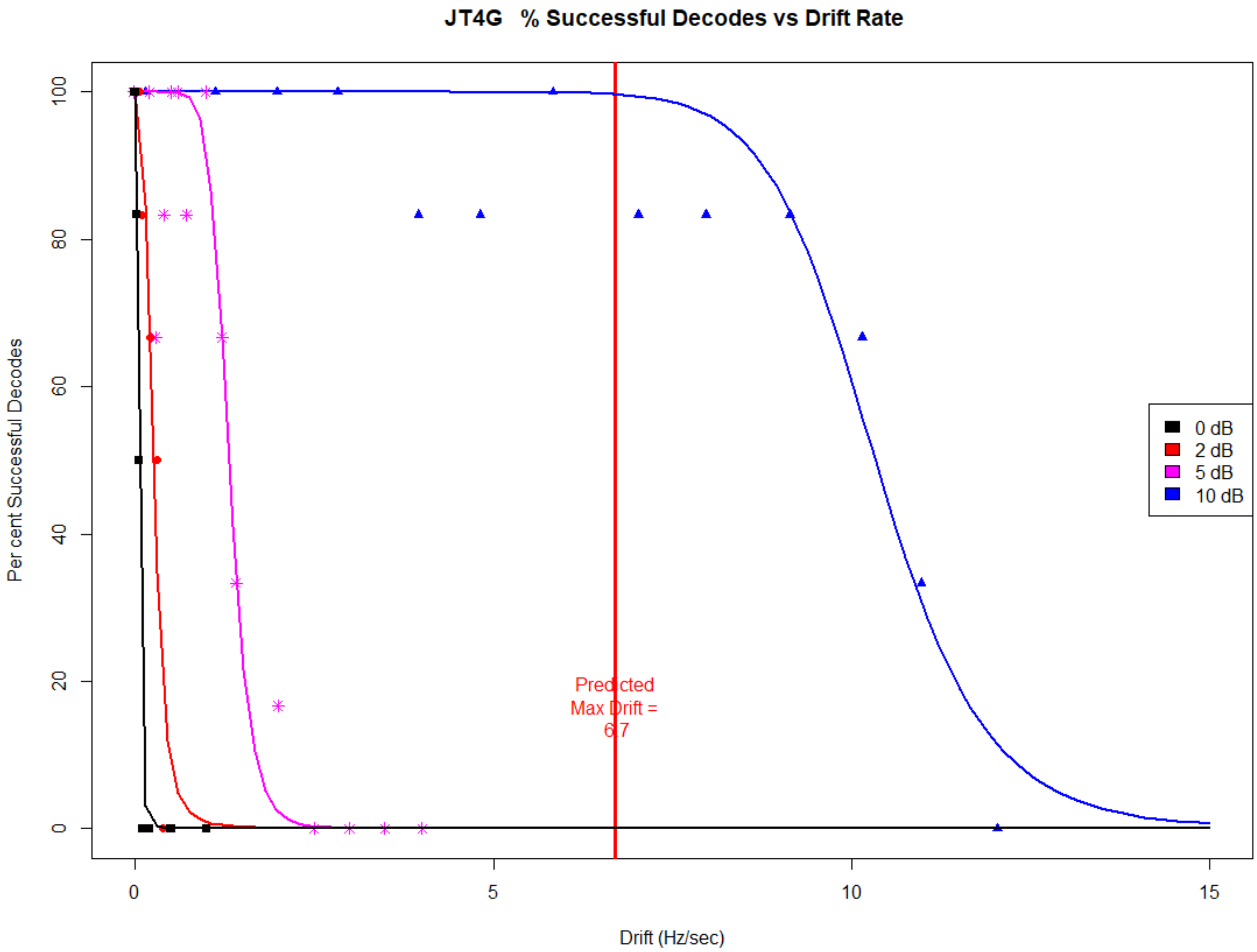
Below is a graph of per-cent successful decodes vs the frequency drift in Hz/Sec for a standard FT8 CQ message at the 4 signal-to-noise levels described above:



The vertical red line at 0.5 Hz/Sec marks the predicted frequency tolerance based on a simple consideration of only tone spacing. You can see that it falls within the range of the frequency shifts that produce 100% successful decoding for the four signal levels. The 0.5 Hz/Sec estimate over-estimates the frequency tolerance for 100% successful decodes at the 0 dB level, but provides a good estimate of the frequency tolerance at the 3 higher signal levels. So with FT8 this tone-spacing-based estimate gives us something that is quite a bit better than just an "order of magnitude" estimate.

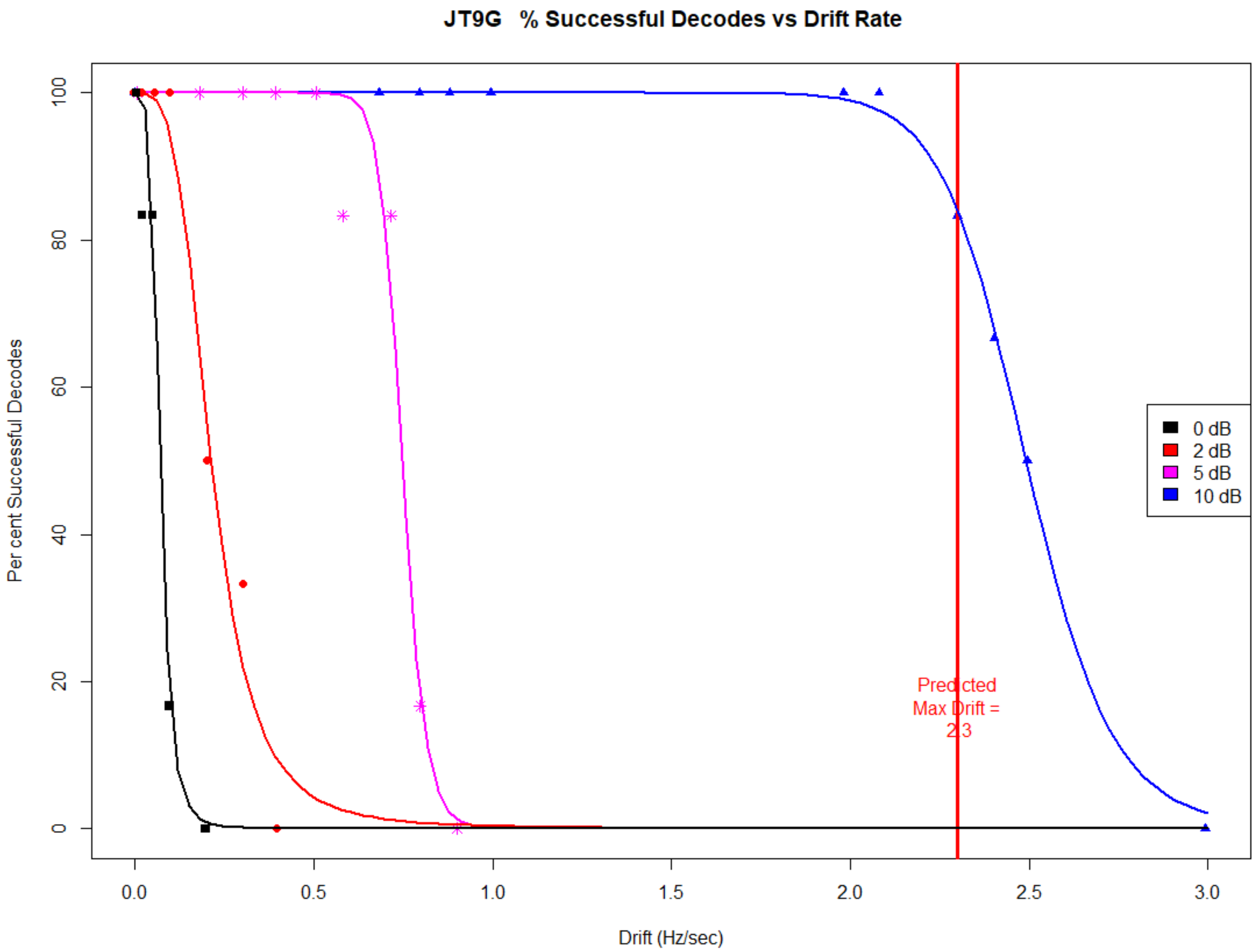
Also, as expected, as signal strength (and signal-to-noise ratio) increases, frequency tolerance increases (improves) substantially.

Next is a graph of per-cent successful decodes vs the frequency drift in Hz/Sec for a standard JT4G CQ message at the 4 signal-to-noise levels described above, presented in the same fashion as was the FT8 graph (but with a much greater X-axis range):



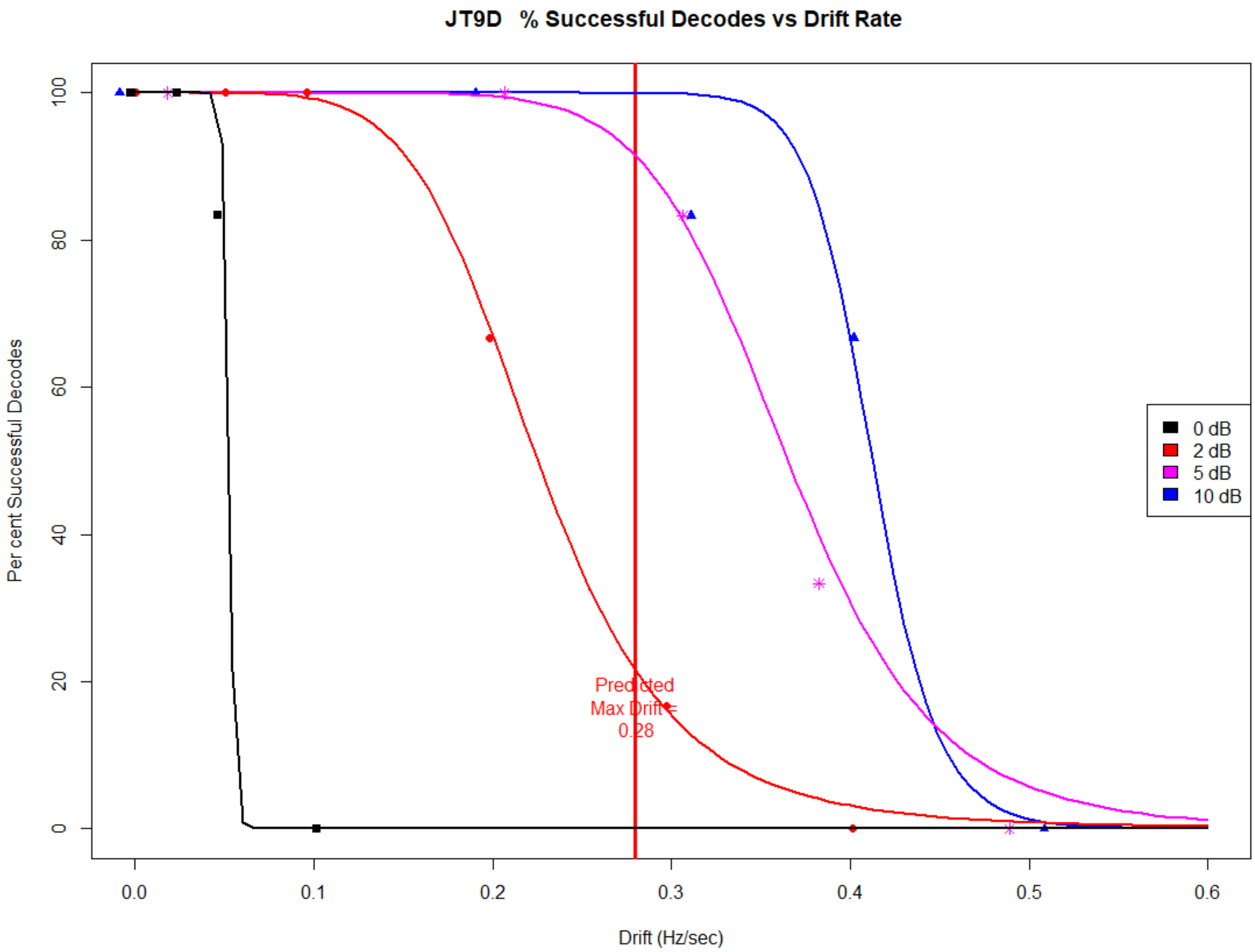
The vertical red line at 6.7 Hz/Sec marks the predicted frequency tolerance based on a simple consideration of only tone spacing. The frequency tolerance of JT4G shows a much wider range as signal levels vary than did FT8; the Frequency tolerance for 100% successful decodes is only 0.05 Hz/Sec at 0 dB, but is 10 Hz/Sec for the 10 dB signal strength level. Again, the tone-spacing-based frequency tolerance prediction overestimates the frequency tolerance at weaker signal strengths. The tone-spacing-based estimate provides a good estimate of frequency tolerance at the 10 dB signal level.

The graphs for JT9G are shown below. These show per-cent successful decodes vs the frequency drift in Hz/Sec for a standard JT9G CQ message at the 4 signal-to-noise levels described above, presented in the same fashion as were the FT8 and JT4G graphs and with an X-axis range that is between the ranges of the two prior graphs:



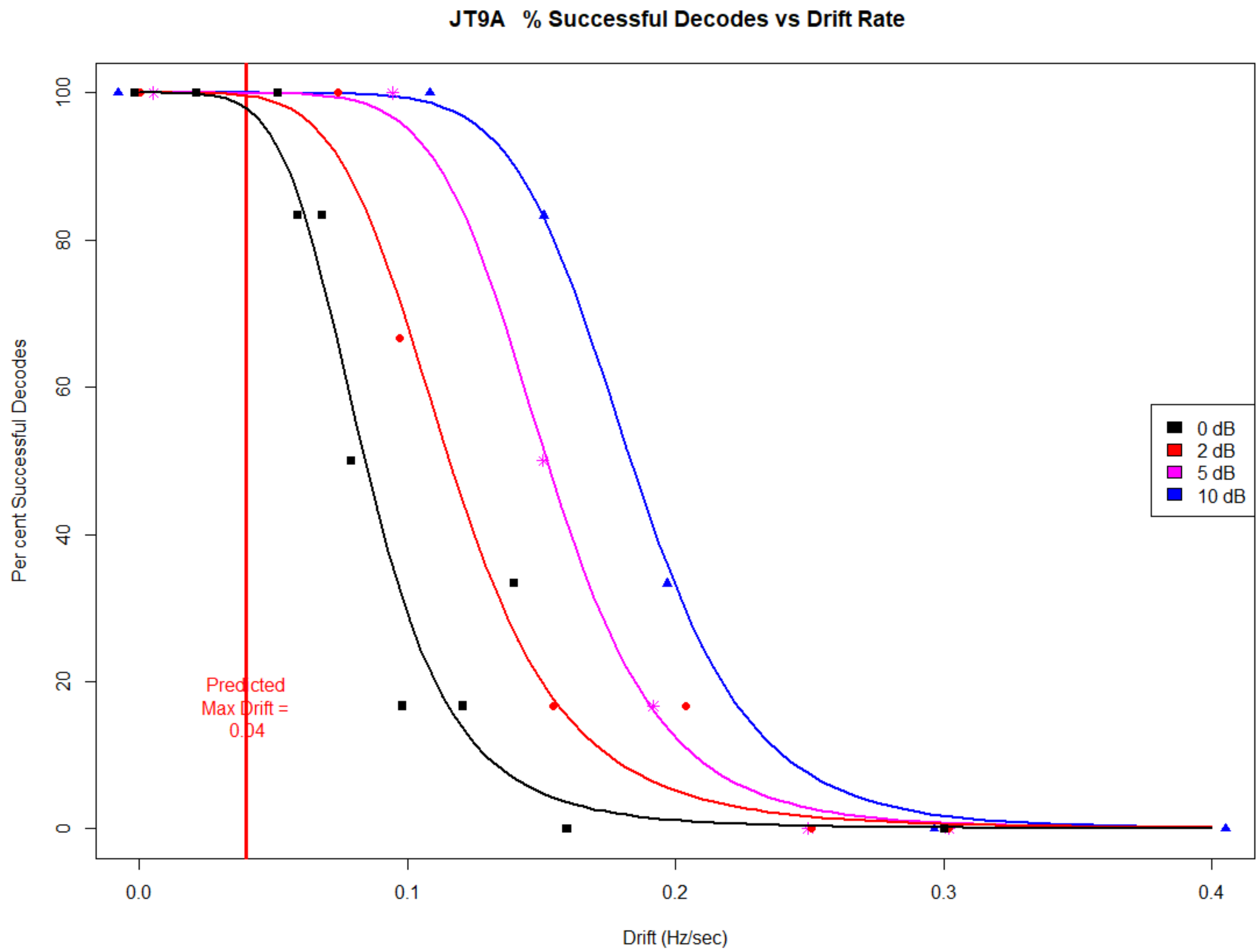
The vertical red line at 2.3 Hz/Sec marks the predicted frequency tolerance based on a simple consideration of tone spacing. The range of variation of frequency tolerance is substantially greater than for FT8, but substantially less than for JT4G. Again in this case the frequency tolerance predicted by the tone spacing is substantially better than just being an order of magnitude estimate. And again, signal strength (actually, signal-to-noise ratio) plays an important role in determining frequency tolerance and must also be considered.

The graphs for JT9D are shown below. These show per-cent successful decodes vs the frequency drift in Hz/Sec for a standard JT9D CQ message at the 4 signal-to-noise levels described above, presented in the same fashion as were the FT8, JT4G, and JT9G graphs and with an X-axis range that is much smaller than the range for any of the previous graphs:



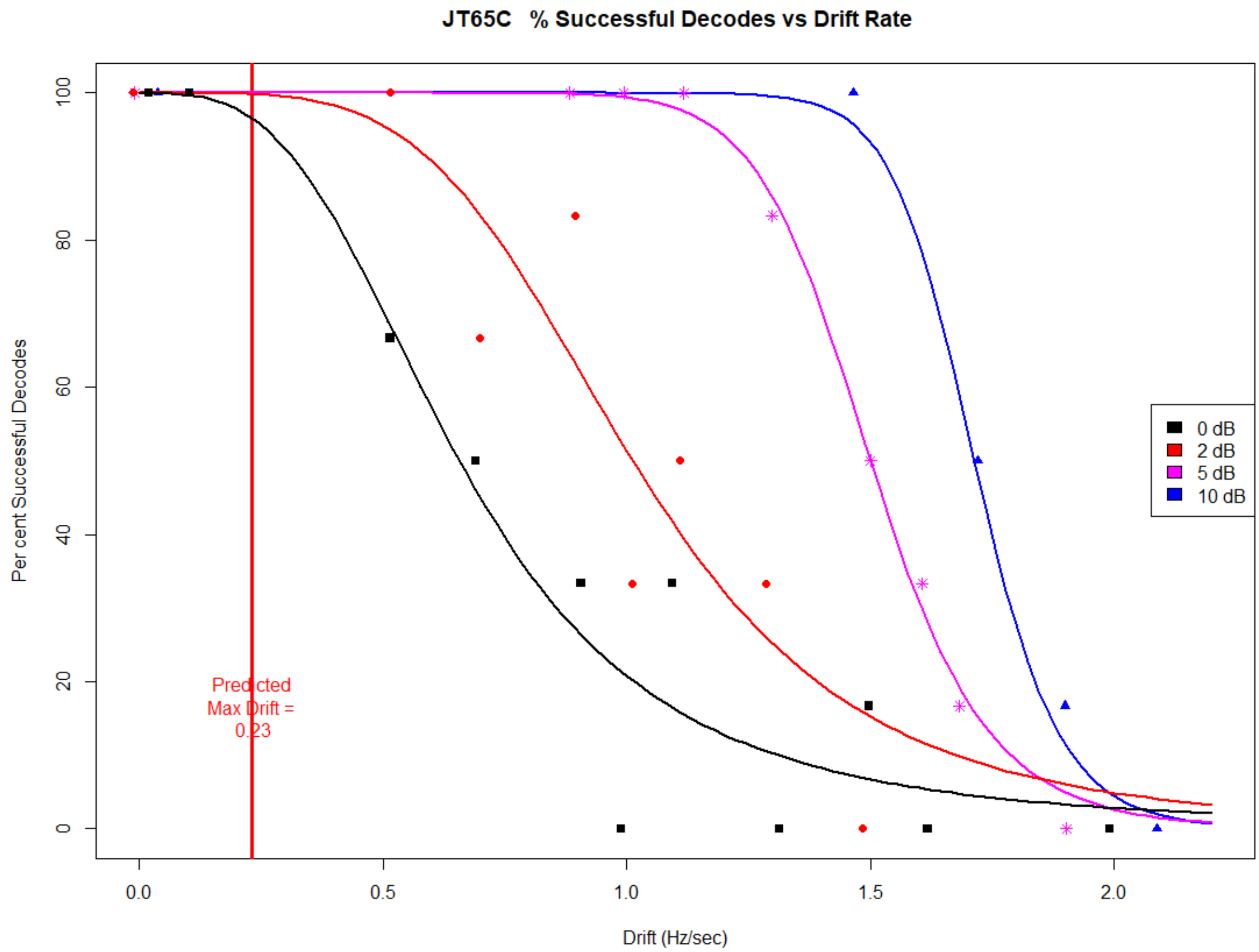
The vertical red line at 0.28 Hz/Sec marks the predicted frequency tolerance based on a simple consideration of tone spacing. Again in this case the tone-spacing-based frequency tolerance prediction is substantially better than just being an order of magnitude estimate. And again, signal strength has a substantial effect of frequency tolerance as well.

The graphs for JT9A are shown below. These show per-cent successful decodes vs the frequency drift in Hz/Sec for a standard JT9A CQ message at the 4 signal-to-noise levels described above, presented in the same fashion as were the FT8, JT4G, JT9G, and JT9D graphs and with an X-axis range that is smaller than the range for any of the other graphs:



The vertical red line at 0.04 Hz/Sec marks the predicted frequency tolerance based on a simple consideration of tone spacing. Again in this case the tone-spacing-based frequency tolerance prediction is substantially better than just being an order of magnitude estimate. And again, signal strength has a substantial effect of frequency tolerance as well.

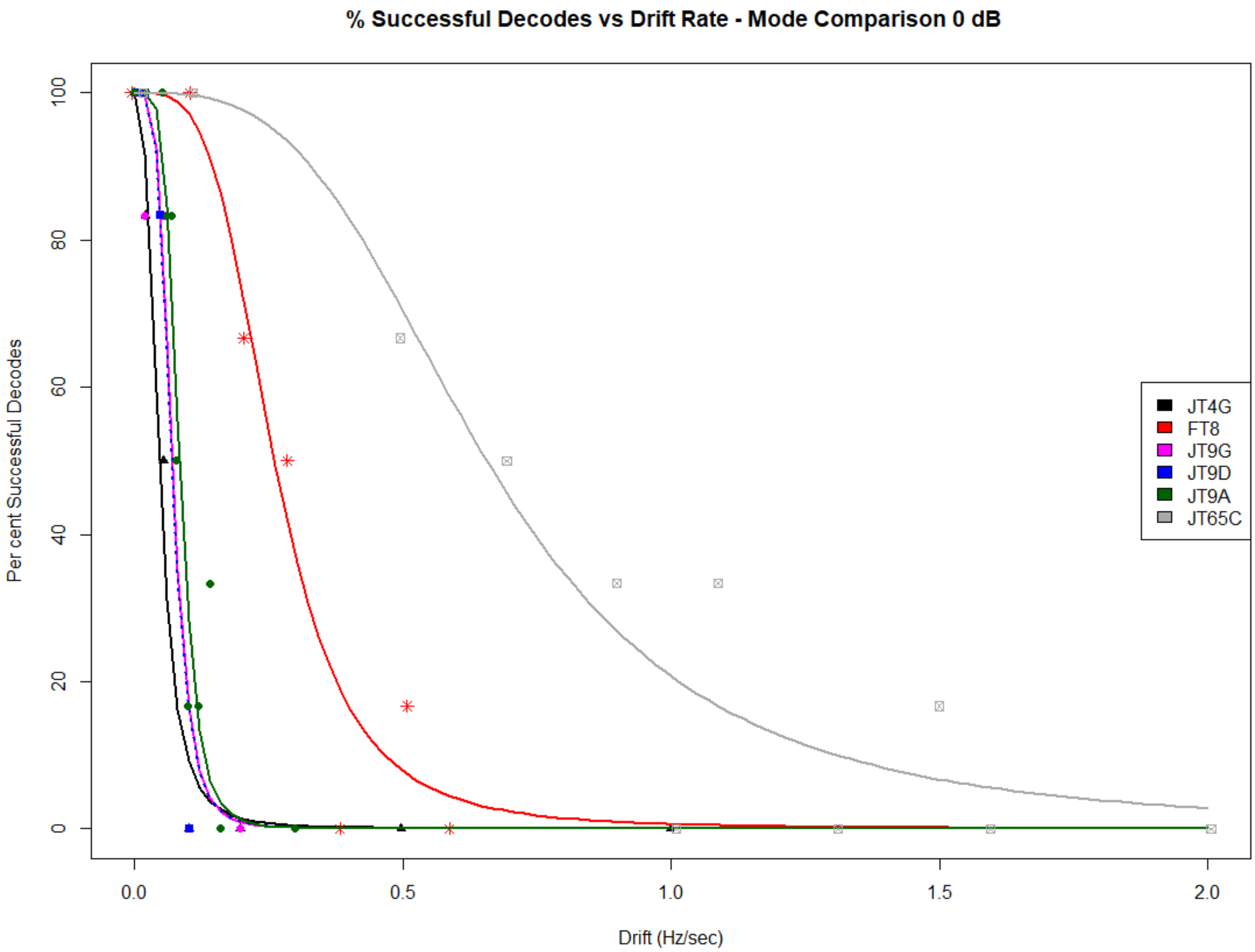
Finally, the graphs for JT65C are shown below. Again, these show per-cent successful decodes vs the frequency drift in Hz/Sec for a standard JT65C CQ message at the 4 signal-to-noise levels described above, presented in the same fashion as were the FT8, JT4G, JT9G JT9D, and JT9A graphs and with an X-axis range that is smaller than the range for the JT4G and JT9G graphs, but roughly double the X-axis range of the FT8 graph and five times the range of the JT9A graph:

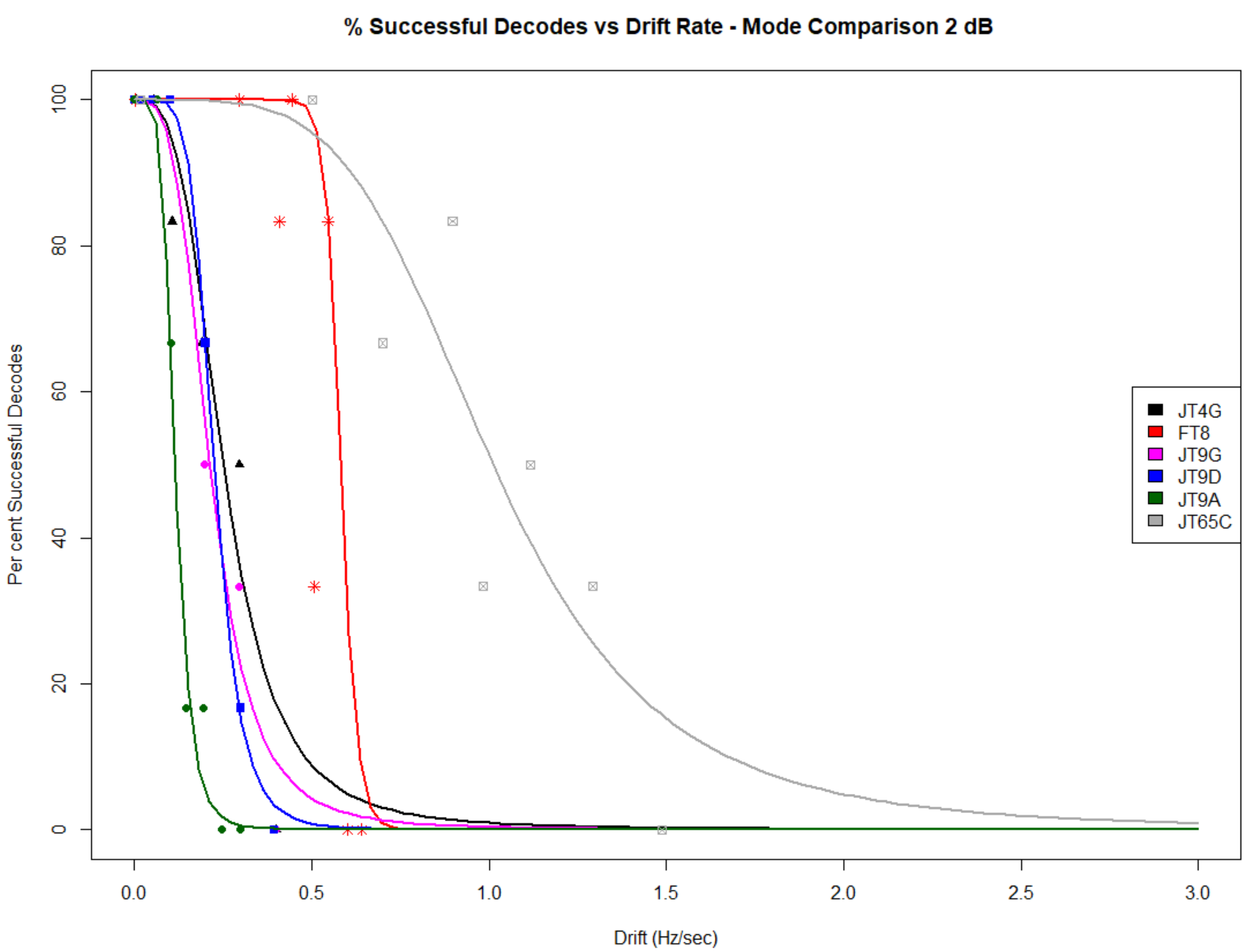


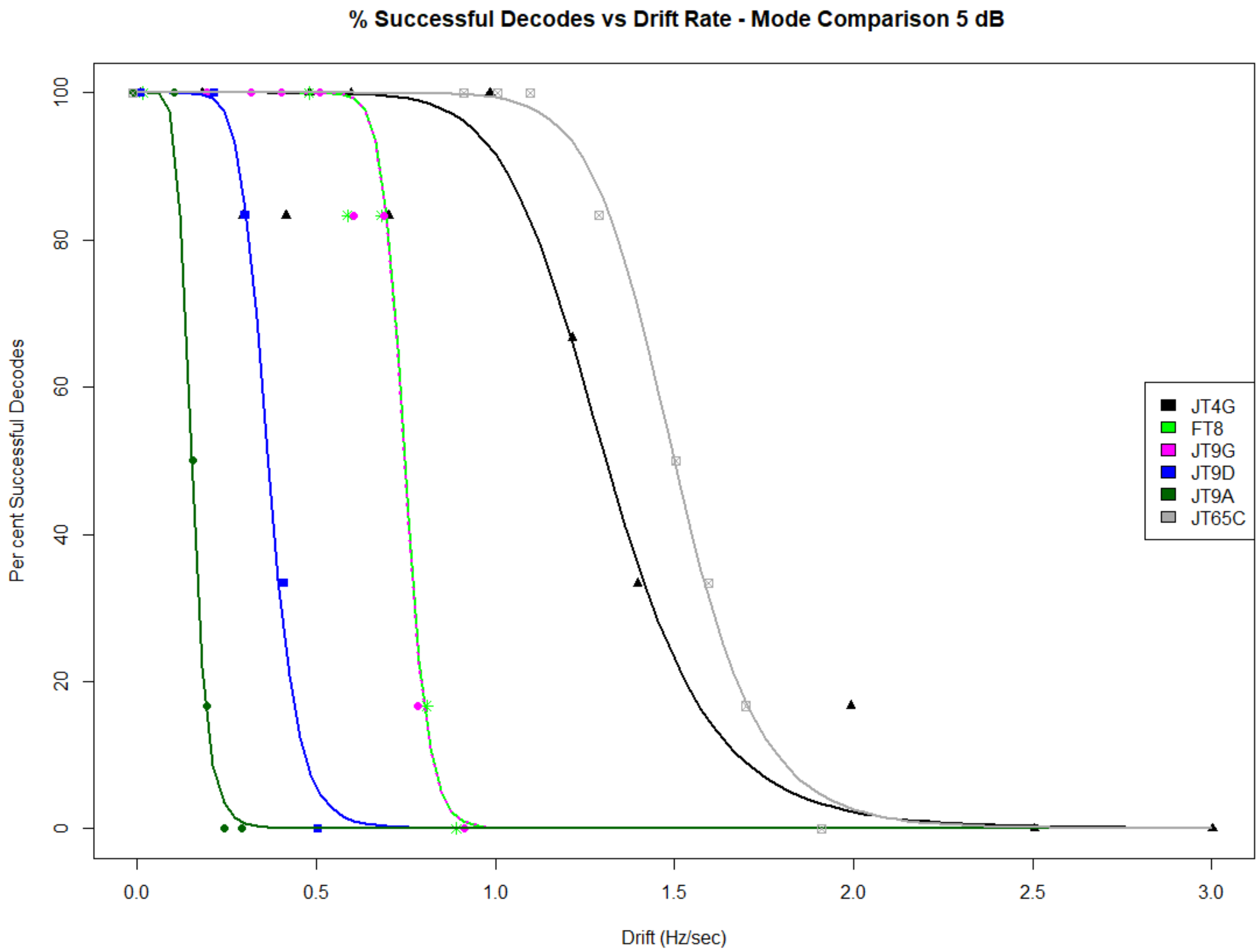
The vertical red line at 0.23 Hz/Sec marks the predicted frequency tolerance based on a simple consideration of tone spacing only. You can see that it significantly underestimates the frequency tolerance of JT65C at all but the threshold level. So while the tone-based frequency tolerance still gives an order of magnitude estimation of the frequency tolerance of JT65C, it does not do nearly as good a job of predicting frequency tolerance for JT65C as it did for the other modes. This may relate at least in part to the “AFC” built into JT65, which would improve its frequency tolerance over that predicted by its tone spacing.

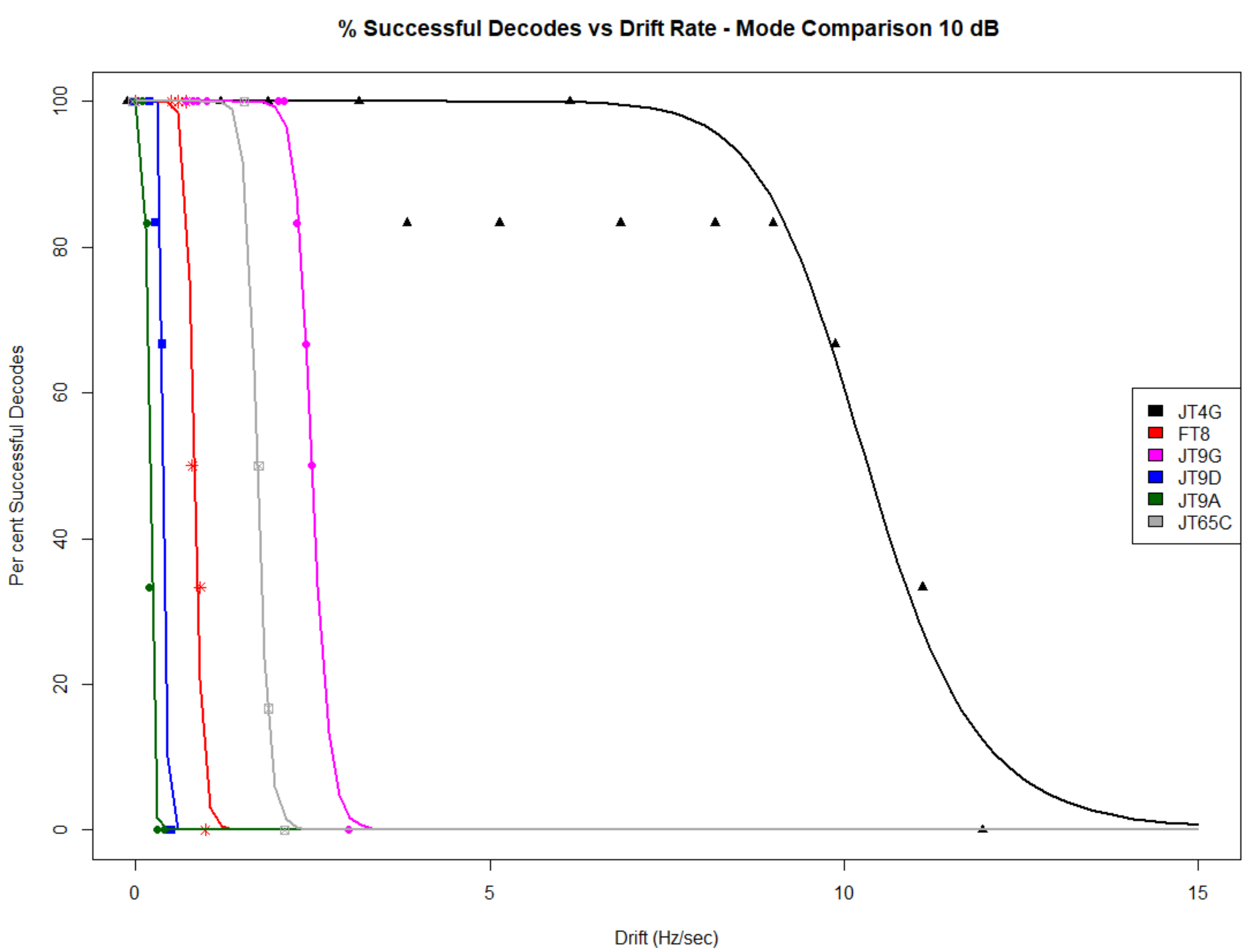
To make it easier to compare the frequency tolerance of the 6 modes tested at each of the signal levels used, 4 graphs are presented on the next 2 pages, one for each of the 4 signal strength levels, with the data for each of the 6 modes tested superimposed on each graph.

You can see in these graphs that near threshold signal levels, FT8 and JT65 perform better than would be expected based on tone-spacing-based predictions, but as signal strength increases the effects of tone spacing become predominant.


% Successful Decodes vs Drift Rate - Mode Comparison 0 dB
Per cent Successful Decodes
Drift (Hz/sec)
0
20
40
60
80
100
0.0
0.5
1.0
1.5
2.0
JT4G
FT8
JT9G
JT9D
JT9A
JT65C


% Successful Decodes vs Drift Rate - Mode Comparison 2 dB
Per cent Successful Decodes
Drift (Hz/sec)
0
20
40
60
80
100
0.0
0.5
1.0
1.5
2.0
2.5
3.0
JT4G
FT8
JT9G
JT9D
JT9A
JT65C


% Successful Decodes vs Drift Rate - Mode Comparison 5 dB
Per cent Successful Decodes
Drift (Hz/sec)
JT4G
FT8
JT9G
JT9D
JT9A
JT65C
0
20
40
60
80
100
0.0
0.5
1.0
1.5
2.0
2.5
3.0


% Successful Decodes vs Drift Rate - Mode Comparison 10 dB
Per cent Successful Decodes
Drift (Hz/sec)
JT4G
FT8
JT9G
JT9D
JT9A
JT65C
0
20
40
60
80
100
0
5
10
15

When reviewing these graphs, remember that the “0 dB” level for each submode is specific to that mode, and dependent on the sensitivity of that mode. That is, the 0 dB level will likely be in the range of -23 JT dB for JT65C (50% success is at -25 JT dB), -15 JT dB for JT4G (50% success is at -17 JT dB), -19 dB for JT9G (50% success is at -21 JT dB), -22 JT dB for JT9D (50% success is at -24 JT dB), -25 dB for JT9A (50% success is at -27 JT dB), and -19 JT dB for FT8 (50% success is at -21 dB), with the 50% success thresholds given here being those presented earlier in this paper, as taken from the WSJT-X Users’ Guide. So the 0 dB results are the results for each mode/submode near the sensitivity threshold FOR THAT MODE/SUBMODE.

In the 0 dB graph above, you can see that at or near the threshold signal strength for each mode, FT8 and JT65C appear to maintain a substantially greater proportion of their frequency tolerance than do JT4G and JT9G.

At 2 dB above threshold, FT8 and JT65C maintain their advantage in this regard.

You can see that at 5 dB above threshold the superior frequency tolerance of JT4G is starting to appear, although JT65 still prevails. The curves for FT8 and JT9G are superimposed at this signal strength level.

And at 10 dB above threshold the frequency tolerance of each mode is well separated from each of the others, with JT4G’s frequency tolerance nearly an order of magnitude better than the remaining modes, with JT9G coming in second, JT65C third, and FT8 fourth. The remaining JT9 sub-modes follow in the order predicted by their respective tone spacings.

Note that the “10 dB” level would represent signals in the range of -13 JT dB for JT65C, -5 JT dB for JT4G, -9 JT dB for JT9G, -12 dB for JT9D, -15 dB for JT9A, and -9 JT dB for FT8, so the frequency tolerance value at the 10 dB level provides an upper bound for the frequency tolerance of each mode, but in practice the results at 0, 2, and 5 dB may represent more useful information as most contacts will likely be with stations with signal-to-noise ratios in the lower signal-to-noise ratio ranges.

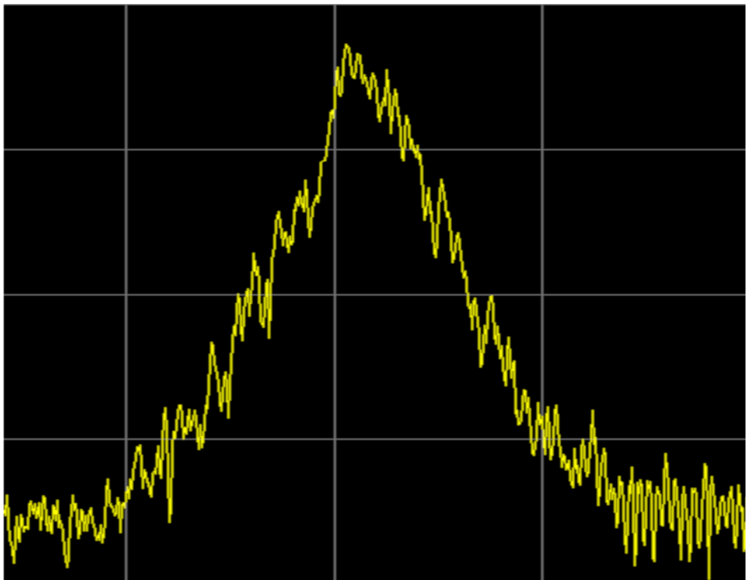
To summarize the frequency tolerance data, we can say that:

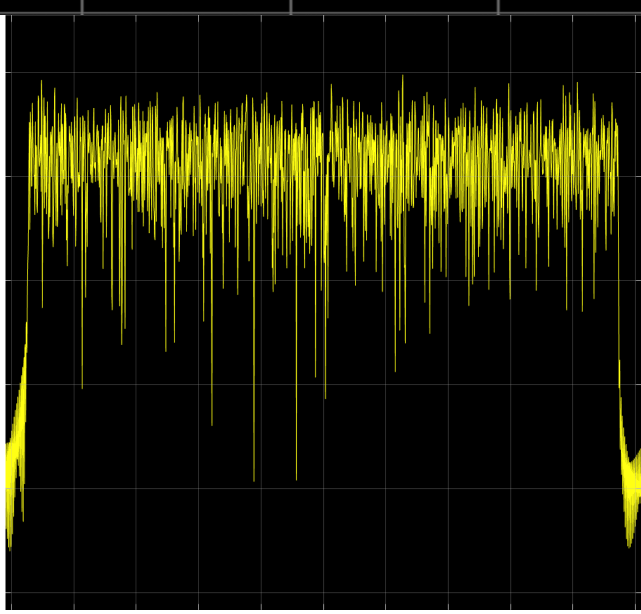
1. Tone spacing <u>does</u> provide a reasonable estimate of the frequency tolerance of the slow modes tested. In general the tone-spacing-based estimate of frequency tolerance overestimates frequency tolerance at weaker signal strengths and it underestimates frequency tolerance at stronger signal strengths. For JT65C, the tone-spacing-based estimate provides a reasonable estimate of frequency tolerance at the threshold level and underestimates frequency tolerance above the threshold level. As noted above, this may be related to the “AFC” built into JT65.
2. Frequency tolerance for a given mode/submode is poorest at the threshold level for detection and improves as signal strength and signal-to-noise ratio increase.
3. FT8 and especially JT65C outperform JT4G and the JT9 sub-modes at the threshold level in terms of their frequency tolerance.
4. At strong signal levels, JT9G and JT4G substantially outperform FT8 and JT65C in terms of their frequency tolerance, as would be expected based on the tone spacings of each of these modes.

The principles and insights gleaned from the frequency drift/shift data on the five modes/submodes presented above can be applied to the remaining slow modes as well.

Frequency <u>dispersion</u> caused by the path or mode of propagation is also an issue. If the frequency of a tone is dispersed (broadened) from a narrow single-frequency tone to a signal with multiple frequency components such as can occur for example with rain scatter, aurora, or with EME when there is libration spreading, then the tone spacing must be chosen so that the frequency extent of the dispersed tone is appropriate for the tone spacing. If a single frequency-dispersed “tone” occupies several tone channels, then proper decoding will be inhibited.

It should be obvious that the spectral characteristics of the spreading will be an important determinant of the effect that a given “amount” of spreading, expressed in Hz, will have on decoding efficiency. One would expect that the effect on decoding efficiency of spreading with a flat frequency profile and sharp skirts, as is shown on the bottom below, would be much greater than would spreading with the same frequency extent, but with a narrow central peak and very gradually tapering shoulders, as shown on the top below.





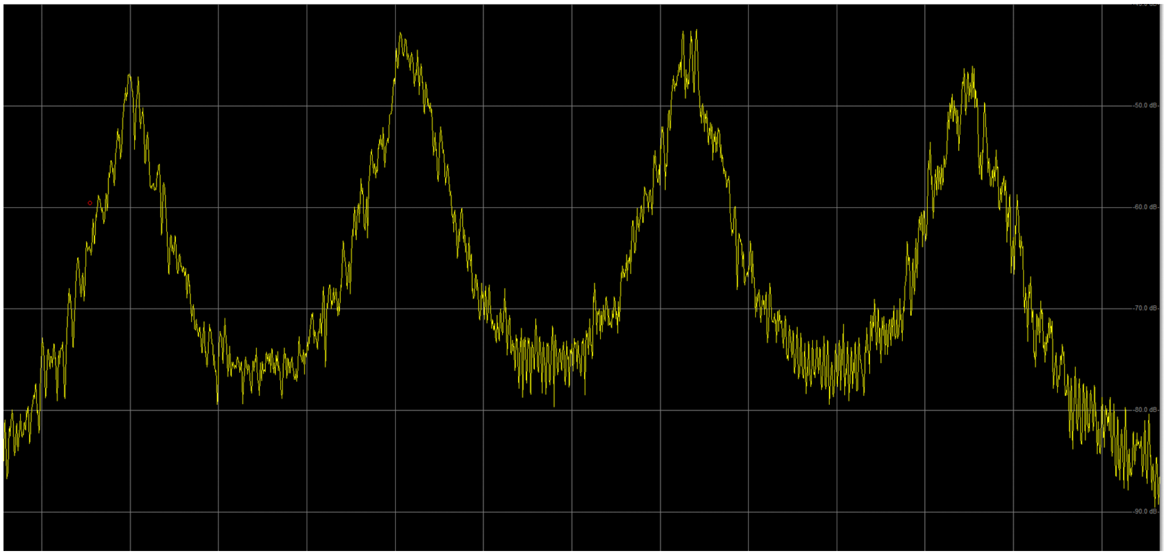
In the evaluation of spreading width presented in this paper, the spectrum of the dispersion produced for this study is that of the upper image on this page, and in fact that spectrum was obtained from the output of one of the dispersion tests performed in the course of preparing this paper. The spectrum presented on the left is one of the broadened tones of a JT4 transmission with 100 Hz tone dispersion, produced by a modified version of WSJT-X, as described in the appendix.

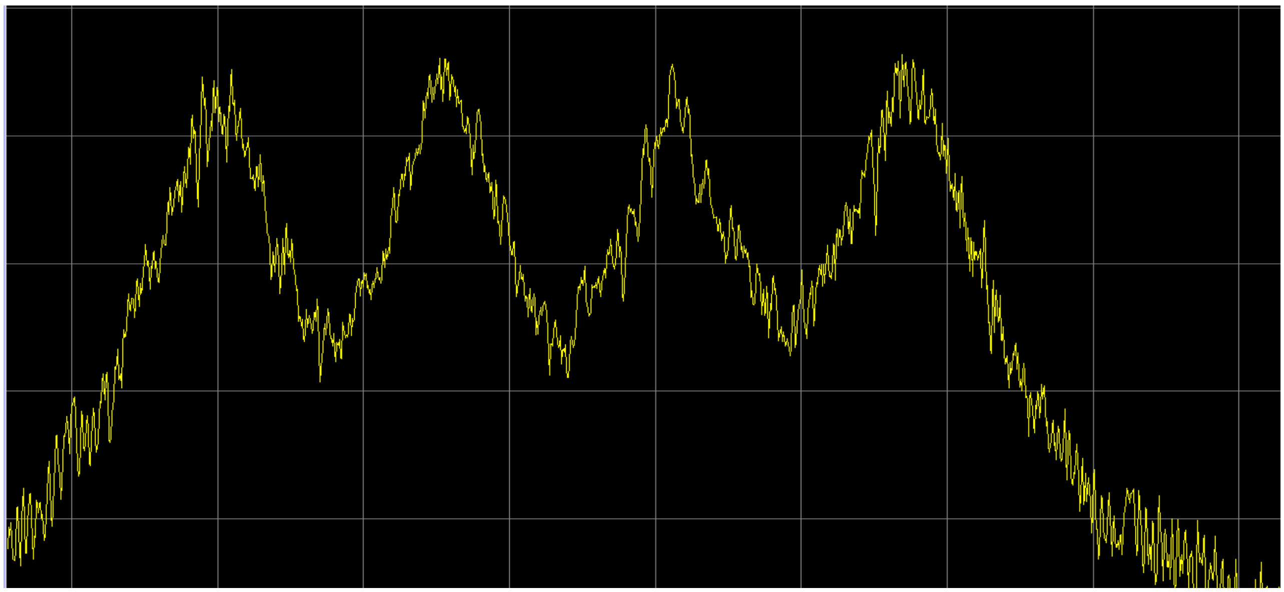
On the next page are the spectra of 3 JT4 transmissions with 100 Hz tone dispersion.

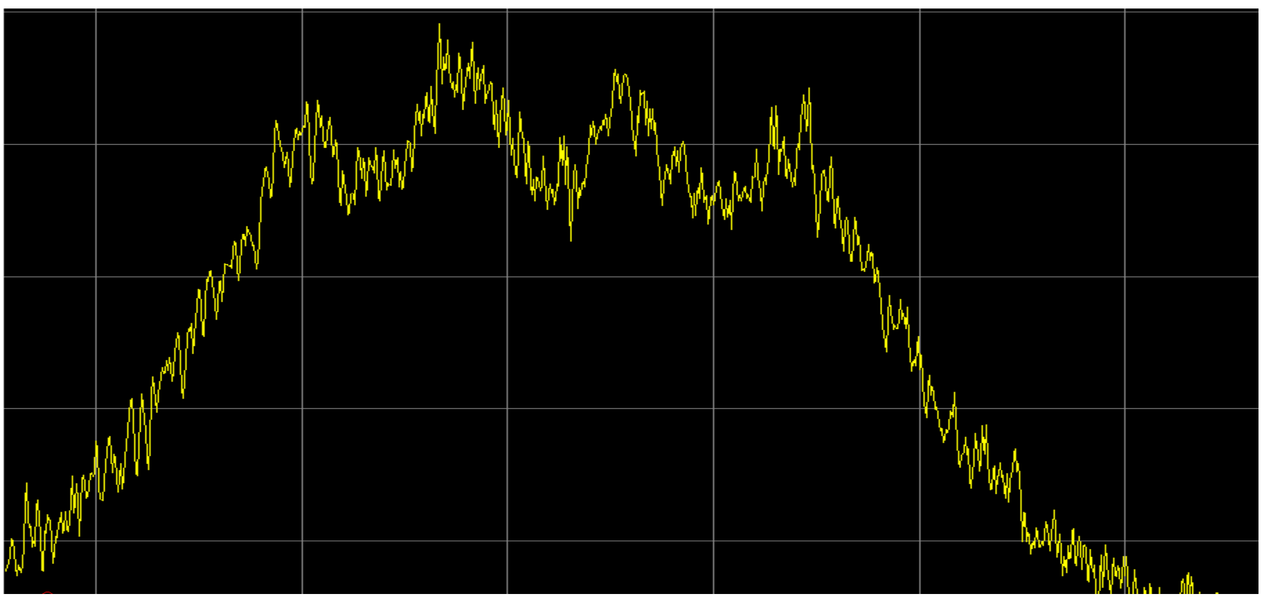
The top spectrum is of JT4G, with 315 Hz tone spacing. You can intuitively see that the 100 Hz tone spreading is not likely to cause problems with signal decoding.

The middle spectrum is of JT4F, with 157.5 Hz tone spacing. You can see that the resolution of the 4 individual tones is more difficult than with JT4G, but still adequate.

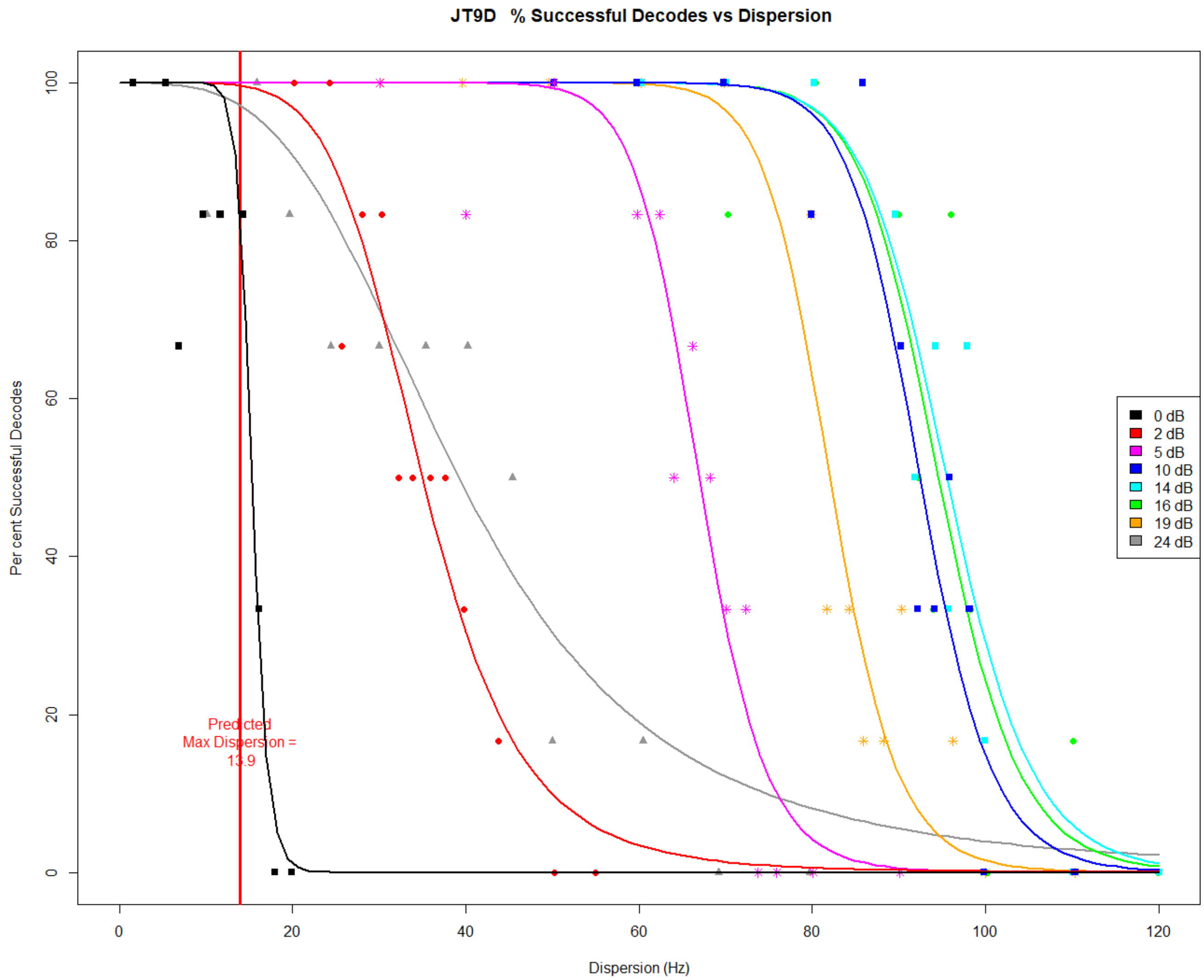
The bottom spectrum is of JT4E, with 78.75 Hz tone spacing. You can see that the resolution of individual tones is now problematic (but visually, at least, not impossible).







On the next pages we will compare the effect of dispersion on decoding efficiency for 3 modes, JT9D, JT9G (Slow), and JT9G-Fast with 15 second TR intervals. The first mode to be discussed will be JT9D. On the next page is a graph of % successful decodes vs signal strength for JT9D.



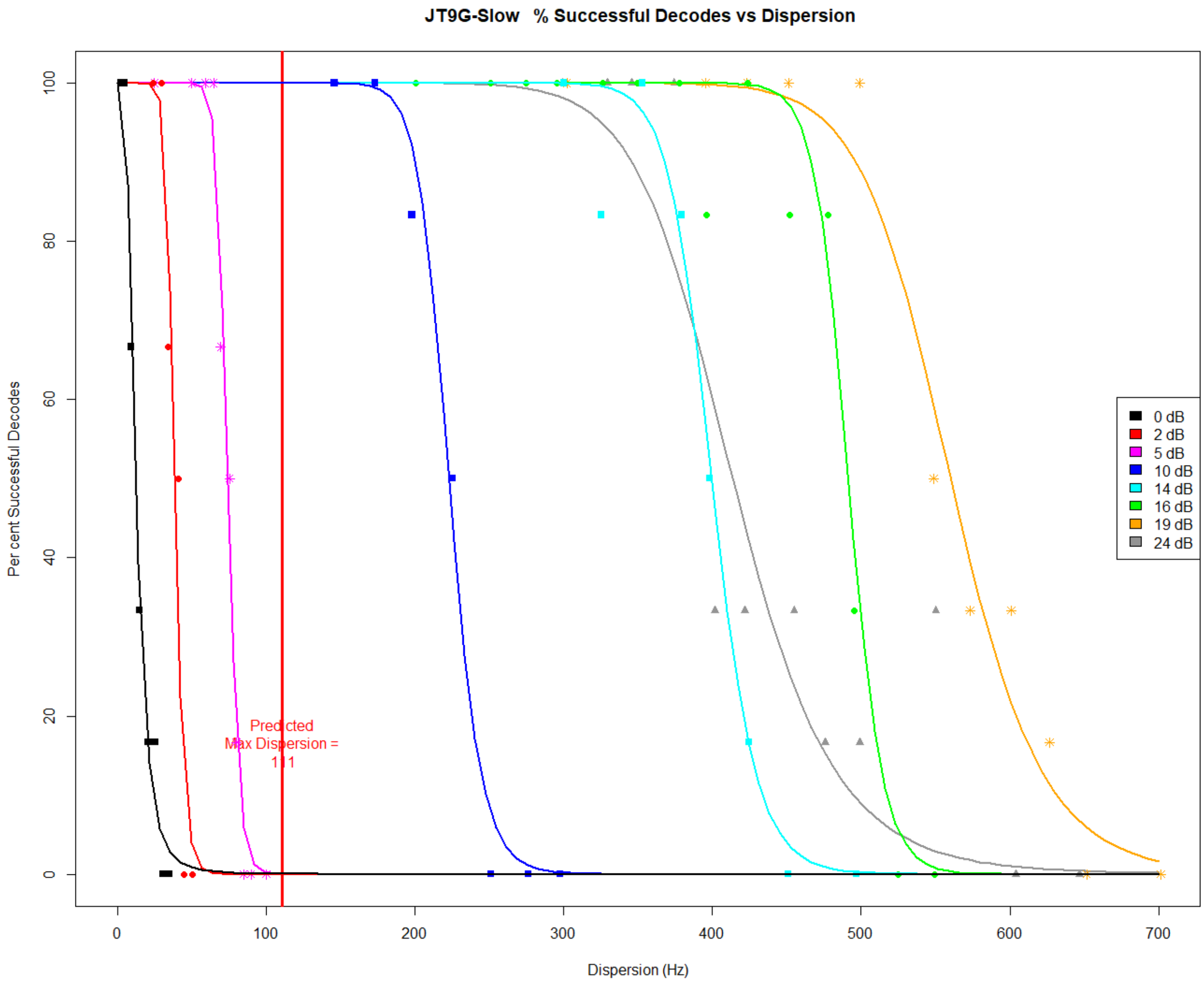
In these graphs the same definitions of signal level are used as were used in the frequency shift experiments described above. Namely, the threshold level of 100% successful detection is defined as "0 dB" for each mode and signal levels above that are defined accordingly.

On the JT9D graph above you can see that the tone spacing of 13.889 Hz overestimates the effect of dispersion on decoding efficiency for all SNR levels except 0, 2, and 24 dB, at least for the shape of the dispersion spectrum used for these tests.

The amount of dispersion tolerated ranges from a bit less than 20 Hz at the 0 dB threshold level to approximately 90 Hz for the 10, 14, and 16 dB levels.

You can see that above these signal levels, at 19 and 24 dB, there is progressively worsening tolerance to tone dispersion as signal strength increases. A similar pattern was seen for JT9G (Slow).

On the next page are the results for JT9G (Slow), presented in similar fashion.

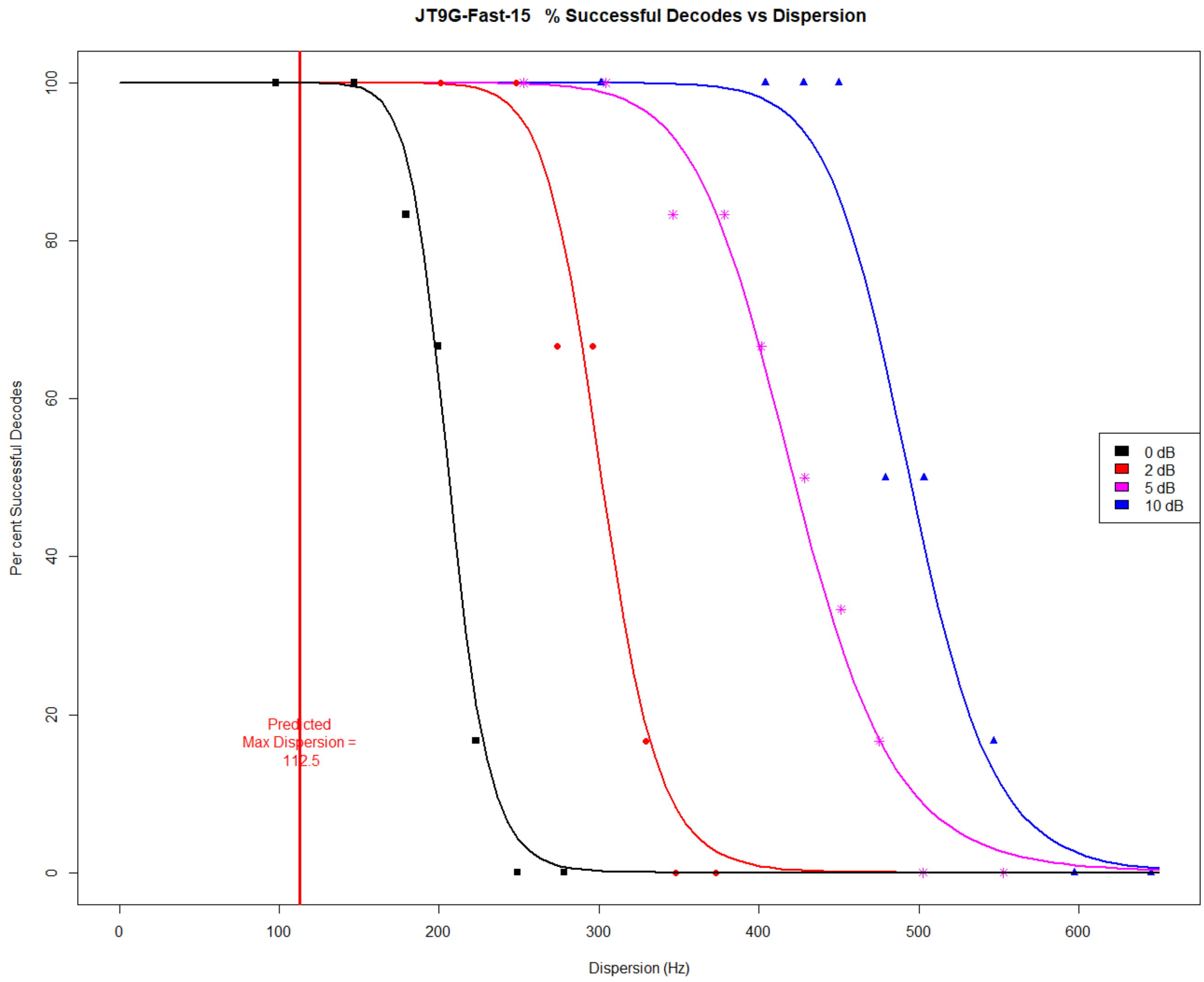


For JT9G the tone-spacing-based estimate of tolerance to dispersion underestimates the effect of dispersion on decoding efficiency for the 0, 2, and 5 dB levels and overestimates the effect of dispersion for the 14, 16, 19, and 24 dB levels. The estimate for 10 dB is appropriate.

The amount of dispersion tolerated by JT9G (Slow) ranges from less than 20 Hz for the threshold 0 dB level to approximately 500 Hz for the 16 and 19 dB levels. The variation of decoding efficiency with SNR is much greater than it was with JT9D.

For JT9G, there is less of a degradation of decoding efficiency at 19 and 24 dB than was seen with JT9D, although there was still a clear-cut deterioration at 24 dB as compared to 19 dB, with the 24 dB level decoding efficiency being similar to that of the 14 dB level.

On the next page is the graph of decoding efficiency vs dispersion for JT9G-Fast 15, which has essentially the same tone spacing as JT9G (Slow).



You can see that for JT9G-Fast the tone-spacing-based prediction of dispersion tolerance is accurate for the threshold 0 dB level, but underestimates the dispersion tolerance of JT9G-Fast at higher signal levels.

The range of dispersion tolerance is from 200 Hz at the threshold level to 500 Hz at the 10 dB level.

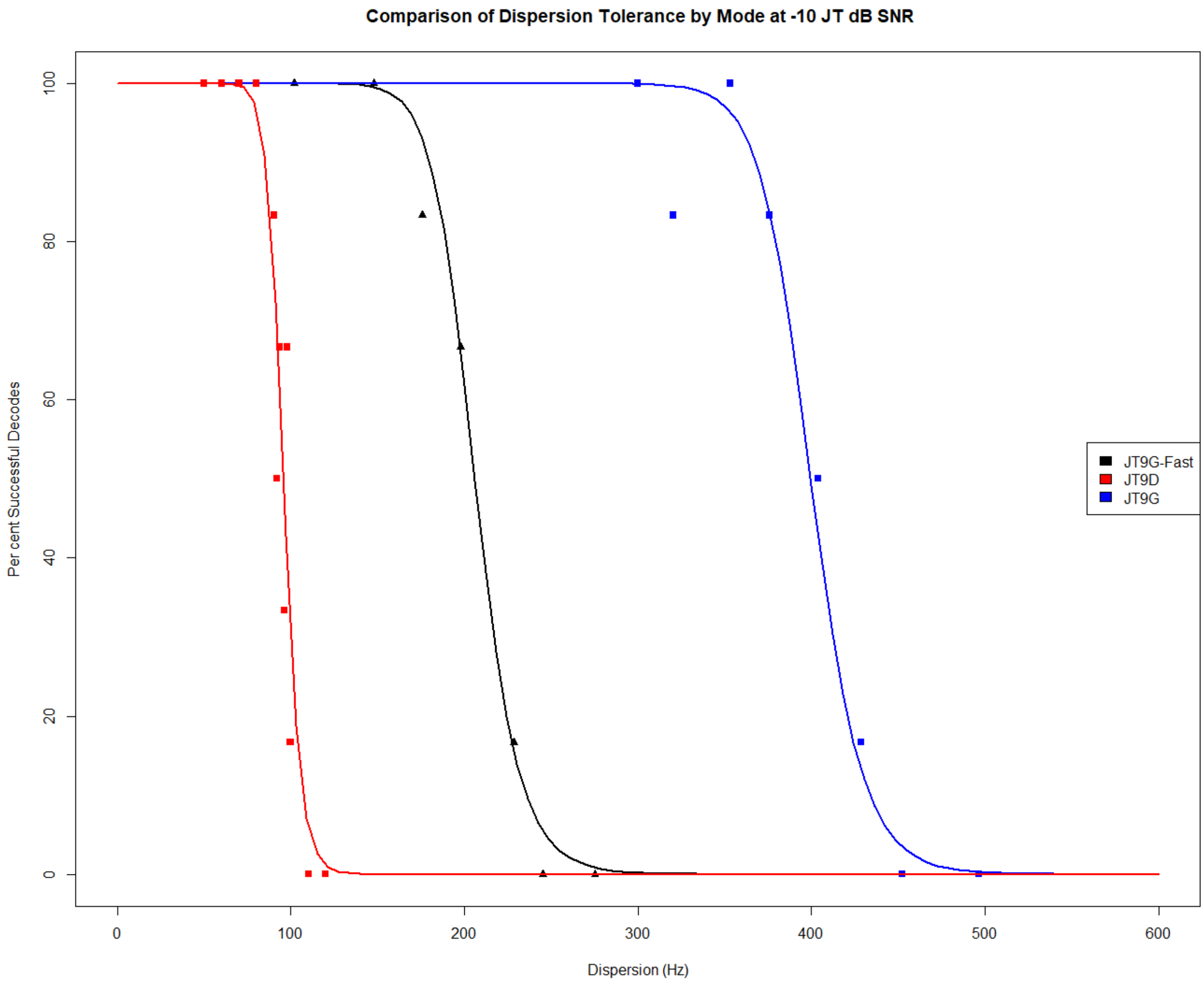
Higher signal levels, which would have been in the positive JT dB range of signal levels, were not tested for JT9G-Fast.

Note that the “best” performances of JT9G (Slow) and JT9G-Fast in terms of dispersion tolerance were similar, at approximately 500 Hz dispersion. As you will see below, and as expected based on theoretical considerations, this congruence of the results for these two related modes is very different from what we will find when we compare the tolerance of these two modes to frequency shift.

Comparisons among the modes can be performed in two ways. The first method, which I chose to use for comparisons of frequency shift, is to compare each mode with the others at equivalent signal levels for each mode relative to the threshold for each mode. The second method, which I use below for further dispersion comparisons, is to compare mode performance at the same absolute signal level for each mode.

Below are graphs comparing the 3 modes for absolute signal to noise levels of 0, -5, -8, and -10 JT dB units. These levels were chosen because they represent, respectively, the 10, 5, 2, and 0 dB levels for JT9G-Fast, which is the least sensitive of the 3 modes whose dispersion tolerance characteristics are being compared here. As there are only 3 modes being compared here, you can easily perform the threshold-based comparisons yourself if you wish by viewing the 3 graphs above.

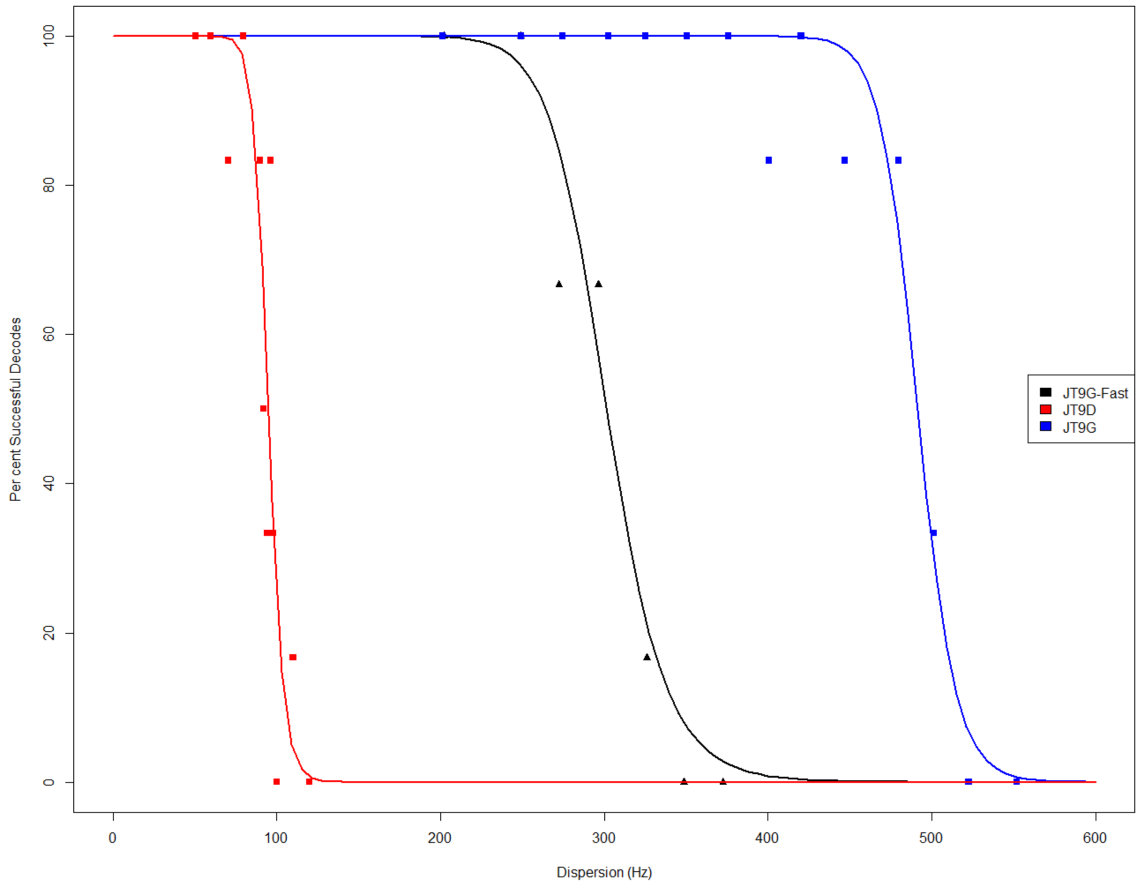
Here is the graph for the -10 JT dB signal level for JT9D, JT9G (Slow), and JT9G-Fast:



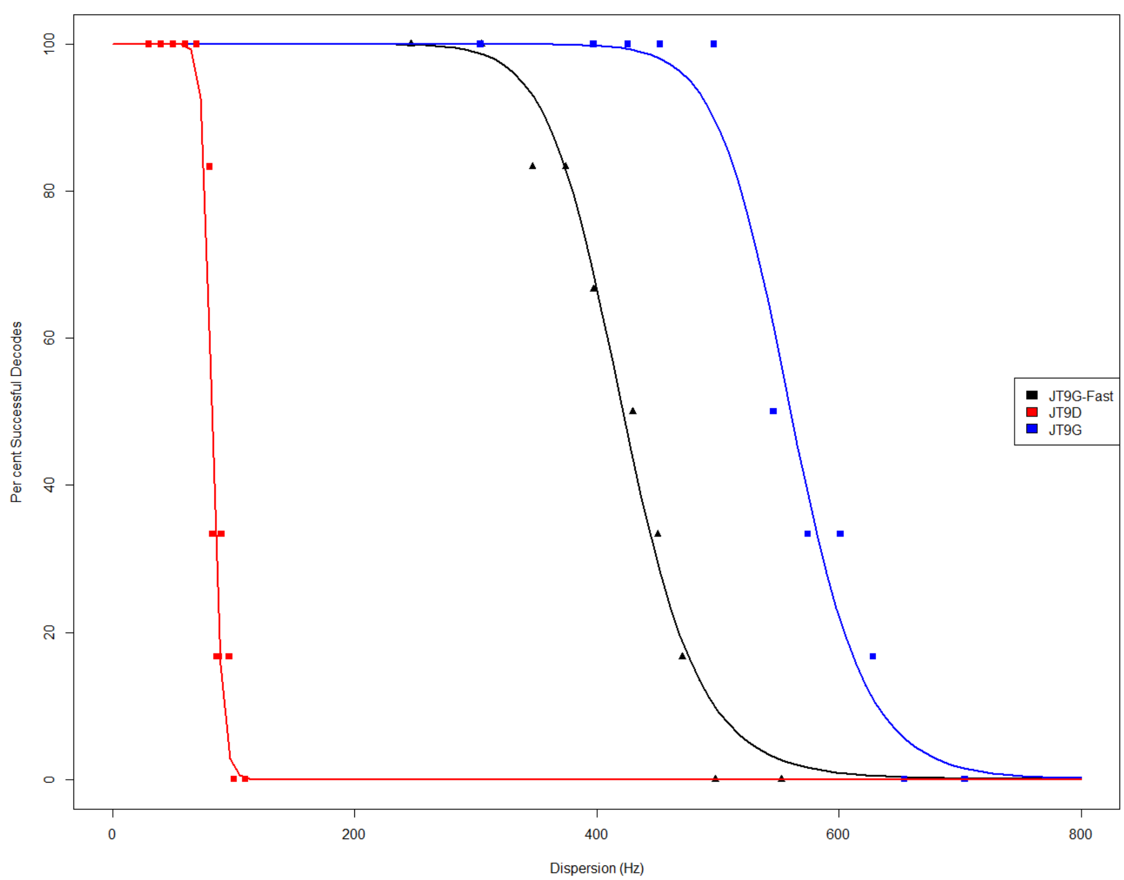
You can see that at this signal level, the threshold level for JT9G-Fast, JT9G (Slow) substantially outperforms JT9G-Fast in spite of the fact that they have essentially identical tone spacings. Both modes outperform JT9D, which has a much smaller tone spacing.

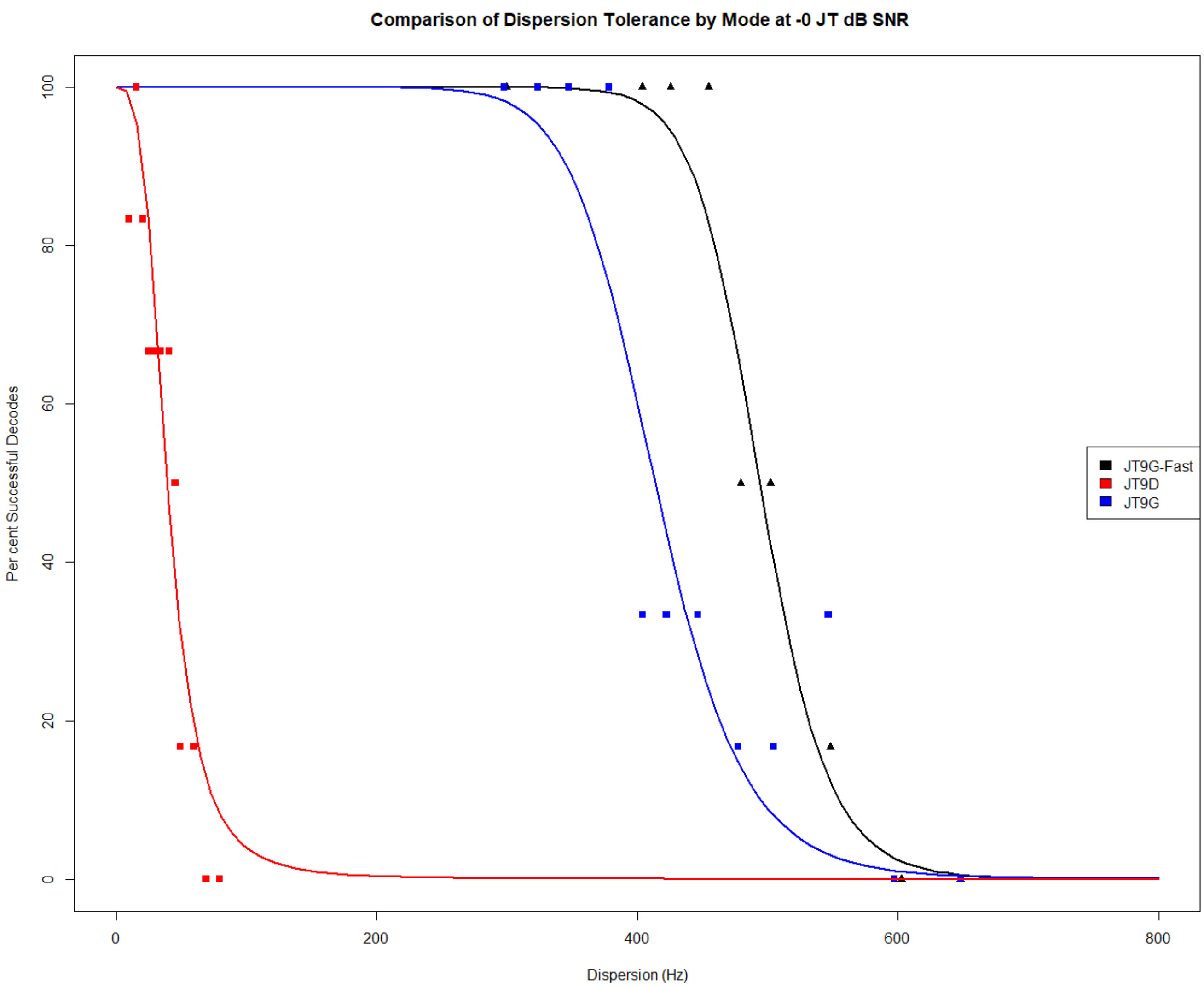
On the next page are comparisons for the -8 and -5 JT dB signal levels. At both of these signal levels JT9G (Slow) retains its advantage over JT9G-Fast, although with each increase in signal level the difference narrows. And at the 0 dB JT signal level, JT9G-Fast has superior performance to JT9G (Slow) in terms of its dispersion tolerance, and you can see in the final graph in this section, on the following page. This is because JT9G-Fast's performance continues to improve as the signal level increases from -5 to 0 dB, while JT9G (Slow) has declining performance.

Comparison of Dispersion Tolerance by Mode at -8 JT dB SNR



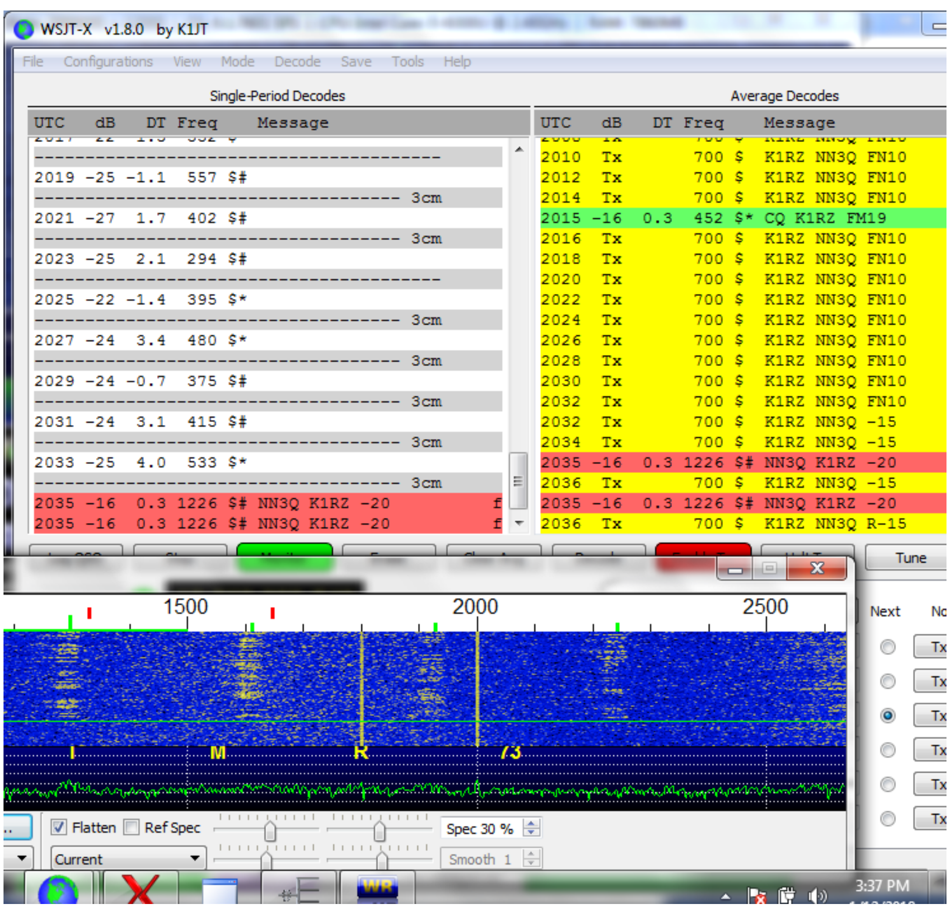
Comparison of Dispersion Tolerance by Mode at -5 JT dB SNR





Comparison of Dispersion Tolerance by Mode at -0 JT dB SNR
Per cent Successful Decodes
Dispersion (Hz)
0
20
40
60
80
100
0
200
400
600
800
JT9G-Fast
JT9D
JT9G

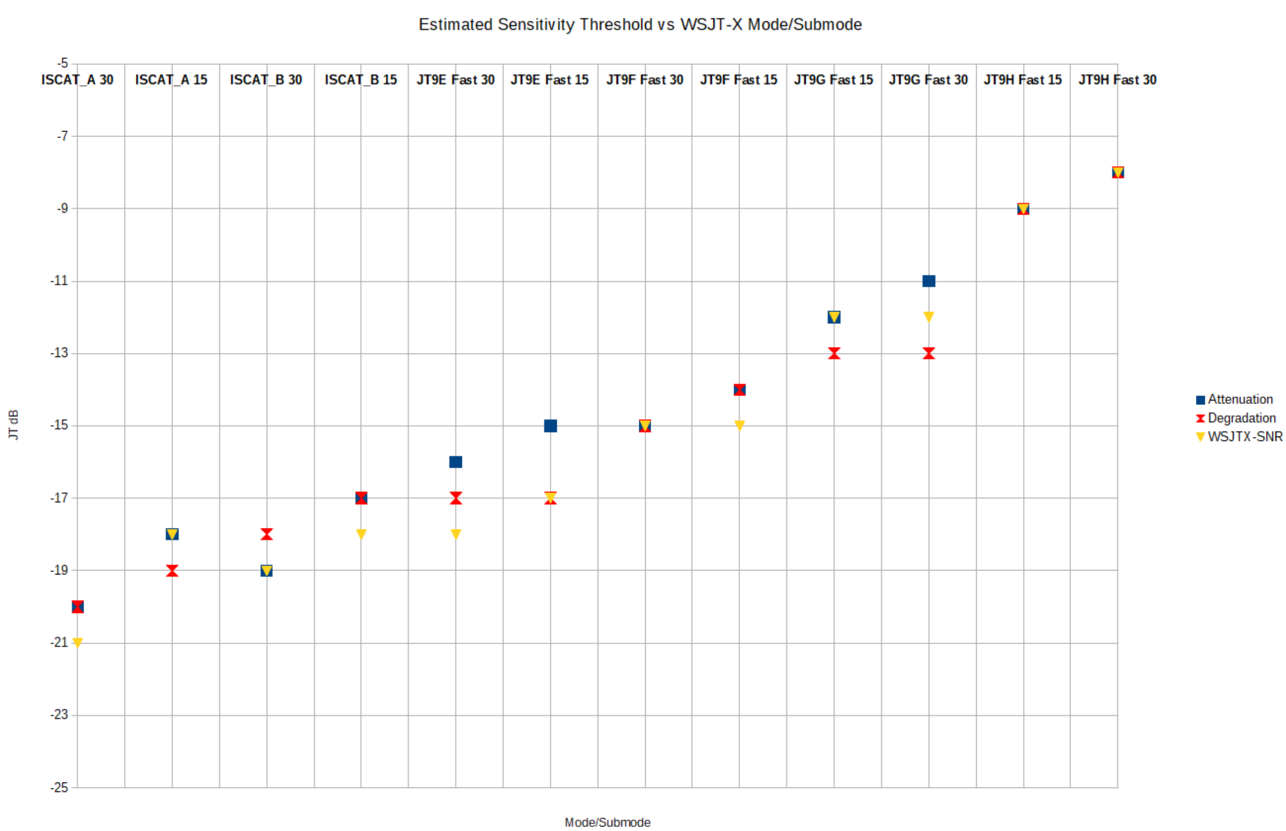
Below is an example of how the frequency characteristics of the path/mode selected for a QSO attempt affect the choice of mode and submode. In January, 2018 while helping the NN3Q/R team get setup prior to that month's contest, I happened to be out in their rover van during a rainstorm. Dave, K1RZ, was kind enough to get on the air so that we could try a rainscatter 10 GHz digital contact. I expected that there would be a lot of dispersion as there was no direct path to Dave, and the entire signal would be rain-scattered. Not knowing how much frequency dispersion we were going to encounter, I chose to use JT4G, as it has the largest available tone spacing of any JT mode, 315 Hz, and I thus expected that it would have the best tolerance to the anticipated frequency dispersion. It has a specified sensitivity of -17 dB, so by choosing the extremely wide tone spacing, we were sacrificing up to 10 dB by not choosing a mode with narrower tone spacing and greater sensitivity. As you can see from the waterfall in the figure below (the received tones are at approximately 1300 Hz, 1615 Hz, 1930 Hz, and 2245 Hz), the frequency dispersion that we actually encountered was on the order of 50 Hz, and there was no appreciable drift or Doppler. So I likely could have used any mode with tone spacing of 50 Hz or more and didn't need the greater-than-300-Hz tone spacing provided by JT4G. Specifically, considering just the simplistic "Max Drift" values in the tables above, we likely could have used JT4E (78.5 Hz tone spacing, -19 dB sensitivity), JT4F(157.5 Hz tone spacing, -18 dB sensitivity, JT9F (tone spacing 55.6 Hz, sensitivity -22 dB), JT9G (tone spacing 111.1, sensitivity -21 dB), or JT9H (tone spacing 222.2 Hz, sensitivity -20 dB) all of which would have provided adequate tone spacing, and each of which would have provided greater sensitivity than did JT4G. But we were lucky and we had enough received signal strength to complete the contact with JT4G. If signals had been too weak for us to complete the QSO using JT4G, we likely would have been successful with the more-sensitive JT9F or one of the other modes just mentioned.



III. Specific Mode/Sub-mode Characteristics: Fast Modes

Sensitivity The fast modes are substantially less sensitive than the slow modes. Their sensitivities are not given in the WSJT-X User Guide, likely because of the complications introduced by their “intelligent” decoders, which adjust the receive algorithm to the characteristics of the particular signal being received.

I used three methods to derive estimates of the sensitivity threshold for each of the Fast Modes/Submodes. The details of these methods are described in the appendix. The methods have good agreement, and the value of the sensitivity threshold shown for each mode/submode in the table below was derived from the averaged results of the three methods, as described in the appendix. The first method (“AWGN”) used MATLAB to add known, incremental amounts of white Gaussian Noise to the audio file generated by WSJT-X for a typical CQ message and indexed the signal-to-noise values for those files to the signal-to-noise value for JT9D in order to determine the estimated threshold SNR for each fast mode/submode. The second method (“Attenuation”) used actual transmission and reception of RF signals at 435 MHz with incremental attenuation added to the RF path in order to determine the sensitivity threshold for each mode/submode. Again, the value obtained for each mode/submode was indexed to the value obtained for JT9D. The third method used a modified version of WSJT-X to add known amounts of white Gaussian noise to the generated audio signal. Calculations were also performed for the FT8 and JT9E-Slow modes using these methods, as a check on the validity of these methods. A graphical comparison of the results obtained for each of the Fast modes/submodes with these three methods is shown below:



You can see that there is excellent agreement among the three methods.

The table below shows the estimated sensitivities for the fast modes as determined by these experiments, in descending order of sensitivity.

Mode	Degradation from JT9D dB	Sensitivity JT dB	Tone Spacing Hz
ISCAT-A 30	4	-20	21.5
ISCAT-B 30	5	-19	43.1
ISCAT-A 15	6	-18	21.5
ISCAT-B 15	6	-18	43.1
JT9E Fast 30	6	-18	28.1
JT9E Fast15	7	-17	28.1
JT9F Fast 30	9	-15	56.25
JT9F Fast 15	9	-15	56.25
JT9G Fast 15	12	-12	112.5
JT9G Fast 30	12	-12	112.5
JT9H Fast 15	15	-9	225
JT9H Fast 30	16	-8	225

The second column shows the degradation in sensitivity of each mode relative to JT9D, rounded to the nearest integer. The third column shows the experimentally-determined estimated sensitivity threshold for each mode. The fourth column gives the tone spacing for each mode/sub-mode listed, as obtained from the Protocols section of the WSJT-X User Guide. Note that the tone spacing for the Fast JT9 modes is very slightly (0.3-3 Hz) different than the tone spacing for the corresponding JT9 slow modes. As you can see, in general the sensitivity decreases from mode-to-mode as the tone spacing increases.

Except for JT9H, the frequency tolerance of the 15 and 30 second versions of each submode were not significantly different at the p=0.05 level. Therefore, the results of the 15 and 30 second versions of each mode were pooled for inter-mode comparisons, except for JT9H. The frequency tolerance of ISCAT-B was not significantly different from that of JT9E-Fast. With that exception, each mode had significantly different frequency tolerance from its neighbors in the table above at the p=0.05 level. All p values were corrected for multiple comparisons.

The JT9 Fast modes are substantially less sensitive than their slow-mode counterparts, and the difference in sensitivity is greater for the submodes with greater tone spacing as can be seen in the table below, derived from the data above:

Mode	Tone spacing	Slow mode sensitivity dB	Fast mode sensitivity dB	Delta dB
JT9E	28	-23	-18	5
JT9F	56	-22	-15	7
JT9G	111/113	-21	-12	9
JT9H	222/225	-20	-9	11

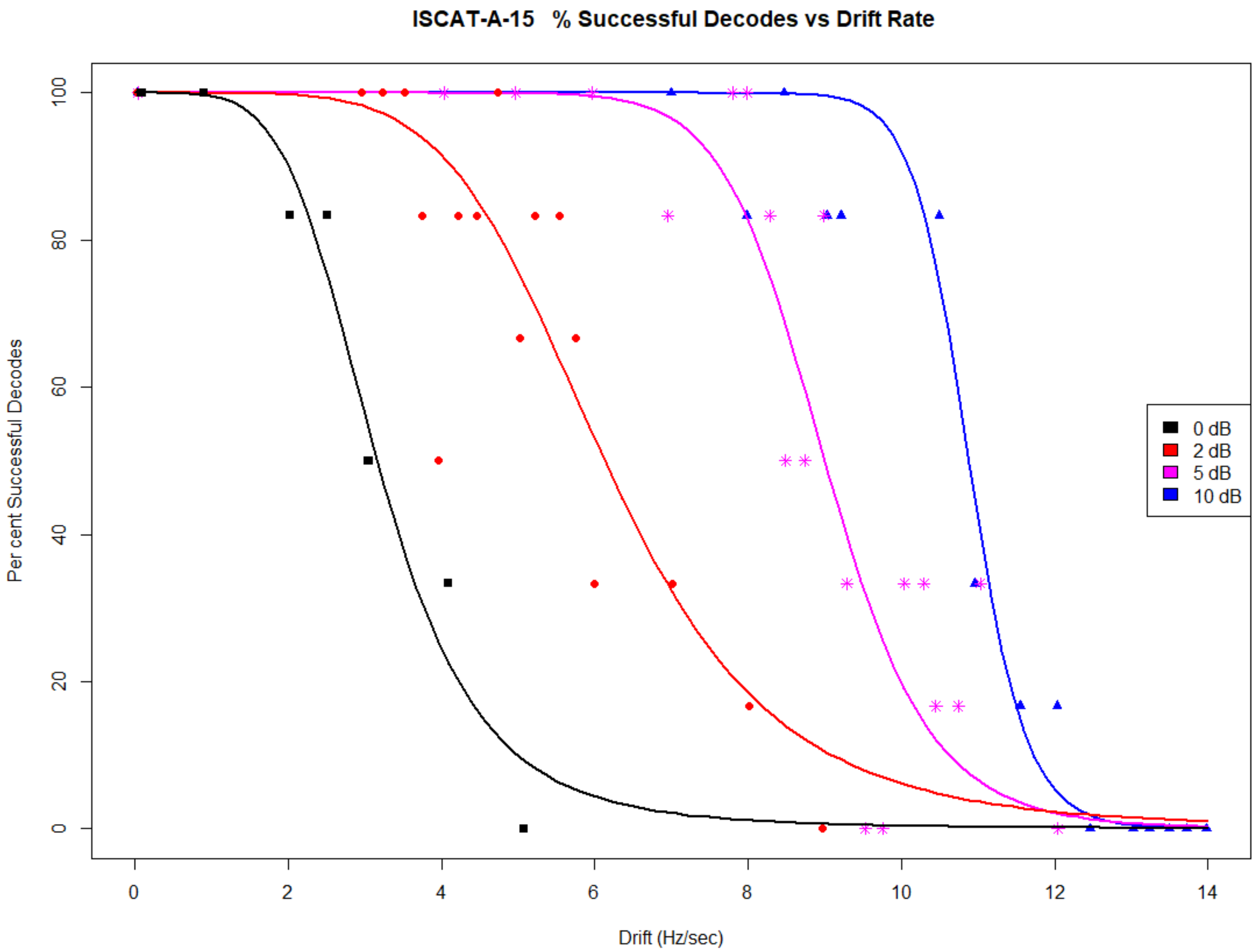
Frequency Tolerance For the fast modes (ISCAT, JT9E-JT9-H Fast, and MSK144) the situation regarding how much frequency drift / Doppler shift will be tolerated by the decoder is more complicated than it is for the slow modes. This is due to a combination of factors. First, these modes have a very short time required for a single complete message ("message frame") to be received ("Tx Duration"), with the message being repeated multiple times during a single receive cycle. Second, the decoder will average multiple message frames from a given receive cycle in order to maximize the probability of a successful decode. Third, the number of message frames that are averaged for any given receive cycle is dependent on the characteristics of the actual received signal, and will not be known in advance by the receive station. Fourth, the receive cycle duration can be adjusted to 5, 10, 15 or 30 seconds for these modes, and if averaging is done over a major portion of the receive cycle, this will introduce another variable into the equation.

The times required for a single complete message to be received ("Tx Durations" in WSJT-X lingo) for each of the Fast Modes are shown in column two of the table below. Column 3 shows the tone spacing, and column 4 shows the tone-spacing-based estimated frequency tolerance of each of the Fast Modes:

Mode	Tx Duration (s)	Tone Spacing (Hz)	Max Drift (Hz/Sec)
ISCAT-A	1.176	21.5	18
ISCAT-B	0.588	43.1	73
JT9E	3.400	28.1	8
JT9F	1.700	56.25	33
JT9G	0.850	112.5	132
JT9H	0.425	225	529

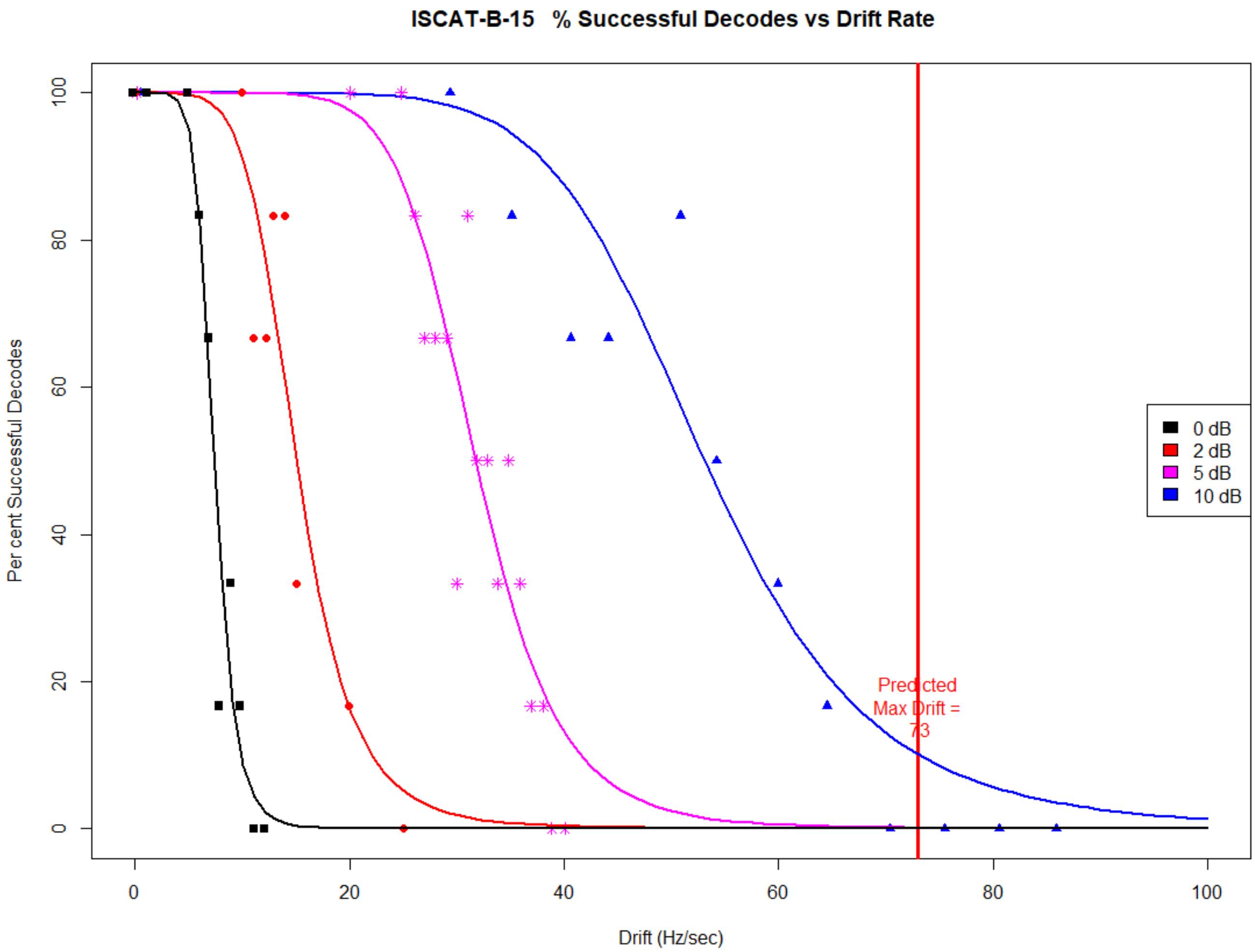
If no averaging affected by shift rates were being performed by WSJT-X, then the estimate of the acceptable maximal drift for a given mode/submode based only on tone spacing would (as already described for the slow modes) be the tone spacing for that mode/submode divided by the "Tx Duration" in seconds for that mode/submode. For example, for ISCAT-B (tone spacing 43.1 Hz, Tx duration 0.588 seconds) the estimated acceptable maximal drift would be 43.1/0.588 = 73 Hz/second. For JT9H Fast the estimated acceptable maximal drift would be 225/0.425 = 529 Hz/second. In the event that averaging affected by shift rates did occur, then the effective Tx Duration would be increased, affecting the results of the above calculations and reducing frequency tolerance.

The same technique that was used above to estimate frequency tolerance for the slow modes was used to experimentally estimate frequency tolerance for ISCAT-A, ISCAT-B, and JT9G-Fast in order to gain some insight into the accuracy (or inaccuracy) of the tone-based predictions of frequency tolerance for the Fast Modes.. In each case the 15-second-duration version of the submode undergoing testing was used. The graph below shows the results for ISCAT-A at 0, 2, 5, and 10 dB above the threshold level:



Note that, as for the slow modes, frequency tolerance increases substantially as signal strength and signal-to-noise ratio improves. Also, note that the frequency tolerance of ISCAT-A is greater than that of slow mode JT4G, which had the greatest frequency tolerance of the slow modes that were tested. The tone-spacing-based estimate of frequency tolerance suggested that the tolerance for ISCAT-A would be on the order of 18 Hz/Sec. This value is not shown on the graph, as it is off-scale to the right, showing that even at signal levels that are 10 dB above the threshold, ISCAT-A's frequency tolerance does not reach this value. This may be due to an effect of signal averaging on frequency tolerance.

Below is the graph for ISCAT-B, which has slightly more than double the tone spacing of ISCAT-A, and a Tx Duration that is roughly half that of ISCAT-A, and therefore a tone-spacing-predicted frequency tolerance that is roughly 4 times that of ISCAT-A, or 73 Hz/Sec, ignoring possible effects of averaging on frequency tolerance:

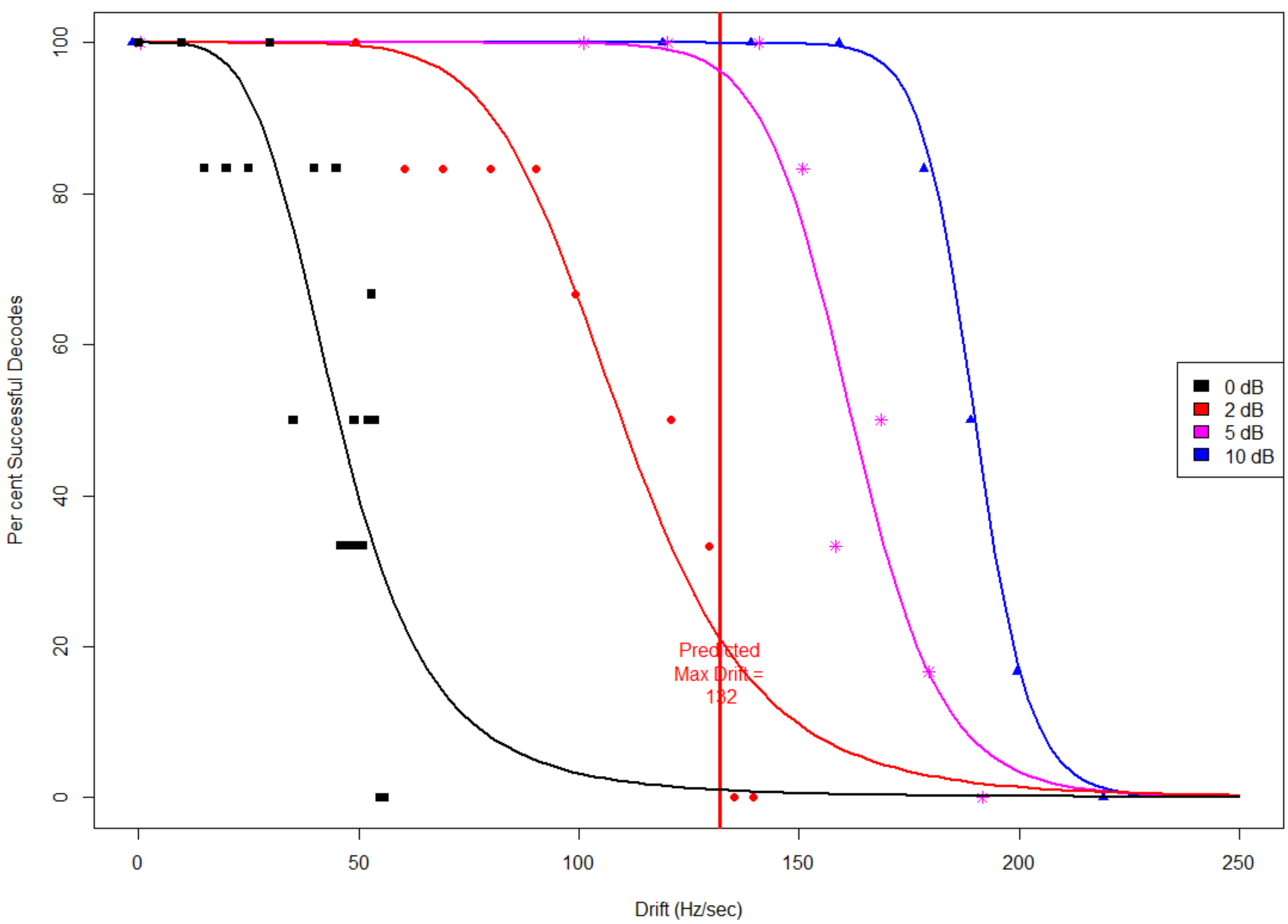


The tone-spacing-predicted frequency tolerance value of 73 Hz/Sec overestimates the frequency tolerance of ISCAT-B. Again, there is a clear-cut effect of signal level on frequency tolerance

The tone-spacing-based estimate of frequency tolerance suggesting that the frequency tolerance of ISCAT-B should be approximately 4 times that of ISCAT-A, appears to hold true for this experimental data, as you can see by comparing the results in the graphs for ISCAT-A and ISCAT-B. This suggests that, while the tone-spacing-based estimate of frequency tolerance given in the table above does not provide an exact value for the frequency tolerance, tone-spacing-based considerations are still important in determining frequency tolerance for these modes, and can be used as a guide to expected frequency tolerance. But signal strength and averaging both affect the results as well, preventing the use of the tone-spacing-based frequency tolerance values in a “cookbook”, rote fashion for the ISCAT modes.

Below is the graph for JT9G-Fast 15:

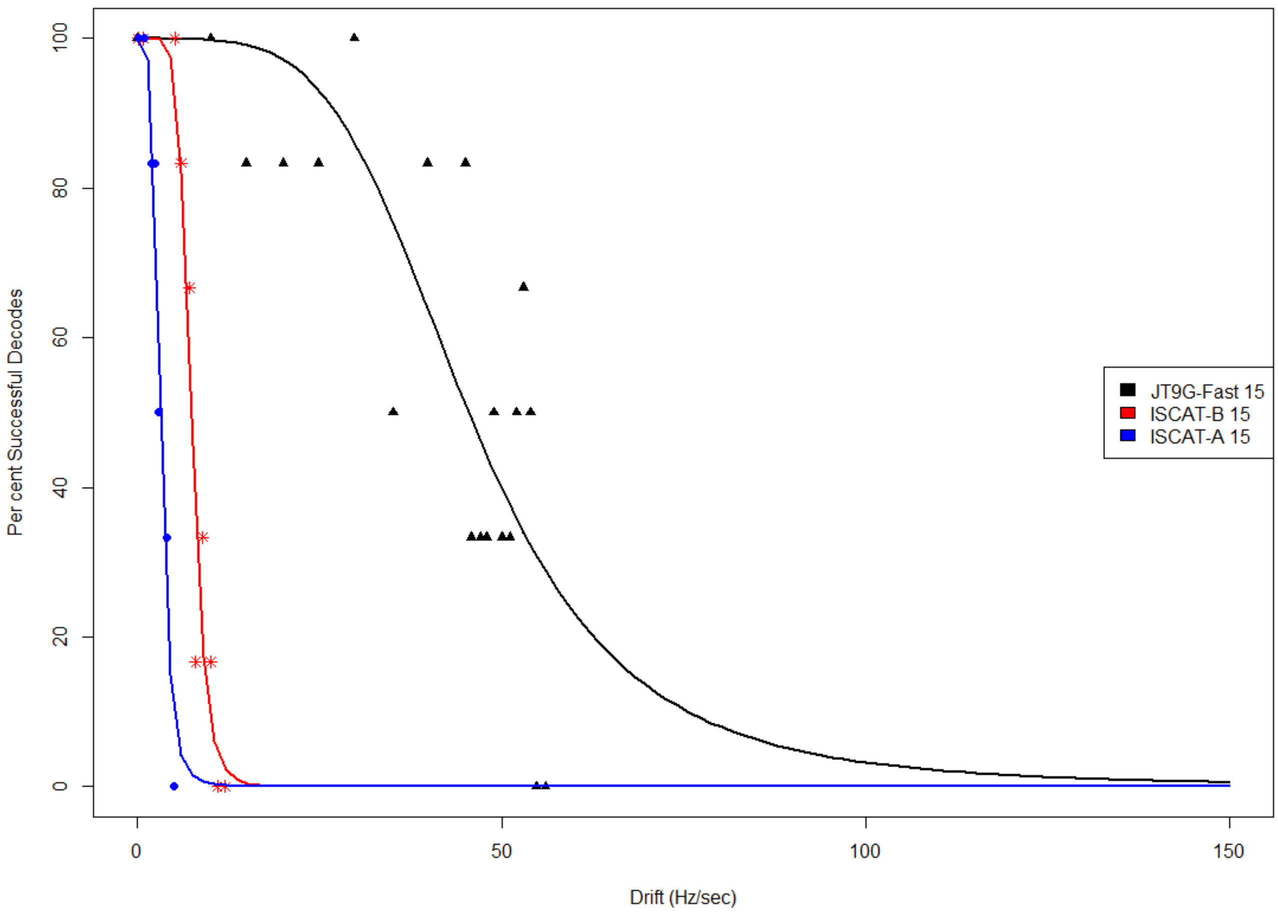
JT9G-Fast-15 % Successful Decodes vs Drift Rate



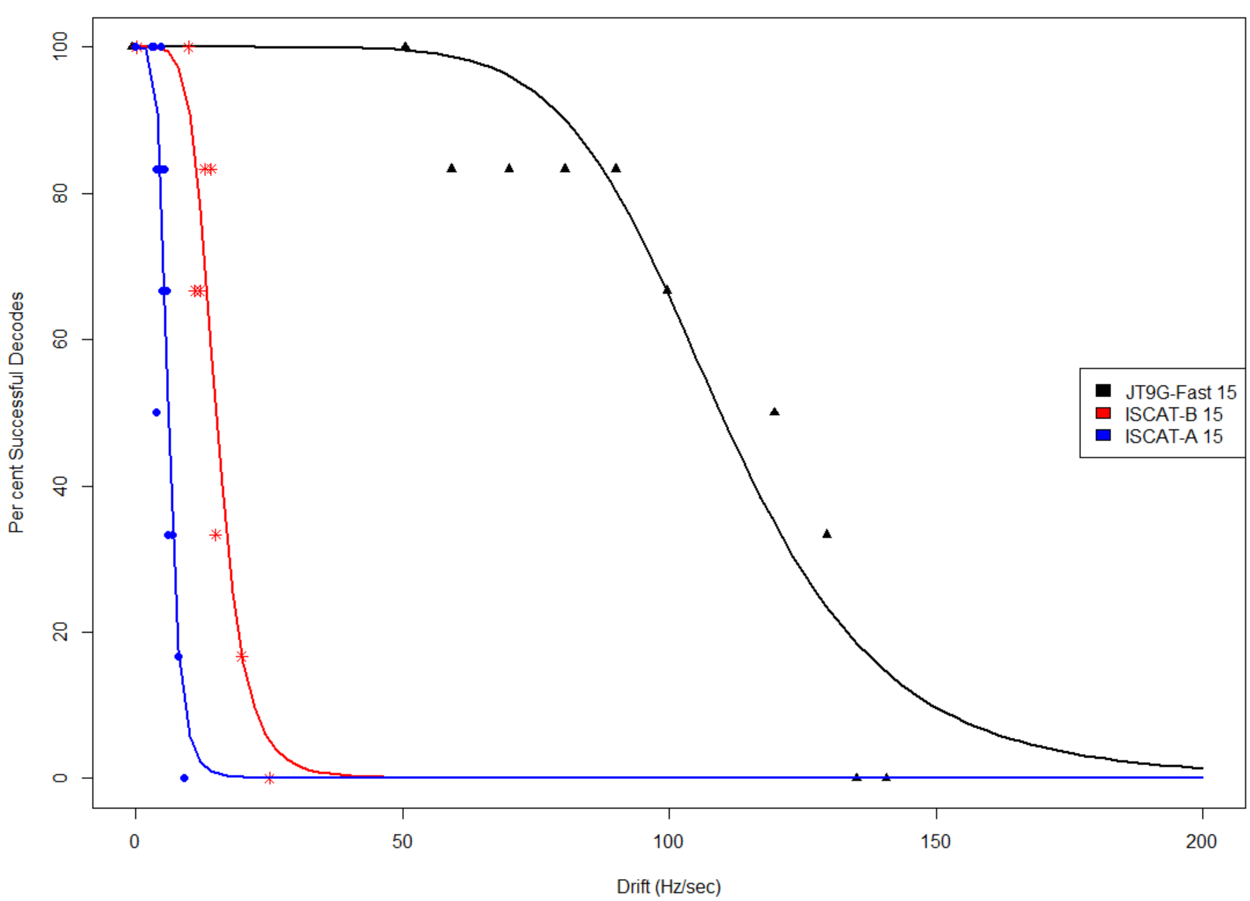
The measured frequency tolerance of JT9G-Fast 15 is, at first glance surprising, with values even at the threshold level far exceeding the best performance of any of the slow modes tested even at the highest signal levels. But the values measured are <u>not</u> out of line with the frequency tolerance as estimated using the tone spacing and Tx Duration of this mode. As you can see, the tone-spacing-based estimate of frequency tolerance provides a reasonable guide to the frequency tolerance of JT9G-Fast. As usual, the tone-spacing-based estimate overestimates the frequency tolerance at the lowest signal levels.

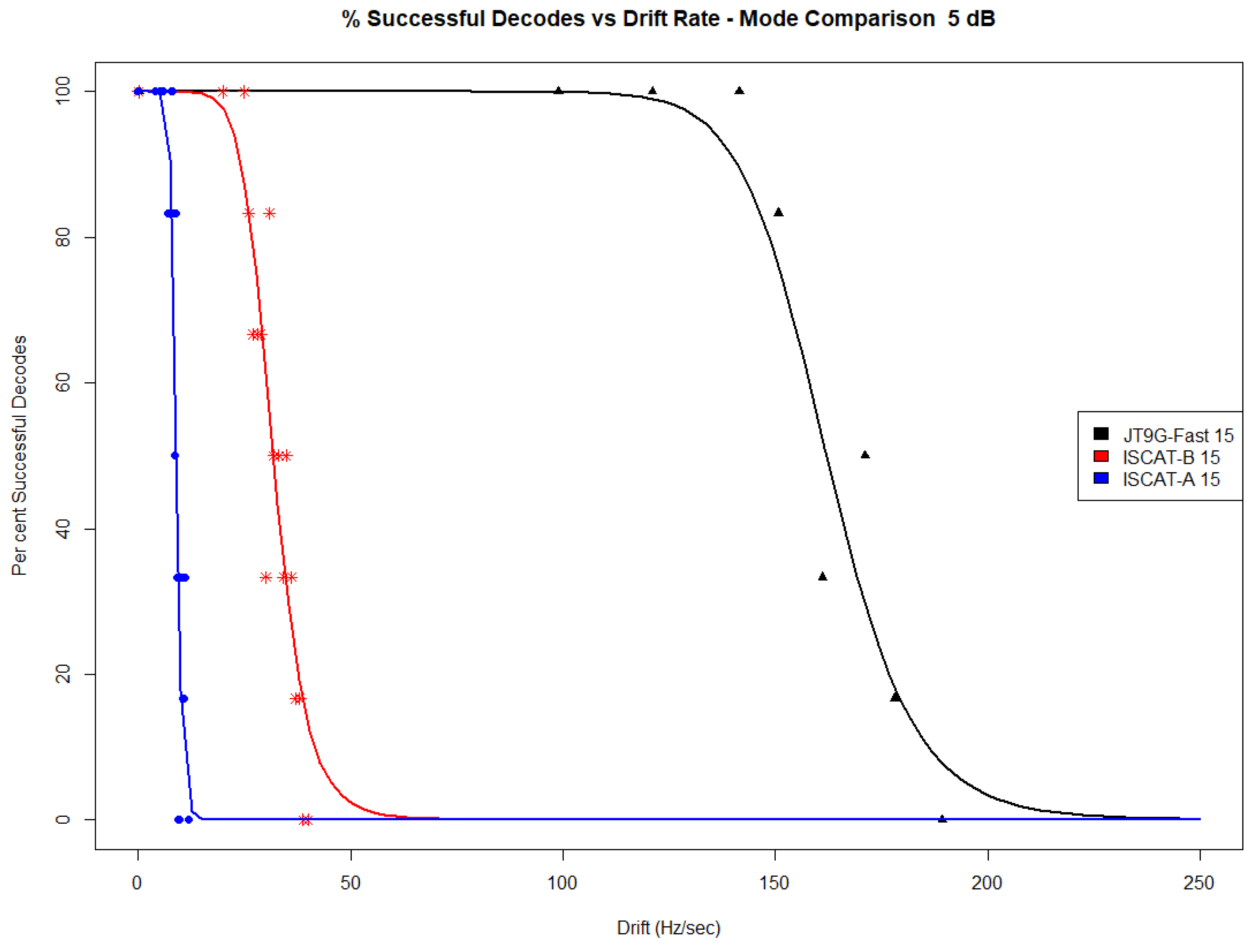
On the next three pages are graphs showing the frequency tolerance of all three fast modes tested at each of the signal strength levels examined.

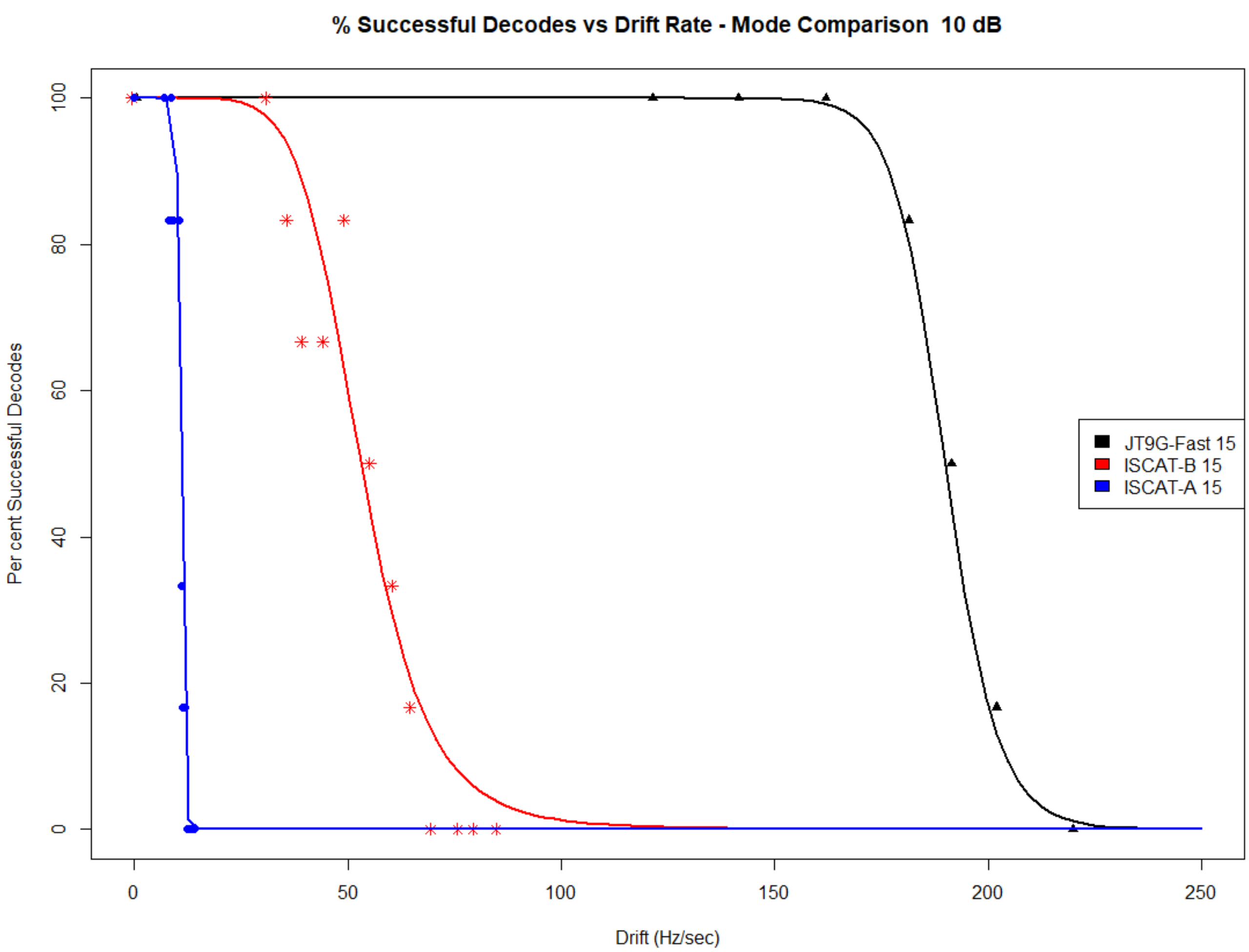
% Successful Decodes vs Drift Rate - Mode Comparison 0 dB



% Successful Decodes vs Drift Rate - Mode Comparison 2 dB




% Successful Decodes vs Drift Rate - Mode Comparison 5 dB
Per cent Successful Decodes
Drift (Hz/sec)
0
20
40
60
80
100
0
50
100
150
200
250
JT9G-Fast 15
ISCAT-B 15
ISCAT-A 15


% Successful Decodes vs Drift Rate - Mode Comparison 10 dB
Per cent Successful Decodes
Drift (Hz/sec)
0
20
40
60
80
100
0
50
100
150
200
250
JT9G-Fast 15
ISCAT-B 15
ISCAT-A 15

To summarize the frequency tolerance data for the Fast modes, we can say that:

1. Tone spacing provides a reasonable estimate of the frequency tolerance of the fast modes, doing a fair job for JT9G but overestimating frequency tolerance for both ISCAT modes.
2. Frequency tolerance for a given mode/submode is poorest at the threshold level for detection and improves as signal strength and signal-to-noise ration increase.
3. ISCAT-B has superior frequency tolerance to ISCAT-A at all signal strength levels, and JT9G-Fast is superior to both ISCAT modes at all signal strength levels.
4. The very short Tx Durations for these Fast modes give them a substantial advantage in terms of frequency tolerance (for frequency drift or shift) over the slow modes.

The principles and insights gleaned from the frequency drift/shift data on the Fast modes/submodes presented above can be applied to the remaining JT9-Fast submodes as well.

IV. Putting all of this together, what should one do to maximize the chances of a successful digital-mode QSO on the higher frequencies?

1. Measure the frequency stability of your station, and then make the frequency stability of your station the best you possibly can. GPS-locking is a great way to achieve this, and easy to do. Looking at the graphs above that show frequency tolerance vs signal strength should immediately demonstrate to you that even if you think that your frequency stability is "good enough", if you have frequency drift of more than about 0.4 Hz/Sec you are likely losing potential QSOs at the threshold signal-to-noise level because of frequency drift regardless of whether you are using FT8 or any one of the slow modes. The Fast modes have better frequency tolerance at the threshold, but you immediately give up sensitivity when you select a Fast mode, so if you want to maximize your QSO possibilities you need to maximize your frequency stability. And when you go to make that QSO, your QSO partner's frequency stability is just as important as yours is, so encourage your QSO partner to ALSO get GPS-locking.

2. When getting ready to make the QSO attempt, determine the amount of frequency drift that you will actually see due to your station characteristics, the path, and your QSO partner's station characteristics. To do this you can use the methods described early in this paper or use any other method that you prefer. Use this drift value (in Hz/Sec) and either the tone-spacing-based estimates of frequency tolerance for each mode/submode or the more accurate signal-strength-based frequency tolerance estimates given above to decide how wide your tone spacing needs to be based on your estimated frequency drift. That will give you a set of modes/submodes that have sufficient frequency tolerance for the task at hand. If you are going to be using aircraft scatter, or if your contact will be made using rainscatter, then the expected Doppler Shift or frequency dispersion will need to be taken into account as well.

3. From that set of candidate modes, select the mode that is the most sensitive. If your time for the QSO will be limited as it might be with aircraft scatter, then select the most sensitive mode from the subset of candidate modes with adequate frequency tolerance that also have 15 or 30 second cycle times.

That is all there is to it! If you have adequate frequency stability and sufficient signal strengths to potentially use FT8 or one of the fast modes, you can reduce your QSO time to 25% of what it would be with the slow modes. You can always try a fast mode (or FT8) first and then drop back to a slow mode if you don't have enough oomph to complete the QSO with one of the fast modes.

For example, if you are in a hurried contest situation and you want to do QSOs with 15 second receive cycle times, then you are limited to FT8, ISCAT-A, ISCAT-B, and JT9E-,F-,G-, or H-Fast, (or MSK144 if you are doing meteor scatter). Of these choices, FT8 has the best sensitivity, so if the given path/mode frequency dispersion and overall frequency instability of the system (including both the transmitting and receiving stations' frequency instabilities as any path-related Doppler shift) is less than about 6.25 Hz over the 12.6 second receive period, then FT8 is likely your best 15-second-T/R-cycle choice. If your system frequency instability is worse than that, then you should pick another mode instead of FT8, using the tables and discussion above as your guide. For the greatest chance of success, always choose the mode that has the greatest sensitivity that will also satisfy the receive cycle duration and frequency drift/dispersion characteristics of your particular situation.

As I noted at the beginning of this paper, a "cookbook" approach is not possible. The best mode for a quiet-condition 10 GHz terrestrial QSO using the direct path between two GPS-frequency-locked stations with no scatter is NOT going to be the best mode for a rainscatter 10 GHz QSO. The optimal direct-path mode/sub-mode might also be the "right" mode/submode for aircraft scatter if the airplane is flying right down the direct path between two stations so that Doppler shift is negligible, but it will NOT be the right mode/sub-mode if the aircraft's path is at a significant angle to the direct path so that there is significant Doppler shift of the received signal. You can play with various aircraft/path geometries for various frequencies using my program AircraftScatterSharp and see what Doppler shifts result from various aircraft scatter geometries at various frequencies, or review the table on page 23 of my recent paper on Aircraft Scatter, given at the NEWS Conference in 2017 for more information in this regard. These resources can be found at:
http://www.nitehawk.com/w3sz/AircraftScatter.htm

A PDF of the paper is here:
http://www.nitehawk.com/w3sz/NEW_W3SZ_AircraftScatterNEWS_2017_Paper.pdf

With each decision you make, you are trading off sensitivity against [1] QSO duration and [2] tolerance for frequency shifts and dispersion. In each case there is likely more than one satisfactory solution, and your best strategy is to pick what you believe to be the likeliest successful mode based on your assessment of signal strength levels, frequency instability and dispersion, and the time available for the QSO. If your first choice doesn't work, then re-assess your options and try again. In the rain scatter QSO with K1RZ given as an example above, I had greatly overestimated the amount of frequency dispersion that we had to deal with. I had therefore chosen a mode that would compensate for more than 300 Hz of dispersion, but the waterfall displays obtained during the first QSO attempt showed that the frequency dispersion was "only" about 50 Hz. So instead of using JT4G with its sensitivity threshold of -17, I could have used JT9F (tone spacing 56 Hz) with its sensitivity threshold of -22. That would have given me 5 more dB sensitivity, and having 5 more dB to work with would have certainly made a huge difference if signal levels hadn't been so strong! This example also illustrates the point that you don't necessarily have to pick correctly in order to complete the QSO. But by choosing wisely, you do increase your chances for a successful QSO.

The best advice that I can give is now that you have this information, get out there and start putting it to use. Pretty soon, mode choice will be second-nature to you.

Appendix

Estimating Sensitivity Thresholds for the Fast Modes

I used three methods to provide independent estimates for the sensitivity threshold for each of the Fast modes. Before describing these methods, I need to emphasize that these are only estimates of the sensitivity threshold for each mode/submode as determined under artificial "laboratory" conditions, and that the actual sensitivity for a given mode/submode in specific real-world conditions is the result of many factors. So take this information with a grain of salt, using it in combination with everything else that you have learned about propagation and the WSJT modes when deciding on a QSO strategy.

The first method that I used for estimating mode/submode sensitivity threshold was the MATLAB-based "AWGN" or Add White Gaussian Noise method.

The first step in using this method is to create for each mode/submode to be analyzed an audio file of the transmit audio as generated by WSJT-X for that mode. I used a simple "CQ" message for this. The difference in peak audio levels among all of these "base" audio files was less than 0.15%, so the necessary assumption of essentially equal peak audio levels in all the base audio files is valid.

Next, a series of modified audio files was constructed for each mode/submode from its base audio file by adding (using MATLAB's "awgn" function[6]) incrementally greater known amounts of white Gaussian noise to each succeeding file in the series of files being generated for each mode/submode, spanning the range of SNR values for which successful WSJT-X decoding could be accomplished and extending into the SNR values for which decoding could not be accomplished.

In this manner, the first AWGN file for every mode/submode will have the same SNR as the first AWGN file for every other mode/submode. The same will be true of the second, third, and all subsequent files in the audio file series for each mode/submode.

The sensitivity threshold of JT9D is known (-24 dB JT) and so it is possible to index every mode/submode to JT9D by comparing the AWGN "snr" value for the lowest snr audio file which WSJT-X was able decode for that mode to the AWGN value for the lowest snr audio file that WSJT-X was able to decode for JT9D. In this way, a value for "degradation compared with JT9D" was determined for each mode/submode, and when that value was added to -24 (the known sensitivity threshold for JT9D), the sensitivity threshold for each mode/submode was determined. Sensitivities for JT9E Slow and FT8 were also calculated by this method, so that they could be compared with the published sensitivity thresholds of those modes as a check on the validity of this method, and the values obtained showed perfect agreement with published values for the sensitivity thresholds for JT9E-Slow and FT8, giving values of -23 and -21 dB JT respectively.

The second method (which we will call the "Attenuation" method) for determining the sensitivity threshold was chosen because it is fundamentally different from the first method. This method uses the transmission and reception of WSJT-X-message-containing RF signals at 435 MHz for each mode/submode with incremental, known amounts of attenuation being added to the RF path until decoding fails as a result of insufficient signal-to-noise ratio. The amount of attenuation present for the weakest successful correct decode for each mode/submode was compared with the amount of attenuation present for the weakest successful correct decode for the index mode JT9D, and the sensitivity threshold for each mode/submode thereby determined. The difference in attenuation between the mode/submode under test and that for JT9D for the weakest successful decode was the "degradation compared with JT9D" and this value added to the published sensitivity threshold for JT9D (-24 dB JT) gave the sensitivity threshold for each mode/submode. Only in this indexing of values to achieve the final result was this method similar to the process described for the AWGN method above.

The level of the "weakest successful correct decode" that defined the threshold level for each mode/submode was determined by placing an arbitrary amount of attenuation in the signal path. Once this was done, the attenuation level was considered to be "successful" if at least 50% of 6 successive decode attempts were successful. If decoding was successful at the attenuation level being tested, then one dB of attenuation was added to the RF path and the process repeated until an attenuation level was reached where decoding was not successful by the above definition. The attenuation level with the greatest amount of attenuation (lowest signal level) that met the criteria for "successful" decoding was designated as the threshold level for that mode/submode. If the initial attenuation level for a given mode/submode failed the above test and was therefore "unsuccessful", then one dB of attenuation was subtracted from the RF path and the process repeated. This iterative process was then continued until an attenuation level was found that met the criteria for successful decoding, and this level was designated as the threshold level for that mode/submode.

For the "attenuation method" I used an SDR software package called SDR-Angel[7] with separate LimeSDR[8] units used for the transmitter and the receiver.   The base frequency for both LimeSDR units was frequency-locked to the same 10 MHz GPS-locked source and testing was begun once GPS lock was achieved. SDR-Angel was used in the Upper Sideband (USB) Full Duplex mode. The RF frequency used was 435.000 MHz.

50 dB of fixed SMA attenuators were placed in the RF path in series with a 0-50 dB (1-dB increment) variable step attenuator and the step attenuator was adjusted in 1 dB increments to determine the attenuation value resulting in the lowest signal level producing successful correct WSJT-X decodes as described above. Five complete sets of data were acquired for each mode/submode using the attenuation method and the results of these five sets were averaged prior to comparison with the results obtained via the other two methods..

The third method, or "Modified-WSJT-X" method was very similar to the AWGN method described above, but used a version of WSJT-X modified by the author to add known increments of white Gaussian noise to the audio signal.

After completing the measurements with the three methods as described above, the results of the three methods were compared. As was shown in the illustration in the text, the estimated values obtained by each of these three methods for the sensitivity threshold for each mode and submode tested were either identical or within 1 dB of each other, except for the data for JT9E-Fast15 and JT9G-Fast30 where the maximum difference between any two of the three methods was 2 dB. Finally, to obtain the average value of the sensitivity threshold using the data from these three methods, the average of the results from each of the methods, derived as described above, was used.

Estimating Frequency Tolerance

For estimating frequency tolerance a version of WSJT-X modified by the author to shift the audio tones at the desired shift rate was used to send these tone messages to a second instance of WSJT-X via Virtual Audio Cable[9]. This represents a change from the method used in the preliminary version of this report, which used hardware SDRs and the software package

SDR-Angel with a Rest API[10] to provide the necessary frequency shifts. This change in method was made for the reasons detailed in the preliminary version of this report, which relate to the potential inaccuracies occurring at extreme shift rates with the SDR-based method, and because of the much greater ease-of-use of the current approach as compared to the RF-based approach.

For each mode/submode, the lowest signal level giving 100% decode success for 6 consecutive decode attempts was determined. This was termed the “0 dB” level for the frequency tolerance experiments. Incrementally greater amounts of frequency shift per second (“drift”) were added and decoding performance was determined for each value of frequency drift as per-cent of 6 consecutive decoding attempts that were successful. After the value of frequency drift that produced a success rate of zero was reached, the signal level was increased by 2 dB (to the “2 dB” level) and this process was repeated until again 0% successful decodes were achieved. The signal level was then increased by 3 more dB (to the “5 dB” level, 5 dB above the threshold level) and the process was repeated until decoding success again reached 0%. The signal level was then increased by 5 more dB (to the “10 dB” level, 10 dB above the threshold) and the process was again repeated until 0% decoding success was achieved.

Curve fitting and plotting were done using R Studio[11] and the least squares method to fit the ROC curves to the logistic function[12] $Y = d + (a-d)/(1 + (X/c)^{**}b)$ where a is the lower asymptote, d is the upper asymptote, c is the midpoint of the transition, and b is the slope factor for the transition. In this case a and d were the constraints of 0 and 100% successful decodes respectively.

The modifications to WSJT-X were simple and consisted of the following:
1. Addition of the code to provide the facility to shift all audio tones in a transmitted message by a user-determined Hz/Sec rate.
2. Addition of 3 text boxes to the main WSJT-X window to allow easy setting of the shift rate described above as well as the SNR value of the transmitted message and the frequency spread (dispersion) of the transmitted message. Unlike the code for providing the shifting of the audio tones, the code for adding known amounts of white Gaussian noise and for spreading the tones was already present in the unmodified version of WSJT-X, and the author merely needed to modify the code to apply this code for the purposes described above, and to make on-the-fly adjustments to the parameters for setting the SNR and amount of tone spread convenient for the user.

An image of the modified WSJT-X main window is here.

Spectrum Lab was used to verify correct calibration of both the spread and shift functions.

Limitations

The primary limitations of this report are [1] the limited number of levels (6) used in the frequency tolerance sensitivity analysis and [2] the limited number of parameter values examined for each parameter varied. These limitations were necessitated by the practicalities of manually collecting the large number of data points required in order to generate this report. The experimental process is currently being automated in order to allow a much greater number of levels / parameter values / data points to be collected, and the results of this automated process will be presented at a future date.
– Roger Rehr W3SZ April 4, 2019

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