The Utah VHF Society

Analysis and recommendations of channel spacing for D-Star operations on the VHF, UHF, and 23cm amateur bands

Purpose of this page:

Amateur radio has long been faced with the adoption of newer technologies: It can be argued that innovation and experimentation are some of the main purposes for the existence of amateur radio. As these new technologies come along, however, there is also the responsibility to accommodate these new systems into the existing framework.

D-Star is a fairly new digital voice system that is loosely based on other commercial standards. It offers the potential advantage of ease of networking, the ability to send data, and the possible advantages inherent to digital modulation schemes in terms of signal quality. Incorporating these signals amongst existing analog operations requires attention to technical details and some foresight in order to maximize the potential of this new technology as well as allow co-habitation of new and old systems.

Additional comments may be found near the end of this document concerning the potential of various interference sources to 70cm and 23cm D-Star operations, notably U.S. Government RADAR.

Important Notes:

- This first portion of this page deals only with the narrowband D-Star modes as found on the VHF and UHF U.S. amateur bands. The segment at the end of this page relates to the 128kbps "DD" mode available on 23cm using certain models of radios, such as the ID-1.
- For the VHF/UHF operations, ***ONLY*** analysis of the disruption of voice transmission was considered. If the transmission of data is to be the primary concern rather than digital voice, even more protection may be required for acceptable performance.

A bit of background:

There has been some mention of how spectrum-efficient D-Star is as compared with analog signals and, because of this, a lot more D-Star signals can be crammed into the same space as one analog signal: One oft-cited instance is the simultaneous operation of several D-Star signals spaced only 6.25 kHz apart from each other. While this sounds like an impressive feat, cursory examination of the bandwidths of the transmitters, receivers, and link margins will immediately reveal that this is ***NOT*** a good thing to do! *(It is worth noting that several Icom D-Star capable radios are **not** capable of tuning 6.25 kHz step - see below.)*

Important note:

Some of the recommendations on this page may apply only to the circumstances that apply in the Utah area. ***It is the responsibility of the reader to study this and other available data in order to come to a reasoned and technically-sound conclusion appropriate to local conditions and patterns of usage!***

Testing under "simulated real-world" conditions:

At the time that this page had originally been created, relatively little had been done to carefully analyze how D-Star signals will co-exist with each other - and with existing analog signals - in the real world, using ***real*** radios that people own. In order to answer some of these questions, we decided to take a typical D-Star radio, an IC-91AD, and put it to the test. To do this, we put together a test fixture. The description and operation of this test system is as follows:

- Two identical laboratory, synthesized signal generators were combined using a hybrid combiner to afford isolation between the two generators.
- For the D-Star to D-Star interference test, both signal generators were modulated using independent D-Star GMSK data streams, the parameters of which were identical to those produced by the IC-91AD when viewed on both a spectrum analyzer (RBW=100Hz) and when observing the "eye" pattern on a demodulation scope.
- For the D-Star to Analog interference test, one of the signal generators was producing a D-Star signal, while the other one was modulated to +- 5 kHz using audio fed from an NOAA weather transmitter for a "consistent" analog signal.
- The output of the hybrid combiner was fed into an Icom IC-91AD HT for the D-Star tests.
- To test the potential of interference, several different receivers were used to determine the potential of D-Star interference to analog signals.
- The "base" signal level used was -90 dBm. This is enough to provide a "solid" signal in both digital and analog, but still allow wide excursions of the other signal with minimal likelihood of overloading the receiver. Because of the loss of the hybrid combiner, the signal level reaching the receiver was 3-4 dB lower than the output levels from the signal generators.
- When the "interfering" signal was set above -50dBm, tests were re-done with both carriers set 10 dB higher lower to determine if receiver being tested was being overloaded.
- For D-Star performance, given the absence of any real BER testing capability (without modifying the receiver) interference was deemed to be occurring when more than one "bloop" (a decoding error) would occur over a period of about 10 seconds. It should be noted that the difference in interference that results in an occasional "bloop" and that at which the audio becomes unintelligible due to too many bit errors is only about 1-2 dB in many cases. Quickly checking the IC-91AD's baseband signal (done by switching to FM-Narrow mode) audibly revealed that interference was present.
- For the tests to determine the interference potential of D-Star signals to analog, both 12 and 20 dB (unweighted) SINAD were measured using a 1 kHz tone modulated at +-3 kHz onto the analog signal being received.
- In our testing, we had brief access to other radios. We have observed that the IC-91AD is the *worst* performer in terms of adjacent channel/interference conditions of the radios that we have tested. This is one of the reasons why we have chosen to do our analysis using the IC-91, as it represents - as far as we know - the *worst case* scenario that D-Star uses can expect to encounter.

Comments:

- According to the IC-91AD service manual the "FM-Narrow" mode is used for demodulating the received D-Star signal in the IC-91AD: The demodulated signal from the FM receiver is passed to the UT-121 (D-Star) module for decoding.
- The IF filtering used by the IC-91AD for both FM-Narrow and D-Star was measured to have a -6 and -30dB bandwidth of 8.6 and 11.2 kHz, respectively.
- Using the above setup, it was also noted the "drop dead" signal level for D-Star using the IC-91AD was about 0.12 microvolts, with largely error-free reception above 0.15 microvolts when no other signals were present. Note that this signal threshold level varies from unit-to-unit.
- There have been reports of homebrewers fitting their "analog-only" radios with D-Star modules. Unless these receivers have the equivalent of the "narrow" filters with which Icom has equipped their receivers, they will *not* be able to tolerate D-Star signals as closely-spaced as those with narrower filters and the recommendations made on this page ***may not apply***.
- Note that D-Star receivers are really just narrow FM receivers with a modem and voice codec attached and as such, they are subject to the same factors that will clobber an analog FM signal! If you are already familiar with 9600 baud packet, then it's worth remembering that D-Star's modulation is very similar - but slower, narrower, and somewhat easier to modulate and demodulate, and both are essentially "bandwidth limited" noise sources.

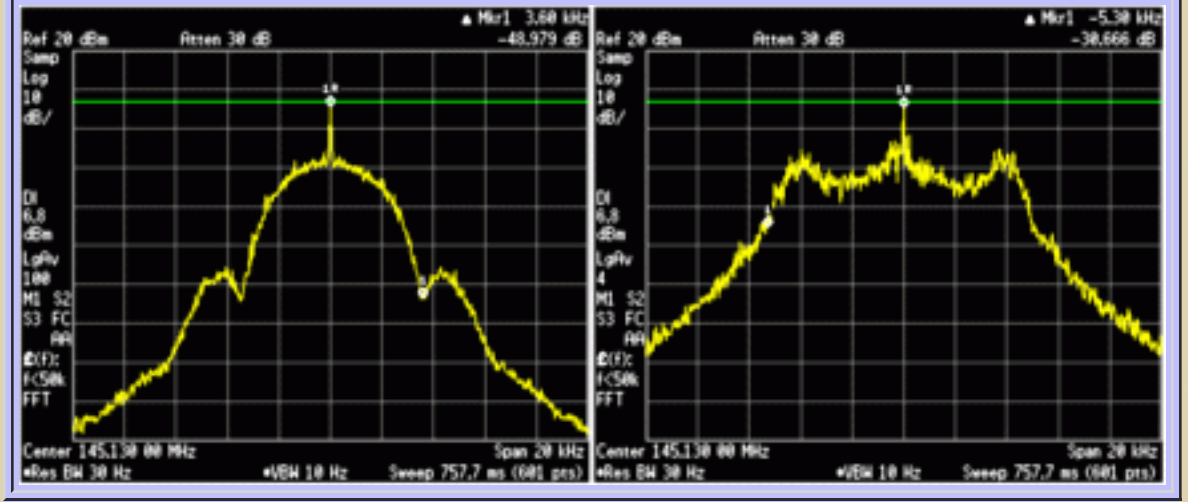

Figure 1:
Comparative spectra of D-Star (left) and typical analog signals (right.) In each case, vertical divisions represent 10dB and horizontal divisions denote 2 KHz. An unmodulated carrier has been overlaid atop both images with the green line representing the level of the unmodulated carrier.
Click on the image for a larger version.

Radio	-6dB Bandwidth	-30dB Bandwidth	-55dB Bandwidth (narrow) or -60dB (wide)
IC-91AD (Narrow FM/DV)	8.6 kHz	11.2 kHz	13.7 kHz
IC-91AD (Wide FM)	10.7 kHz	17.25 kHz	20.6 kHz
IC-2200H (Narrow FM/DV)	7.7 kHz	10.7 kHz	13.9 kHz
IC-2200H (Wide)	12.9 kHz	17.9 kHz	21.2 kHz

Figure 2:
Measured bandwidth of several ICOM D-Star capable radios in their wide and narrow modes. Note that Icom specifies a -55dB bandwodth for "narrow" mode and a -60dB bandwidth for "wide" mode.

Occupied transmit signal bandwidth and receiver bandwidth:

It is important to note that two major factors affect how two signals - whether they are D-Star or analog - interact with each other:

- The occupied bandwidth of the transmitted signal. **Figure 1** shows the occupied bandwidth of a D-Star signal (left) and a typical analog signal (right). These traces represent the "peak + average" distribution of energy, including that of the unmodulated carrier. *Please take note of the resolution bandwidth of these analyzer plots and its effect on the relative power density of the modulated carriers.*
- The detection bandwidth of the receivers being used.

The relative "narrowness" of the D-Star signal is oft-touted as one of its strong points. To be sure, more of the total transmitted energy is confined near the center frequency than is the case for the analog signal. For the D-Star signal, the majority of the energy is constrained to within +-3.6 kHz of the center frequency. In the case of the analog signal, the majority of the energy is constrained to within +-5 kHz of the center frequency. This only tells part of the story: If one looks at the -30dB points of the two signals, one notes that the bandwidth of the D-Star and analog signals are +-5 kHz and +-6 kHz, respectively - and it is the energy in these sidebands that, in part, dictates adjacent-channel concerns. If one considers just the -30dB points of the transmit signals, a minimum D-Star to D-Star spacing of 10 kHz and a D-Star to Analog spacing of 11 kHz is suggested.

Perhaps even more important is the detection bandwidth of the receiver. Ideally, the D-Star's receiver's filter need only be wide enough to accommodate the primary "hump" that contains the majority of the energy - that is, out to +-3.6 kHz, or a total bandwidth of about 7.2 kHz, but practical considerations (manufacturing tolerances in the manufacture of the filter, achievable shape factor, group delay, expected transmit or receive frequency errors, etc.) require that the filter be wider than this. As mentioned previously, the -6dB bandwidth of the IF in the IC-91AD is, in fact, 8.6kHz (+-4.3 kHz), dropping to -30dB at 11.2kHz (+-5.6kHz). It is largely the combination of the receiver filtering plus the occupied bandwidth of the adjacent signal that dictates the minimum spacing of two D-Star signals.

Receivers designed for traditional analog FM use in amateur service are designed for a signal with a +-5 kHz modulation, so the receivers' filters are necessarily wider - typically 15 kHz wide at the -6 dB bandwidth and about 21 kHz wide at the -30 dB bandwidth. For this reason - plus the fact that the analog signal is wider - it is necessary that the spacing between an analog signal and either another analog or even a D-Star signal must be wider than that between two D-Star signals.

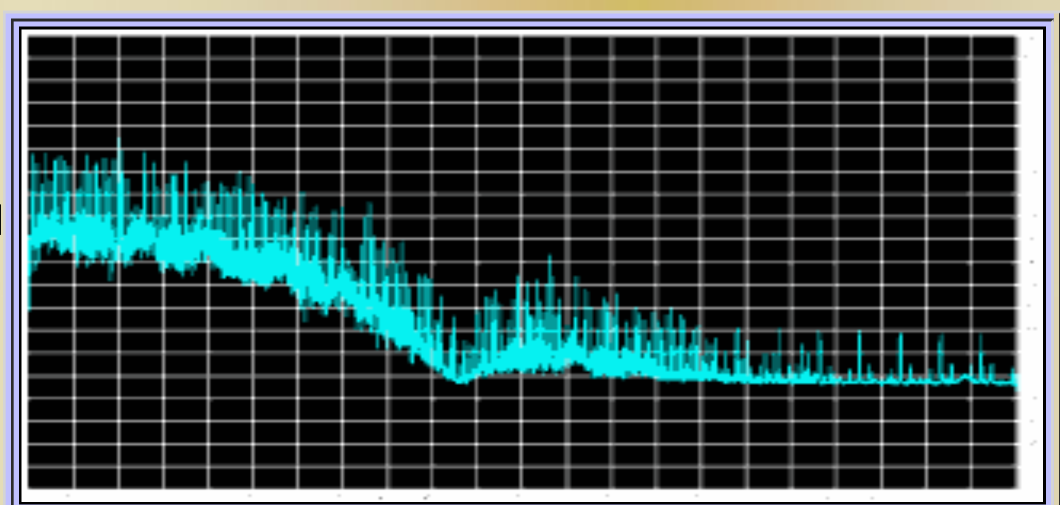

Figure 3:
*Spectrum analysis of D-Star's **baseband**. There is a null at 4800 Hz correlated with the bit rate and there are strong spectral components at intervals of 50 Hz that related to the 20ms voice frame.*
Click on the image for a larger version.

"Equivalent SINAD" test:

Because the IC-91AD uses the FM-Narrow mode for demodulation, it is possible to relate the SINAD in FM-Narrow mode to the performance in D-Star digital voice mode. This is is possible because the SINAD measurement tells us something about the amount of extraneous noise in the receiver's baseband - something that correlates well with data errors. ***The SINAD readings noted in the tests below are unweighted, using audio taken from the speaker connector of the IC-91AD.***

This test was conducted to provide a means to analyze the level of an interfering signal that would be required to degrade a D-Star signal.

For this test, three levels of D-Star signal disruption were investigated:

1. "Clean" audio decoding: No bit errors were observed over a period of 60 seconds or so.
2. "Mostly clean" decoding: One "bloop" (an unrecoverable bit error) occurred every 10 seconds or so.
3. Loss of D-Star sync: At this error rate, not only has recovered speech become unintelligible, but the receiver can no longer maintain synchronization on the D-Star signal.

For this test, two types of situations were simulated using test equipment:

- Weak signal degradation: For this test, the signal level of a D-Star signal was reduced until each of the 3 levels of D-Star signal disruption were achieved.
- D-Star adjacent channel degradation: For this test, another D-Star signal was generated 8 kHz offset from the one being received. With the test signal set at -90 dBm, the level of the interfering signal was increased until each of the three levels of D-Star signal disruption were achieved.

When each of the three levels of disruption were reached, the IC-91AD was switched to FM-Narrow mode while, at the same time, the test generator was switched from generating a D-Star signal to generating an FM signal modulated with a 1 kHz tone at +-1.5 kHz deviation: At this point, an un-weighted SINAD measurement was taken using the audio from the IC-91AD's speaker connector.

As it turned out the SINAD readings for each of the "D-Star" signal disruption levels were the same whether the degradation was due to a weak signal or adjacent-channel interference. The correlating SINAD levels were:

1. "Clean" audio decoding: At 17-18 dB SINAD was required in FM-Narrow mode to produce a signal that did not suffer audible decoding errors in D-Star mode.
2. "Mostly clean" decoding: At 15.5-16 dB SINAD or so, there was one audio "bloop" (an unrecoverable decoding error) in about 10 seconds.
3. Loss of sync: At 9-10 dB SINAD, synchronization of the digital signal was intermittent and no intelligible audio was recovered.

Comments:

- With the narrower bandwidth used for D-Star recording, a 2-2.5 dB weak-signal gain is obtained due to the reduction in detection bandwidth, as compared to the normal FM mode.
- Please note that the "thresholds of degradation" and the radios used in the tests noted on this page are slightly different from those used by N5RFX in his excellent paper, "DStar Co-Channel and Adjacent-Channel Performance" which may be found online at the link near the bottom of this page.

D-Star to D-Star interference test:

The first test was to see how two D-Star signals interfered with each other, depending on relative signal levels and frequency separation. In each case, the "weak" signal was monitored for errors while the adjacent signal was increased in strength. A "solid" audio tone was transmitted on each D-Star data stream using a different tone for each transmitter (to tell them apart.) In this way, bit errors were easily noted as "bloops" or disruptions in the received tone. The levels below were those necessary to obtain "clean" tones with no obvious disruptions over a period of about 10 seconds.

In each case, one D-Star signal was being monitored while another D-Star signal (the one being varied in amplitude and/or frequency) was being used as the interference source.

Situation	Result
On-channel interference	The interfering D-Star signal must be at least **12 dB *weaker*** to avoid interference.
Equal signal strength	A minimum separation of at least **6.25 kHz** is required to avoid interference from another D-Star signal that is of **equal strength**.
10 dB differential	A minimum separation of at least **8 kHz** is required to avoid interference from a D-Star signal that is 10dB stronger.
20 dB differential	A minimum separation of at least **9.5 kHz** is required to avoid interference from a D-Star signal that is 20dB stronger.
30 dB differential	A minimum separation of at least **10.5 kHz** is required to avoid interference from a D-Star signal that is 30dB stronger.
40 dB differential	A minimum separation of at least **12 kHz** is required to avoid interference from a D-Star signal that is 40dB stronger.
50 dB differential *(see note)*	A minimum separation of at least **15 kHz** is required to avoid interference from a D-Star signal that is 50dB stronger.

Figure 4: Interference between two D-Star signals

Note: Amplitude differences of 50 dB or greater are pushing the filtering and dynamic range limits of the receiver, as well as the ability of the test gear to simulate real-world signals.

Comments pertaining to this and other tests:

- In the case of the "on-channel" interference, it appeared that, using the IC-91AD, "mostly intelligible" (but obviously degraded) voice communications was possible with the interference at a level of 9dB below the desired signal.
- The numbers above were obtained using an Icom IC-91AD to receive the D-Star stream.
- An Icom IC-2200H was tested briefly, and in the "On-channel interference" test it fared 3-4dB ***better*** (that is, it was error free when the interfering signal was 8-9dB below the desired signal) than the IC-91AD, and the IC-2100H seemed to perform slightly better than the IC-91AD on some of the other tests as well. In the future, it will be interesting to compare other radios. The IC-91 was chosen because it is a "typical" radio used by many D-Star operators and it is reasonable to design a system based on the performance of lesser-performing radios that might be used by a large percentage of the user base.

- Please note that the D-Star signal can suffer several dB more degradation before it becomes unusable. These results were intended to indicate the maximum level of on-channel and co-channel interference ***before*** the user might begin to notice degradation.

- In the real world, with shifting propagation, signal levels will shift several dB, possibly enhancing (or degrading) either (or both!) signals. It is for this reason that the usability of signals near the margins of acceptability may vary wildly.

D-Star signal susceptibility to interference from analog signals:

Because D-Star signals inhabit the same amateur bands as analog signals, consideration must be given to how these should be spaced to avoid the analog signal's causing interference ***to*** the D-Star signal. Unlike D-Star signals, the modulation and bandwidth of analog signals can vary widely - from being a CW carrier when there is no modulation, to a signal spread over a fairly wide bandwidth when fully modulated with voice energy. Because of this, the interference to a D-Star signal from an analog FM signal can be somewhat transient and it the field it may not be immediately recognized as an interference source under uncontrolled conditions.

For this test audio was taken from an NOAA weather transmission to provide a source of voice modulation that was consistent and repeatable in terms of amplitude and spectral content. The analog signal was modulated to +-5 kHz deviation, with limiting and pre-emphasis applied in the manner that is standard amateur practice. Interference to D-Star was noted by the appearance of "bloops" (caused by unrecoverable errors) in the received signal, and more than one "bloop" in a period of 10 seconds or so was considered to represent a degraded signal: It was noted that only slight (1-2 dB) increases in signal strength of the analog signal caused the D-Star signals to deteriorate very rapidly.

The results of this testing, using an IC-91AD for receiving, are as follows:

Situation	Result
On-channel interference	Interfering analog signal must be at least **17 dB *weaker*** to avoid interference.
Equal signal strength	A minimum separation of at least **9 kHz** is required to avoid interference from an analog signal that is of equal strength.
10 dB differential	A minimum separation of at least **11 kHz** is required to avoid interference from an analog signal that is 10dB stronger.
20 dB differential	A minimum separation of at least **13 kHz** is required to avoid interference from an analog signal that is 20dB stronger.
30 dB differential	A minimum separation of at least **16 kHz** is required to avoid interference from an analog signal that is 30dB stronger.
40 dB differential	A minimum separation of at least **19 kHz** is required to avoid interference from an analog signal that is 40dB stronger.
50 dB differential *(see note)*	A minimum separation of at least **22 kHz** is required to avoid interference from an analog signal that is 50dB stronger.

Figure 5: Interference to a D-Star signal from an analog NBFM signal

Note: Amplitude differences of 50 dB or greater are pushing the filtering and dynamic range limits of the receiver, as well as the ability of the test gear to simulate real-world signals

Analog susceptibility to interference by D-Star signals:

The amount of interference caused by a D-Star signal to an analog signal is a rather difficult parameter to judge because, unlike with the D-Star signal, interference will gradually get worse as the interfering signal's strength increases and/or the separation is reduced. The amount of interference experienced by the analog user also depends on the design of the receiver used and, in particular, the bandwidth of the filters in its I.F. To provide some indication of the severity of the amount of degradation of the analog signal, two parameters were measured:

- Amount of interfering D-Star signal required to reduce the SINAD to 12 dB. **This represents a significant and *unacceptable* amount of degradation.** While noticeably degraded, a signal of 12dB SINAD is still very copyable to even a semi-experienced radio user.

- Amount of interfering D-Star signal required to reduce the SINAD to 20 dB. This represents a ***noticeable*** amount of degradation (e.g. an increase of "hiss" or other background noise) but not enough to likely cause a loss of intelligibility under normal conditions. Even this amount of degradation is likely to be unacceptable to many users.

The analog signal used in this test was modulated at +-3 kHz with a 1 kHz sine wave.

For this test, several receivers were used, including:

- Icom IC-91AD (in "FM" mode, not "FM-Narrow" mode)
- Icom IC-2AT
- Yaesu FT-530
- Yaesu FT-817 (in "FM" mode, not "FM-Narrow" mode)

It was noted that the filters in the IC-91AD used for "normal" +-5 kHz deviation were narrower than those typically seen in similar radios, around 10.7 and 17.25 kHz at the -6 and -30 dB points respectively. The receiver filters in the other three radios were all about the same, approximately 15.0 and 21.0 kHz at the -6 and -30 dB points, respectively.

For the susceptibility of an analog receiver to interference to D-Star, the performance of the IC-91AD (in FM mode) was ***worse*** in the on-channel and 5 kHz spacing cases than the other receivers tried. For the list below, typical numbers are shown for the various receivers tested. The typical signal level for the analog test signal was -93 dBm, a signal that resulted in a SINAD of about 30dB. In certain cases, the levels of the two signals were varied by equal amounts to verify that the noted degradation was largely independent of absolute signal levels.

Situation	Degradation to 12 dB SINAD	Degradation to 20 dB SINAD
On-channel interference	D-Star signal must be **> 3 dB weaker**	D-Star signal must be **> 11 dB weaker**
5 kHz spacing	D-Star signal must be **> 3 dB weaker**	D-Star signal must be **> 7 dB weaker**
8 kHz spacing	D-Star signal must be **> 3 dB weaker**	D-Star signal must be **> 6 dB weaker**

9 kHz spacing	D-Star signal may be **<= 1 dB stronger**	D-Star signal must be **> 2 dB weaker**
10 kHz spacing	D-Star signal may be **<= 8 dB stronger**	D-Star signal may be **<= 4 dB stronger**
11 kHz spacing	D-Star signal may be **<= 16 dB stronger**	D-Star signal may be **<= 13 dB stronger**
12 kHz spacing	D-Star signal may be **<= 26 dB stronger**	D-Star signal may be **<= 22 dB stronger**
13 kHz spacing	D-Star signal may be **<= 32 dB stronger**	D-Star signal may be **<= 29 dB stronger**
14-20 kHz spacing *(see note)*	D-Star signal may be **<= 40 dB stronger**	D-Star signal may be **<= 40dB stronger**
30 kHz spacing *(see note)*	D-Star signal may be **<= 60 dB stronger**	D-Star signal may be **<= 60 dB stronger**

Figure 6: Interference to an analog signal from a D-Star signal

Notes:

- For 14-20 kHz spacing tests the results were fairly constant. When the D-Star signal was more than about 40 dB stronger than the analog signal, the reception of the analog signal began to degrade very rapidly. This is probably mostly a function of how signals within the IF of the receiver interact with such disparate signal strength. While different receivers varied at this amount of separation, the numbers shown were "average" - some receivers could handle more, some less. Note that at such spacings, off-channel signals may not be effectively filtered by the 1st IF's "roofing" filter, allowing additional degradation in later stages. Other noise sources (PLL phase noise, limiter noise from other IF stages, etc.) may also be a contributing factor in some cases.

- At 30 kHz spacing, the 1st IF filter of many receivers is beginning to have more of an effect, relieving some of the dynamic range limitations of the later IF stages. Also note that at this spacing, the primary limitation becomes one of dynamic range of the receiver's IF and RF stages more than the ability of the IF filters to reject off-channel signals and with a such a strong signal (e.g. one that is >= 60 dB stronger than the one being receiver) it is likely that ***any*** signal will begin to cause degradation.

Analysis of D-Star <> Analog interference:

As can be seen from the above data, the D-Star signal was actually ***more*** susceptible to interference from the analog signal than the analog signal was to the D-Star signal. This is likely a result of the "transient" nature of adjacent channel interference from an FM signal: While, on average, the energy from an FM signal is contained fairly close to the center frequency, occasional peaks of modulation or in the spectra of the signal being modulated will cause energy to occasionally appear farther afield. These occasional "peaks" will cause bit errors to occur in the received D-Star signal and if the number of errors gets to be too great, obvious decoding errors will result.

Note that in the analog domain, one has the obvious advantage in that the degradation increases more gradually as the interference worsens and this degradation is noted as the appearance of noise on the signal: Even moderate amounts of noise does not necessarily result in the loss of intelligibility.

D-Star signals and "Squelch Clamping" of analog signals:

It hasn't been mentioned above, another potential interference potential of D-Star signals to Analog signals is ***squelch-clamping***. If, for example, both an analog and digital signal are overlapping - either in terms of coverage or due too-close channel-spacing - the digital modulation of the D-Star signal - which is, in effect, noise - can "fool" the squelch of an analog FM receiver into thinking that the analog signal is weaker than it really is.

The result of this is that interference of a D-Star signal to an analog signal - particularly a weak analog signal - can cause squelch clamping - that is, the receiver's squelch closing even when the signal would otherwise seem to be strong enough that the squelch *shouldn't* close! ***Both laboratory and field tests indicate that placing an Analog and D-Star signal 10 kHz apart (or closer) will result in levels of interference (including squelch-clamping) that analog users will find unacceptable, especially in those geographical areas where both signals overlap.***

Channel spacing recommendations:

In real-world situations, it is recommended that ***at least*** 30dB of margin be designed into the systems when it comes to interference potential - and even more is preferred where practical. It is perfectly reasonable to expect that two adjacent channels could have amplitude differences of 30 dB within their primary coverage areas, so suitable margins must be considered when frequency coordination is done. In some cases, even more than 30 dB of margin will be required - as might be the case for repeaters with extremely large coverage areas, links, or in the consideration of frequency-reuse in some cases.

It should also be recognized that even if such a margin is designed into a system, a significant interference potential still exists, particularly when one considers that due to multipath and various propagation phenomena, signals from both the desired and undesired transmitters can be momentarily enhanced or degraded considerably - an effect that is most likely to be a problem in those areas with overlapping coverage. In such situations, D-Star tends to fare worse, as the codec may take some time to re-synchronize after it has lost lock and several syllables may be lost.

Another consideration is that the normal tolerances of frequency stability for amateur gear may result in a transmitter (or receiver) being somewhat off-frequency: It is not unreasonable for a UHF transmitter to be 1-2 kHz off frequency after normal component aging, when it is hot or cold, or if the radio has been exposed to severe mechanical shock - values that may still be within the manufacturer's specifications. In these cases, degradation of the communications link can be expected and sufficient channel-spacing margin must be allowed for such occurrences - and those where radios, for whatever reason, are beyond the manufacturer's specifications.

"What about the 'Real World'?"

With all of this talk about "Simulated" D-Star signals, you might be asking why we just didn't use "real-world" signals?

Well, we have, to some extent.

As you might imagine, the real world isn't particularly cooperative when it comes to trying to set up experiments - particularly when arbitrary signal levels and specific scenarios are required. In lieu of that, one may make observations of real-world signals and then try to simulate similar conditions (relative signal levels, adjacent interference conditions, etc.) in a laboratory environment and see if they correlate.

While we have only a limited number of data points - primarily because there are so few systems and only a small number of users that are currently active in this area - we have found nothing that would indicate real-world results that are significantly different from those "simulated" conditions.

Based on the above test data as well as frequency and spectral analysis, the following are recommendations of the Utah VHF Society:

- **D-Star to D-Star channel spacing: 12.5 kHz *minimum***

- **D-Star to Analog channel spacing: 15 kHz *minimum***

On 2-meters, the above recommendation is complicated by the fact that the channel spacing in Utah is 20 kHz - something that does *not* readily lend itself to the adoption of 12.5 kHz spacing. This has two important implications:

- Several D-Star systems should be placed on adjacent frequencies. If two consecutive channels are available (a total of 40 kHz) that means that a total of 3 D-Star channels may be placed within this space and still provide protection of adjacent analog channels from interference. Given the current heavy usage of the 2-Meter band, careful coordination will be required to find contiguous spectrum.

- A single D-Star signal may be placed where there was an analog signal. Unfortunately, in this situation, one cannot take advantage of the spectrum-reducing capabilities of D-Star.

It is also worth noting that, theoretically, D-Star offers ***no spectrum savings at all*** when compared with the use of "FM-Narrow" ("FM-N" using +-2.5 kHz deviation) mode! This should come as no surprise, as the ***same*** receiver filters and demodulator are used in both D-Star and the "FM-N"! One important difference, however, is that unlike analog voice, D-Star's modulation is rather consistent in its power density unlike analog voice, which can have peaks that vary with the voice modulation - something that could cause occasional impacts on adjacent voice and data channels were they spaced too-closely.

The transmit bandwidth of a D-Star signal has been analyzed and measured to be over 60 dB down at +-10 kHz, so it ***may*** be possible to place a D-Star signal 10 kHz away from a band edge and maintain compliance with FCC rules pertaining to spurious and out-of-band emissions, but transmitter frequency tolerance considerations must still be observed!

On 70cm, with 25 kHz analog channel spacing being used in Utah, it is perfectly reasonable to place two D-Star channels within one analog channel: One D-Star signal would have a frequency 6.25 kHz below and the other would be placed on a frequency 6.25 kHz above the center frequency of the analog channel. Such spacing would also afford protection between adjacent D-Star and analog users. The caveat to this recommendation is that *not all D-Star capable radios are able to tune in 6.25 kHz steps -* ***see the warning below***.

Why 12.5 kHz minimum spacing instead of 10 kHz?

Why 12.5 kHz D-Star to D-Star spacing when others have said that even 10kHz might be wasteful?

- **An oft-overlooked consideration is transmitter and receiver frequency stability.**

For example, the specifications for the IC-91AD are +-2.5ppm - and this implies that the transmitter or receiver could be a bit over 1 kHz off-frequency on 70cm. With adjacent channels, this means that two channels could be 2 kHz closer to each other (if, say, the lower one was 1 kHz high and the upper one was 1 kHz low) and reduce the spacing to less than 10.5 kHz - a difference that reduces margins somewhat.

Conversely, if a 10 kHz spacing is used, frequency variances could reduce the spacing to less than 8 kHz under worst-case conditions - a separation that pushes against the skirts of receivers' IF filters, not to mention the transmit signal spectra!

- **The bandwidth of the receivers' IF filtering must be taken into account.**

One often hears about D-Star signals taking up less than 7 kHz of transmit spectrum. While this may be the case, in theory, the fact is that the receivers that one uses to decode such signals necessarily have filters that are ***wider*** than this! If you refer to **Figure 2** (above) you'll notice that the -6dB bandwidth of a typical receiver is over 8 kHz and that the -30dB bandwidth is over 11 kHz!

Tests with actual radios indicate that if an adjacent D-Star signal is 30dB stronger that the one to which you are trying to listen, it is required that the two signals be separated by at least 10.5 kHz in order to minimize interference. You might wonder why we would care about 30dB difference between two signals: Admittedly, it's a rather nebulous figure, but its fairly representative of many situations in which there is a rather distant and nearby transmitter and the amount of signal difference that one might expect to see between the two.

In more rural areas - such as those where both potentially-interfering repeaters may be quite distant - this 30dB figure may be rather conservative. Conversely, even 30dB may be an insufficient margin in an area in which many users of two repeaters happen to be located quite nearby one of them. The upshot of this is that you will *probably* be safe with this "30dB" figure (with reference to the 10.5 kHz spacing measurement) and 12.5 kHz spacing is just the next step up.

- **Most D-Star radios exhibit characteristics of "Frequency Wobble".**

If one carefully scrutinizes the output of most D-Star transmitters - specifically, those that modulate the PLL - you'll observed that they tend to wander about several hundred hertz. This is the inevitable result of the conflicting requirements that the PLL maintain the transmitter on-frequency *and* that to modulate the transmitter, you must knock it off-frequency!

Because the D-Star modulation contains spectral components down to the 10's of Hz (such as those resulting from the 50 Hz "frame" rate) it is necessary that the PLL be designed to avoid countering of those low-frequency components - yet one must make it fast enough that the radio's synthesizer locks up quickly when the radio is keyed. A result of these seemingly conflicting requirements is that a compromise had to be made in the design and this results in the radio's transmit frequency wandering up and down as the "average" frequency of the carrier-plus-modulation is biased one way or another.

The magnitude of this "wobble" seems to vary, but it has been observed to be as much as +/- 500 Hz on some radios. What this means is that the occupied bandwidth of the transmit spectra is actually up to 1 kHz *wider* than simple theory might suggest.

Some radios - such as the ID-1 and the ICOM repeaters - impart the modulation on the transmitted carrier differently and do not exhibit this phenomenon.

Remember: The above are ***minimum*** spacing recommendations. Depending on the specific situation, there may need to be other considerations based on the necessity to protect existing systems.

Comments:

- *These recommendations assume that the primary mode of operation is to be voice. D-Star data transmissions tend to be more susceptible to errors than voice transmissions, owing mostly to the inbuilt FEC in the voice coding as well as the redundant nature of human speech and the ability of the listener to mentally "fill in" missing pieces: Data transmissions may not be so forgiving to errors in reception and require greater margins. If time permits, similar tests may later be run using "data-only" transmissions.*

- *The above Analog<>Digital interference tests* ***do not*** *include measurements pertaining the use of "FM-Narrow" (+-2.5kHz) operation. While many newer* *amateur transceivers include such a mode - along with narrower IF filtering in the receiver - unless there is a mandated, strict adoption of its use, it is unlikely that it will become commonplace in the near future.*

Other D-Star Co-channel and adjacent channel tests:

Mark, N5RFX, has also done some adjacent-channel testing for D-Star signals: The results of this testing are in his paper, ***found at this link***. *Due to the original link disappearing, this is a locally-archived copy.*

Please note that the presentation, methods, and criteria of these tests were slightly different from those that we have done, so one must read both writings carefully before making comparisons. If anything, Mark's results show a greater tolerance of D-Star signals to the various interfering sources than what we observed. At least some of these differences are due to the fact that the the ID-800, the receiver used by Mark, seems to be better at tolerating adjacent-channel signals/interference than the IC-91AD, the radio that we used for our testing, plus the fact that the threshold of acceptable degradation to the D-Star signal may have been different: Because the Icom gear available at the time of this writing lacks means of making quantitive error measurements, measurements of degradation are inevitably somewhat subjective.

Channel spacing for 128kbps D-Star ("DD" mode) on 23cm:

Another D-Star standard may be found on the 23cm (1200 MHz) amateur band. On this less-crowded band it is permitted to run much higher symbol rates than is permitted on 2 meters and 70cm and a 128 kbps mode is available: One radio that can operate using this protocol is the Icom ID-1. Also capable of the "standard" 4800bps DV mode found on the 2 meter and 70cm band, the addition of 128kbps makes higher-speed links practical. The ID-1 has its own Ethernet interface, allowing standard internet IP protocols to be passed around over the air using half-duplex with a reported throughput of up to 90kbps.

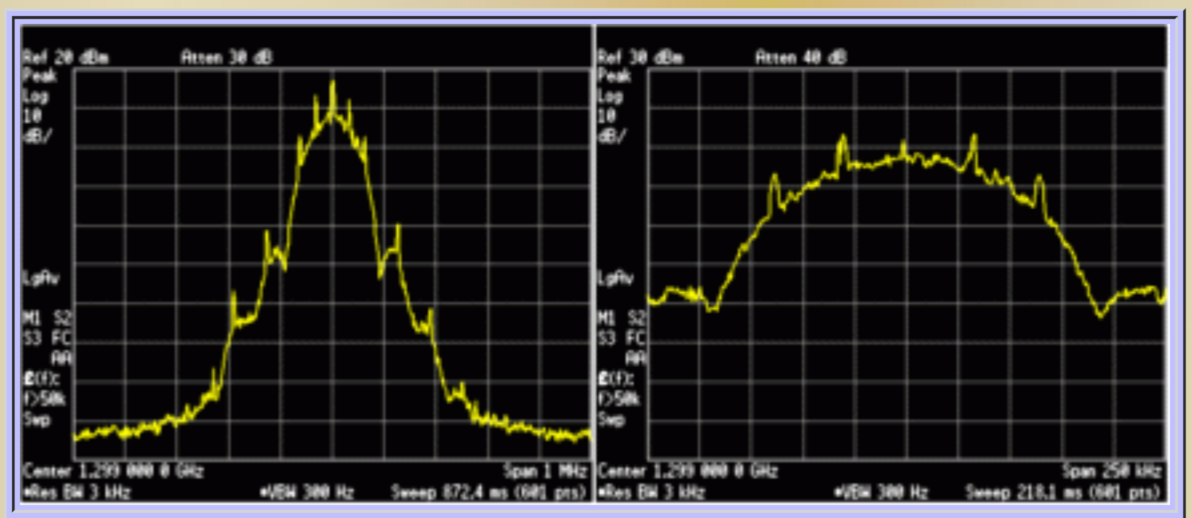

Figure 7:
Spectrum analyzer plots of a 128kbps D-Star signal on 23cm in a span of 1 MHz (left) and 250 kHz (right).
Click on image for a larger version.

With this higher speed comes a much wider bandwidth, but how wide, exactly? **Figure 7** shows the transmitted spectra of an Icom ID-1 in **DD** mode (128kbps.) As can be seen from this plot, the signal is about 150kHz wide (at the -26dB points) as is mentioned by the specifications, but one can also see that sidebands extend beyond this, albeit at much lower levels.

Channel spacing:

Given that the bandwidth appears to be on the order of 150 kHz, one might believe that 150-200kHz channel spacing would be adequate - ***but this would be incorrect***. According to ICOM's own specifications, the receive bandwidth characteristics for the ID-1 are:

- >140 kHz at -6dB
- <520 kHz at -40dB

It is this latter figure that dictates the minimum channel spacing. Clearly, 150kHz spacing is far too narrow, so allowing for a reasonable degree of adjacent-channel isolation, the Utah VHF Society recommends a channel spacing for these carriers of **500 kHz**.

Comment on the IF filtering used in the ID-1:

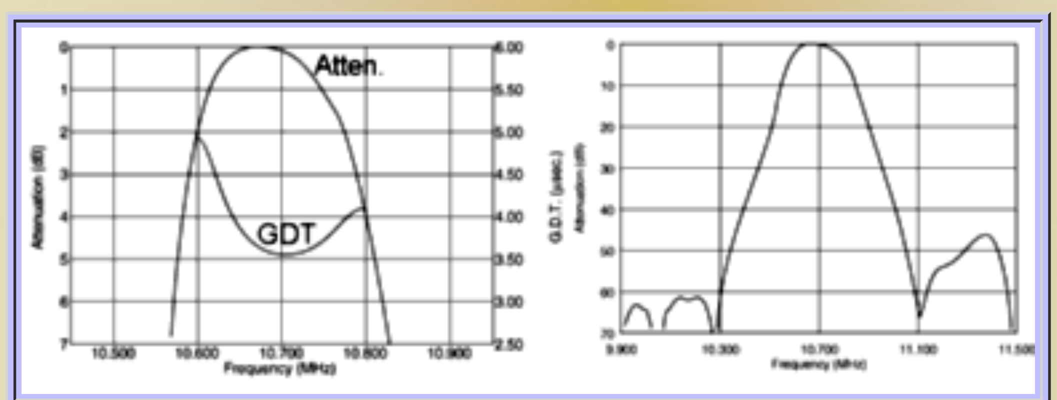

Figure 8:
*Passband and group-delay plots of the 10.7 MHz 2nd IF filters used in the ID-1 for 128kbps DD mode. These plots are for single filters, but note that the ID-1 uses **two** such filters in cascade to set the receiver bandwidth. (Source: Murata)*
Click on image for a larger version.

It was noted that the ID-1's final IF frequency is 10.7 MHz. Inspection of the ID-1's service manual reveals that it uses a pair of cascaded 10.7 MHz ceramic filters of the sort used in commercial FM broadcast receivers. These particular filters (Murata SFELA10M7HA0G-B0) are designed specifically for data use and have a slightly poorer shape factor than standard ceramic filters used in FM broadcast receivers to optimize group delay response to minimize distortion of the data. According to Murata (and as can be seen in **Figure 8**) the stated specifications for these filters are:

- 3dB bandwidth of 180 kHz
- 6dB bandwidth of 250 kHz
- 20dB bandwidth of 400 kHz
- 40dB bandwidth of 600 kHz

*Note that **two** of these filters are used in series in the IF chain to improve the response, with an MC3356 used as a demodulator. In the first IF (at 243.95 MHz) there is a SAW filter that provides "roofing" filtering for all digital and analog modes: The nominal bandwidth of this filter appears to be on the order of 750 kHz, but further specifications are not yet known.)*

It is hoped that we will be able to aggregate several Icom ID-1's and perform more detailed tests to determine adjacent-channel tolerance at various spacings and signal levels. Being that 23cm isn't a heavily-utilized band in Utah and that presently-available D-Star systems are synthesized, the 500 kHz spacing seems to be a "safe" value and, if further testing warrants that a narrower (or wider) spacing is more appropriate, changes can be made at that time with little inconvenience.

The GMSK modem used in the ID-1 and IC-91AD:

The ID-1 uses a CMX589A GMSK modem chip for recovering data from the GMSK baseband signal from the MC3356 demodulator in both the low-speed (DV) and high-speed (DD) modes: The ID-1 uses a separate modulator to generate I/Q signals for transmit, leaving half of this chip unused. The ID-91AD, on the other hand, uses this chip for both reception of and generating the GMSK baseband waveforms.

The CMX589A is an integrated receiver/transmitter that is designed to receive and generate GMSK baseband waveforms. *(A data sheet for this chip may be found **here**.)* Interestingly, this chip has an "RX S/N" pin that outputs a signal that can be used to approximately estimate the signal-noise ratio of the received signal, but alas this connection (pin 23) is left disconnected in the ID-1 and IC-91AD: This is a pity, as the use of this pin might have proven helpful in determining optimal signal quality when setting up D-Star links, not to mention in everyday use by the casual user!

Comment: *The ID-1 uses this chip only for receive while the IC-91AD uses it for both receive and transmit. It is worth noting that "BT" (e.g. the ratio of the transmit filter's -3dB bandwidth and the bit rate) is set for 0.5 in the IC-91AD's modulator, a reasonable compromise between occupied bandwidth and **ISI**.*

A Warning about the selection of channel spacing and center frequencies:

It should be remembered that not all Icom D-Star capable radios have the ability to tune in the same size of frequency steps. In order to better-fit into the bandplan of existing systems, it might be tempting to pick a frequency that is based on a multiple of 6.25 kHz.

Not all Icom D-Star radios are capable of tuning in 6.25 kHz steps! An example of a radio that ***cannot*** tune 6.25 kHz steps is the Icom IC-2200H: This radio can tune in 5 and 12.5 kHz steps and various multiples of of those step sizes.

Before deciding on a frequency plan for your D-Star channels, make sure that the center frequencies that you pick are, in fact, based on multiples of 5 or 12.5 kHz or you will leave people out!

Disclaimers:

- **The above recommendations are based on experience, analysis, and the testing described. They also take into account current Utah frequency coordination policies, which are based on previous and ongoing experience and geographical considerations.**
- **The above recommendations should *not* be applied in other areas of the world without due consideration of local operating practices, needs, and conditions to determine if they are appropriate.**

Other Utah VHF Society links related to D-Star:

- **Using conventional test gear to evaluate and test D-Star systems** - This page covers some aspects of D-Star and analog signals and related test equipment that may make it easier to evaluate the performance of D-Star systems and links.
- **Observations of the codec used for D-Star** - How does the codec used for D-Star respond if subjected to sounds other than those of the human voice? We decided to find out.
- **D-Star repeater installation - **Experiences, problems encountered with the installation of a D-Star Stack at a *very* busy radio site - and solutions to these problems.

The following are FAQ's provided by the Utah VHF society. Note that these may topically overlap the links above:

- **FAQ: A brief overview of D-Star**
- **FAQ: D-Star and sharing with other D-Star and analog users**
- **FAQ: Direction-finding and D-Star signals**
- **FAQ: D-Star vs Analog audio quality**
- **FAQ: Utah channel spacing recommendations for D-Star and Analog signals**

Misc. links related to D-Star:

- **http://en.wikipedia.org/wiki/D-STAR -** This has a general overview of D-Star.
- **http://www.arrl.org/FandES/field/regulations/techchar/D-STAR.pdf** - This document specifies various aspects of D-Star and its protocols.
- **http://www.ccarc.net/images/CCARC-Spectrum%20Committee%20Report-%20Rev%203.pdf -** This is a document produced by the Colorado frequency coordination body discussing D-Star channel spacing.

70cm and 23cm RADAR and D-Star

It is easy to forget that most of our amateur bands are actually shared with other users - and that in many cases, the amateur radio operators are ***secondary*** users - in many cases, second to the U.S Government.

Most of the time, the needs of the two do not conflict, but one needs only look as far as the recent "mitigation" efforts relating to the the "Pave Paws" (see the story "**ARRL, DoD, FCC Try to Come to Terms with Pave Paws**") that have required several repeater operators to modify their operations by reducing power, changing antenna patterns, or curtail operations entirely - that is, go off the air!

It should also be noted that even if amateur operations do ***not*** cause harmful interference to other users, those other operations ***may*** have a negative impact on amateur operations!

For example, 70cm users of analog modes in some areas may be well aware of the interference caused by such RADAR systems: In many cases, the interference is quite obvious - possibly annoying - to the various users, but it does not prevent the use of the frequency.

Such cases of interference may simply be too much for users of digital audio modes, however! While D-Star includes various error-correcting techniques, these are better-suited for handling the "occasional" bit error rather than a continuous barrage of pulses - say, from a RADAR system. Furthermore, an affected system - often at a high location - may be more-subject to such interference sources than would the average users. Finally, since many of these RADAR systems are adaptable in terms of their transmitter characteristics (pulse types, power, beam pattern, etc.) and the fact that propagation conditions change, a given repeater system may experience degradation only occasionally. The sporadic nature of such interference situations - plus the unfortunate fact that D-Star has very little in-built diagnostic capability - could mean that such situations could be extremely difficult to diagnose, let alone correct!

Users of 23cm "DD" modes also should be aware that the 23cm band is heavily utilized for long-range RADAR as well! These transmitters often have ERPs in the megawatt range and can raise the noise floor over 10's of MHz around their center frequency due to a number of different mechanisms! Additionally, with such high signal levels it is possible that front-end components of the radios being used will simply experience degradation due to overload - even if the interference source is significantly removed in frequency from the amateur operations and there is little or no on-frequency energy!

When a 23cm D-Star system is planned, it is ***imperative*** that one determines where and how 23cm is used for RADAR in your area! Sometimes, this isn't an easy task and you'll have to make discreet inquiries through well-connected people - especially since anyone making such inquiries may initially be viewed with suspicion. Even after all of this, you should be prepared to drag a spectrum analyzer *(and someone who knows how to use it to capture transient pulses like a RADAR!)* to a prospective site and look at the 23cm band and surrounding frequencies to see what sort signals might be there - keeping in mind that you may be unlucky enough to do so at a time that the potentially-offensive RADAR may not be active or operating at full power!

If 23cm RADAR activity is noted in your area, be prepared to do further investigation - particularly in determining if it will still cause notable degradation to the site's noise floor at a frequency many MHz away! Also, be prepared to install filtering that is ***additional*** to the "standard" duplexer provided with the repeater!

Since the 23cm DD mode is fairly broad-band, it is arguably more susceptible to such interference sources than the lower-rate audio modes. Such interference - especially due to its likely periodic nature - will cause packet loss and retries and reduce throughput - especially since the DD modes don't have as robust error rejection as the speech modes! Again, the dearth of built-in diagnostic tools available to the D-Star system operator can make the identification and resolution of such problems even more difficult!

- **http://groups.yahoo.com/group/dstar_digital** - This group harbors discussions and information about D-Star.
- Mark, N5RFX, has conducted similar Adjacent and Co-Channel testing, the results of which may be seen here: **http://home.roadrunner.com/~mdmiller7/images/dv/ch_sp/Dstar_Co.pdf.** Note that the equipment used, methodology, and the thresholds for various aspects of these tests are slightly different from those described on this page, yielding slightly different results: The reader must take these differences into account before attempting to draw direct comparisons between these two sets of results.
- **http://dstarutah.org** - The Utah D-Star group

The above list is, by no means, exhaustive: Other information may be found via web searches.

This matter is open for discussion: If you have concerns or opinions one way or another, please make them known to the frequency coordinator at the email address below.

Questions, updates, or comments pertaining to this web page may be directed to the frequency coordinator.

Return to the Utah VHF Society home page.

Updated 20121220

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