10 GHz Aircraft Scatter with Q65

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Q65 has proved very effective for 10 GHz rain-scatter and tropo-scatter on a 568 km obstructed path using 60 and 120 second Tx/Rx periods [(1)]. Subsequent tests of Q65 in 15 second periods on the same 568 km path have shown that it is also very effective for aircraft-scatter. Our initial aircraft-scatter tests were done with WSJT-X Version 2.4.0-RC4 which proved to be limited to Doppler shifts below about 5 Hz/second. This in turn limited its use to aircraft crossing the path at no more than about 30 or 40 degrees at 10 GHz.

WSJT-X Version 2.5.0-GA[(2)] introduced tracking of frequency drift (along with the Max Drift spinner control) and this has proven effective for aircraft crossing at up to 90 degrees at 10 GHz and producing Doppler shifts of up to at least 20 Hz/sec. An enhanced version of the Q65 decoder was introduced in WSJT-X Version 2.5.1, that provides a further improvement of 1 to 3 dB for large Doppler shifts once both callsigns are known. In general the enhanced version is around 5 dB more sensitive than modes such as ISCAT and JT9 which were previously used for microwave aircraft scatter and up to 12 dB more sensitive for large Doppler shifts (10 to 20 Hz/s).

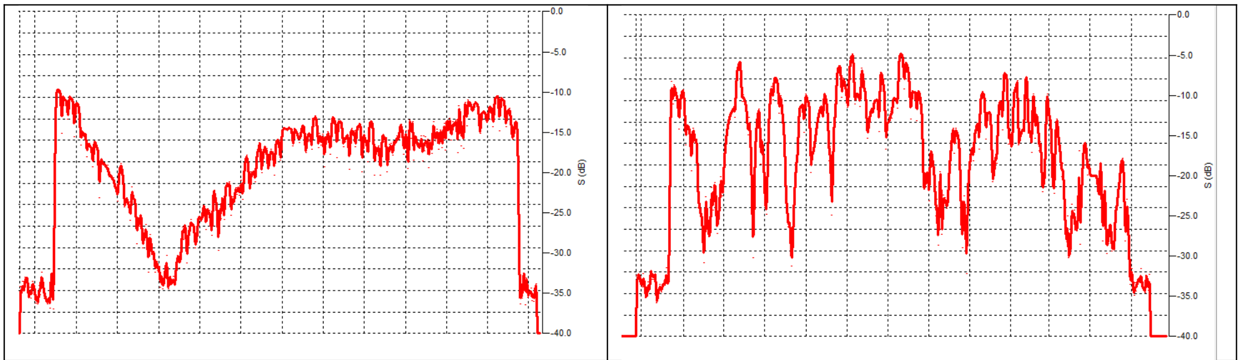
Aside from Doppler shift, another characteristic at 10 GHz of aircraft-scatter on aircraft crossing at large angles is that the scattered signal has significant amplitude bursts. In this article we have examined the implications of both Doppler shifts and amplitude bursts on the performance of Q65 and compared the performance of Q65 to other WSJT-X modes. A significant advantage of the enhanced version is that it works on short bursts of just a few seconds when both callsigns are known such as when working a sked.

While tropo-scatter is typically limited on 10 GHz to 500 to 600 km path lengths for 10 watt 60 cm dish stations, aircraft-scatter has the potential of extending the distance to 800 to 900 km if both stations have close to zero elevation take-offs. Thus Q65 has a niche role for collecting grid locators on 10 GHz using aircraft-scatter in the range 500 to 900 km.

Characteristics of Aircraft-Scatter

The assessment of the performance of digital modes, such as in WSJT-X is generally described for signals of constant level and frequency, and reported as the SNR in a 2.5 kHz passband at which 50% of attempted decodes are successful. In the case of aircraft-scatter performance is affected not only by the SNR, but also by the rate of change of Doppler shift and by substantial short-term variations in the signal level produced by the narrow beamwidth of the forward scatter lobes at microwave frequencies [(3)].

At VHF the Doppler variations even for crossing aircraft are not an issue and as the forward scatter lobes are several degrees wide the amplitude variations are minimal. But at 10 GHz with civil jet aircraft crossing the path at about 25 degrees the Doppler shift can be around 2 Hz/sec and amplitude variations of around 20 dB over several seconds can occur. At 10 GHz for civil jet aircraft crossing perpendicular to the path the Doppler shift can reach 20 Hz/sec and the amplitude variations can occur over periods of less than a second. Fig 1 gives examples of amplitude variations for Doppler variations of 1.8 and 15.5 Hz/sec. Given the irreproducibility of amplitude variability it is difficult to make quantitative comparisons between modes with on-the-air testing. An alternative which we have followed is to run simulations with a range of Doppler shifts with constant amplitude signals (Fig 3) and try to confirm the results with more limited on-the-air tests.



Doppler shift 1.8 Hz/sec 568 km path	Doppler Shift 15.5 Hz/sec 382 km path

Fig 1: Examples of amplitude bursts with different Doppler shifts. The horizontal scale as represented by the vertical lines are at one second intervals. The vertical scale numbers are at 5 dB intervals

Fig 2 shows Doppler shifts in situations one is likely to encounter in practice at 10 GHz. WSJT-X Version 2.5.1 can handle Doppler shifts of up to 26 Hz/sec by setting the "Max Drift" spinner to its maximum value of 50. Accordingly, Version 2.5.1 should be suitable for almost all situations one is likely to encounter.

		Crossing angle			
Distance	**Crossing Point**	**10 Degrees**	**20 Degrees**	**50 Degrees**	**90 Degrees**
300 km	Centre of Path	-0.6 Hz/sec	-2.4 Hz/sec	-12.9 Hz/sec	-22.7 Hz/sec
500 km	Centre of Path	-0.3 Hz/sec	-1.3 Hz/sec	-7.6 Hz/sec	-13.6 Hz/sec
700 km	Centre of Path	-0.2 Hz/sec	-0.9 Hz/sec	-5.3 Hz/sec	-9.7 Hz/sec
900 km	Centre of Path	-0.1 Hz/sec	-0.7 Hz/sec	-4.1 Hz/sec	-7.6 Hz/sec
300 km	25% of Path	-0.7 Hz/sec	-3.0 Hz/sec	-17.0 Hz/sec	-30.3 Hz/sec
500 km	25% of Path	-0.3 Hz/sec	-1.7 Hz/sec	-9.9 Hz/sec	-18.2 Hz/sec

Fig 2: Doppler shifts for an aircraft speed of 800 km/hr at 10.368 GHz. For other aircraft speeds and frequencies the data can be proportioned.

Simulations

W3SZ had previously developed a software simulation approach to test the effect of Doppler shift on digital mode performance. Applying this approach to various WSJT-X modes with constant-amplitude signals and various rates of Doppler shift produced the results in Fig 3 below.

Mode	Tone Spac-ing (Hz)	Mess-age Dura-tion (secs)	BW (Hz)	S/N Shift 0 (Hz/s)	S/N Shift 2 (Hz/s)	S/N Shift 4 (Hz/s)	S/N Shift 5 (Hz/s)	S/N Shift 10 (Hz/s)	S/N Shift 15 (Hz/s)	S/N Shift 20 (Hz/s)
Q65-15A*	6.67	12.8	433	-23	-18	X	X	X	--	--
Q65-15B*	13.3	12.8	867	-22	-20	X	X	X	--	--
Q65-15C*	26.6	12.8	1733	-21	-20	-19	X	X	X	--
Q65-15A$	6.67	12.8	433	-23	-21	-20	-20	-19	-18	-17
Q65-15B$	13.3	12.8	867	-22	-21	-20	-20	-19	-18	-18
Q65-15C$	26.6	12.8	1733	-21	-21	-20	-20	-19	-19	-18
Q65-15A#	6.67	12.8	433	-23	-21	-21	-20	-19	-20	-18
Q65-15B#	13.3	12.8	867	-22	-21	-21	-21	-21	-21	-21
Q65-15C#	26.6	12.8	1733	-20	-20	-20	-20	-20	-20	-20
ISCAT-A-15	21.5	1.17	905	-16	-15	-13	-12	X	--	--
ISCAT-B-15	43.1	0.58	1809	-15	-15	-14	-13	-11	-10	-9
JT9-15E	25	3.4	225	-14	-13	-12	-11	-9	X	X
JT9-15F	50	1.7	450	-13	-12	-12	-11	-10	-10	-9
JT9-15G	100	0.85	900	-10	-11	-10	-10	-9	-9	-9
JT9-15H	200	0.425	1800	-7	-7	-7	-6	-7	-6	-7
MSK144	1000	0.072	2400	-9	-9	-8	-8	-7	-6	-6
FT8	6.25	12.6	50	-20	X	X	X	X	--	--

* WSJT-X Version 2.5.0 with Max Drift set to zero (equivalent to Version 2.4.0 RC4)
$ WSJT-X Version 2.5.0 with Max Drift set to 50
\# WSJT-X Version 2.5.1 with Enhanced Q65 decoder with Maximum Drift set to 50
X Means did not achieve 90% level
-- Tests not undertaken but assumed to result in nil decodes

Fig 3: Simulations showing the impact of the Doppler shift on various modes and sub-modes (Based on decoding probability above 90%). Because performance as a function of SNR generally drops off rapidly as SNR falls below the value required to produce 90% successful decodes and given the short time available to complete aircraft scatter QSOs we chose a successful decode probability of 90% as the criterion for comparing the performance of the various modes and sub-modes.

From Fig 3 it is seen that for signals of a constant amplitude the enhanced version of Q65-15 is around 5 dB more sensitive than ISCAT when there is little Doppler shift and up to 12 dB more sensitive at high Doppler shift rates.

Implications of Amplitude Bursts on Decoding

While 10 GHz aircraft-scatter signals often come in short bursts of just a few seconds the heavy Forward Error Correction provided in Q65-15 typically allows decoding with weak and variable bursts of no more than 5 seconds and even less when both callsigns are known such as when running a sked.

Right Angle Crossing Aircraft

Figs 4a and b show an example of an aircraft crossing at right angles on a 568 km path and producing a Doppler shift of around -13 Hz/sec. The signal peaks in the centre period file 015230, but in the preceding and succeeding sequences the signal is limited to short bursts. Both of these short bursts decode -- the first which is shorter and weaker requires AP but the second which is only slightly longer does not require AP as is seen in Fig 4b.

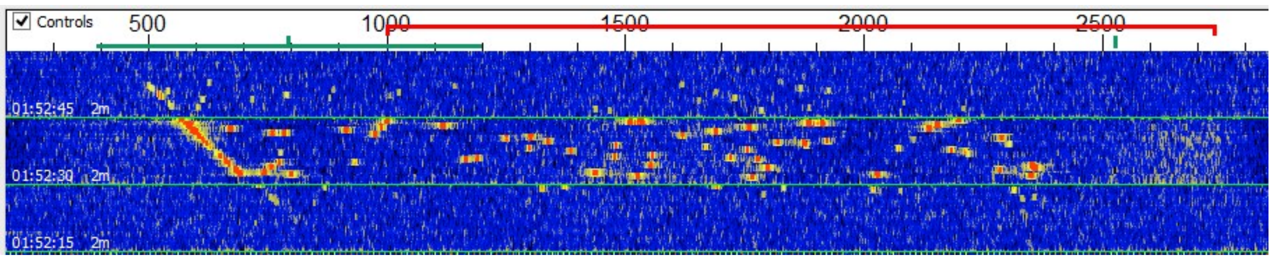


Fig 4a: Waterfall display of a Q65-15C signal from an aircraft crossing at right angles to the path of propagation

UTC	dB	DT	Freq		Message	
015215	-11	0.2	739	:	VK7MO VK3WE -15	q3
015230	6	0.1	632	:	VK3WE VK7MO R-15	q0
015245	-11	0.1	492	:	VK7MO VK3WE -15	q0

Fig 4b: Decodes for the situation in Fig 4a

At first glance it seems odd that the file 015215 decodes with the Q3 decoder, which does not have Doppler correction, despite a Doppler shift of -13 Hz/s. The likely explanation is that on a very short burst the total Doppler variation (= Burst Duration x Doppler shift rate) is much less than it would be with a signal present throughout the 15-second T/R period. Nevertheless when we applied degradation to this file it was possible to achieve decodes at a lower level with the enhanced decoder.

Based on a number of tests with right angle crossing aircraft we can report that because of the very narrow forward scatter lobe at 10 GHz it is generally not possible to achieve more than 2 or 3 decodes on a single aircraft pass and thus for right-angle crossing aircraft it is generally necessary to wait for two or three aircraft to complete a QSO.

Examples of use of the Enhanced Decoder

The enhanced decoder in WSJT-X Version 2.5.1 provides Doppler correction of the standard Q3 decoder. It provides an additional 1 to 3 dB sensitivity when the Doppler is large (e.g. above -4 Hz/s on the B sub-mode or above -7 Hz/s for the C sub-mode) for messages with reports once the callsigns are known. The enhanced decoder is implemented only when "Max Doppler" is set to 50. Enhanced decodes are identified as “q5” at the end of the decode line.

Fig 5 is an extract of one test session conducted over a 500 km path between W3SZ in Pennsylvania and W1FKF in New Hampshire. This session ran for about 90 minutes and produced about 70 decodes at W1FKF's end. In most cases the Doppler shift was only a few Hz/s and the enhanced decoder was not required. However, Fig 5 focuses on those files that decoded with more than -7 Hz/sec Doppler shift with the "Fast" decode setting. As can be seen, for this subset of signals with high Doppler shift the enhanced decoder increased the number of decodes from 4 to 7. While this is a small sample it does suggest a very useful advantage with the enhanced decoder, consistent with the results we obtained with simulation as summarised in Figure 3.

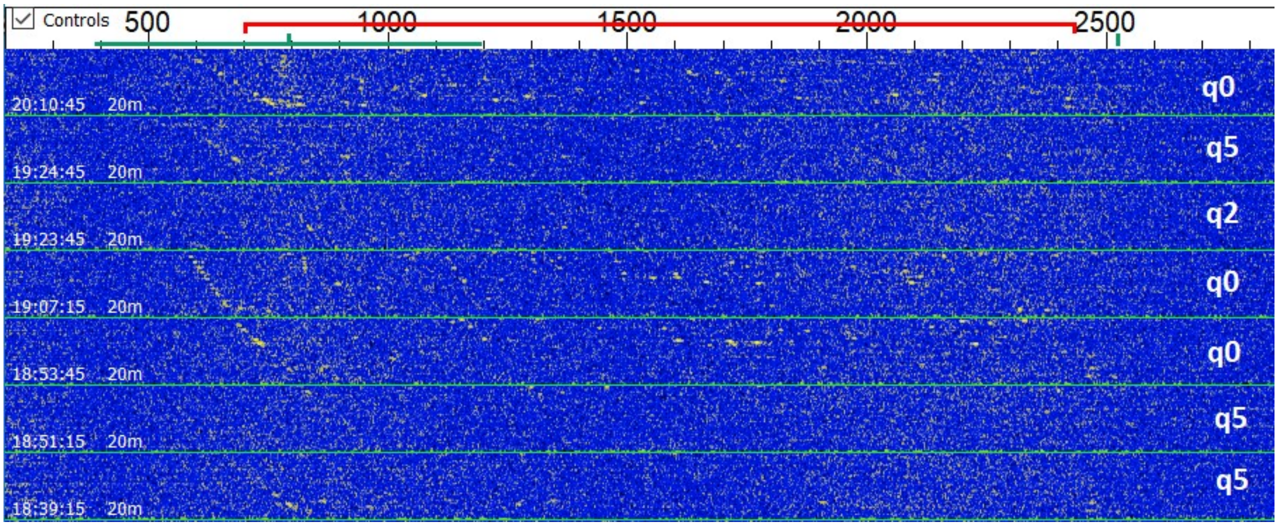


Fig 5a: Examples of enhanced decoder (q5 identifier) compared to the standard decoders. Note that the enhanced decoder is able to give correct decodes with very short and weak bursts.

UTC	dB	DT	Freq		Message	
183915	-13	0.3	818	:	W1FKF W3SZ -15	q5
185115	-14	0.3	978	:	W1FKF W3SZ -15	q5
185345	-9	0.3	744	:	W1FKF W3SZ -15	q0
190715	-9	0.3	624	:	W1FKF W3SZ -15	q0
192345	-14	0.2	811	:	W1FKF W3SZ -15	q2
192445	-13	0.2	738	:	W1FKF W3SZ -15	q5
201045	-8	0.3	664	:	W1FKF W3SZ -15	q0

Fig 5b: Decodes relevant to Fig 5a above.

False Decodes

We have done extensive testing of Version 2.5.1 and have not seen one false decode in on-air tests. Compared to ISCAT which frequently produces false decodes this is a major advantage.

Practical Considerations

Because of the very narrow beamwidth of the forward scatter lobes at 10 GHz it is necessary to minimise QSO duration and thus to use the fastest T/R period available and for this reason all our tests were done with 15 second T/R periods. A short T/R period is also important for reducing the total amount of Doppler variation during a transmission (total Doppler variation = T/R period x Doppler shift rate). 15 second periods also have a significant advantage over longer periods when the received signal consists of short bursts, because the duration of each tone in a 15 second period is half the duration of a tone in a 30 second period. So while it is possible to achieve an AP decode in say a 2 or 3 second burst with a 15 second period, one would need a burst twice as long to achieve that decode in a 30 second T/R period, as it would take twice as long to receive the same number of tones in a 30 second period.

The simulation results as set out in Fig 3 suggest there are only small differences in performance between the A, B or C sub-modes of Q65-15. The B sub-mode has a small advantage over both the A and C sub-modes at high Doppler shift rates. As the Doppler compensation is based on a linear fit the C mode with its wider 26.7 Hz tone spacing may have an advantage over sub-modes A and B if the Doppler variation is not linear. One issue with the C sub-mode is that the total BW for Q65-15C is 1733 Hz and with Doppler typically adding up to +/- 200 Hz, up to ~1933 Hz must be accommodated within the transceiver bandpass.

Given the above issues we recommend the use of the Q65-15B sub-mode with TX audio frequency of 1000 Hz and "Max Drift" spinner set to the maximum of 50 as the standard for 10 GHz aircraft-scatter. It is generally sufficient to set FTol to 200 Hz. Just occasionally we have seen Doppler shifts of more than 200 Hz up to 300 Hz but the wider FTol does take more time to decode and may be an issue on slower computers.

The time available to complete a QSO is reduced significantly when an aircraft crosses at large angles. This occurs because the aircraft needs to be closely aligned to the path of propagation to produce a strong forward scatter lobe in the direction of the receiver and if it crosses the path at a large angle it does not stay aligned for as long as it would if were to fly along the direct path between the two QSO stations. The Doppler shift is also related to the angle at which the aircraft crosses the path and thus high rates of change of Doppler are accompanied by less time to complete a QSO. At 2 Hz/s Doppler shift one can typically achieve decodes on six or eight 15 second RX periods -- sufficient to complete a QSO on a single aircraft pass. But at 10 Hz/s one may not achieve more than 2 or 3 decodes on a single aircraft pass and it will be necessary to wait for more than one aircraft. It is useful to use the auto-sequence facility to help complete a QSO.

While this article is focused on 10 GHz it should be noted that the rates of Doppler shift will be proportionally less at lower frequencies and the durations of bursts proportionally longer. Thus Q65 should then be an even more effective mode for aircraft-scatter at lower frequencies.

Conclusions

From both our simulation and on-the-air tests it is shown that Q65 has a significant advantage over other modes used for aircraft-scatter at 10 GHz -- of the order of 5 to 12 dB. In comparison to ISCAT which was previously used for aircraft-scatter Q65 has the additional advantage that it uses very effective Forward Error Correction and is virtually immune to false decodes.

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