Some Initial Testing of Mobile Data Modes via QO-100

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Introduction

In the mid-1980s I attended a conference at the IEE entitled "Mobile Systems for Satellite Communications and Navigation". One of the papers that was particularly intriguing was about some military experimental tests of mobile data transmission through the then-new Skynet-4 satellite, using 300 baud FSK on the 7/8GHz up/down links. The antennas were dielectric "mushroom shaped things" for omnidirectional azimuth coverage, with an elevation pattern that was optimised for the area of operations. The gain would have been roughly around 6 - 8dBi and, if memory serves correctly, transmit power was a 'few' watts. Solid state power at GHz was expensive and rare in those days.

Roll on to now, with the advent of the geostationary QO-100 satellite transponder I wondered what might be possible for one way transmission of data through that satellite from a mobile platform like a car.

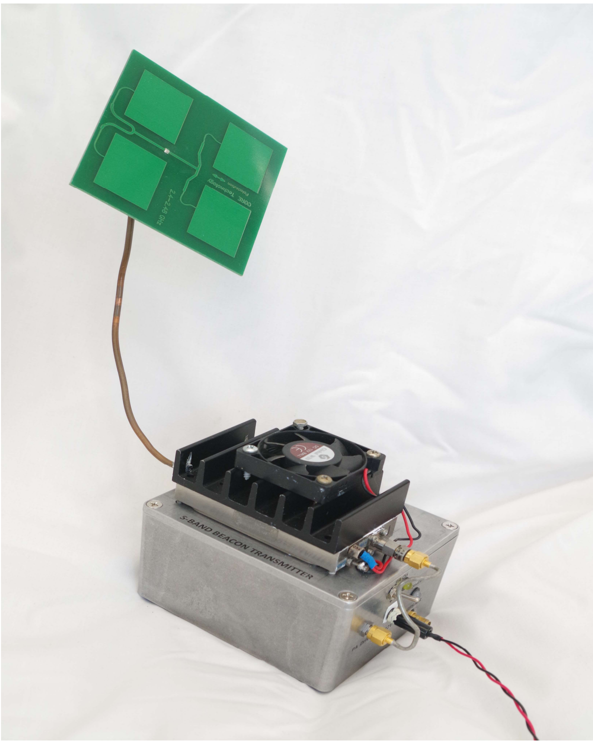
Antenna

The antenna used for the Skynet trials was a customised dielectric unit for which I had no details and, in any case, would be appreciably larger for 2.4GHz than that for the Skynet tests, so some other design was needed. It needed ideally to be circularly polarised and omnidirectional in azimuth. I did originally contemplate using a 'big-wheel', one of the small printed antennas available, from WA5VJB and did try a test transmission from a 1 Watt PA through the satellite using one of these, but being horizontally polarised there is an inherent 3dB loss in gain. A carrier was just detectable when looking at the receiver output in a narrow bandwidth of a few Hz with the '*Spectran*' spectrogram software, but the signal was quite weak, and didn't appear to be useable.

The Quadrifilar helix or QFH is popularly used for GPS/GNSS receive antennas and fits the omni / circular requirement perfectly. There are a few versions of this for home construction to be found on the web and I had successfully built a couple in the past. The dimensions were linearly scaled for the higher frequency, reducing them by a factor of 1.575/2.4 and a similar QFH antenna constructed for 2.4GHz. The gain is of the order of 2 – 3dBic. A test with 1 Watt of carrier did indeed result in a signal a few dB up on that from the big-wheel.

Doppler Shift

At 2.4GHz, Doppler shift from a moving antenna in a line directly to or from the receiver results in 8Hz per metre per second, or about 3.6 Hz / mph, change in frequency. The satellite is at an elevation of 26° so the resolved velocity at that elevation is reduced by COS(26°) = 0.9 of the resolved ground speed in the satellite direction. So travelling at 40mph on a bearing exactly towards or away from the satellite would introduce 128Hz of Doppler shift; 70mph would give 224Hz.



Initial Tests

Several years ago I had put together a small S-Band personal beacon source transmitting the nine-tone JT9D mode, part of the WSJT suite, on 2.3GHz. The hardware was based around a GPS module, PIC controller and LMX2541 Fractional-N synthesizer using an ovenned oscillator as the reference. A surplus 1 Watt power amplifier completed the personal beacon source. With the QFH antenna, this gave around +3dBW EIRPc towards the satellite

JT4D was selected as a datamode, its 39Hz tone spacing being enough to take care of any scattering from moving objects likely to occur on a path between fixed locations.

In the absence of any real published QO-100 payload specification, a spreadsheet was put together for the link budget to QO-100, based on estimated and approximate guesstimates for the transponder parameters. From this it could be seen that with 3dBW EIRP in the reference bandwidth of 2500Hz used for all WSJT modes, a perhaps rather optimistic S/N in that bandwidth of -10dB might be expected from this beacon source. Even after allowing a decent fade margin this ought to be more than adequate for JT9. However, JT9 is a narrow band mode with a symbol rate and equivalent noise bandwidth of just 1.74Hz. So it would be unlikely to be able to withstand much changing Doppler shift over the 50 second transmission period.

	Satellite Link Budget			G4JNT				
Tx Power	1	*Watts*						
Tx Ant Gain	3	*dBi*	Ground Station EIRP	3.0	*dBW*			
Uplink Frequency	2400	*MHz*						
Signal (ref) Bandwidth	2500	*Hz*						
			Satellite Parameters			Ground Station Parameters		
Distance	38000	*km*	Uplink Path Loss	191.6	*dB*	Downlink Path Loss	204.4	*dB*
			Rx Signal power at sat	-170.6	*dBW*	GS Rx noise Temp	115.1	*K*
Sat Rx Ant Gain	18	*dBi*	Sat Rx noise Temp	300.7	*K*	GS G/T	13.4	*dB(/K)*
Sat Rx Ant Temp	250	*K*	Sat G/T	-6.8	*dB(/K)*	Prx (signal)	-182.0	*dBW*
Sat Rx Noise Figure	0.7	*dB*				Sat Noise Received	-181.3	*dBW*
Transponder Gain	140	*dB*	Signal Tx Power from sat	1	*mW*	Local Rx Noise (ref BW)	-174.0	*dBW*
Sat Tx Antenna Gain	19	*dBi*	Tx signal EIRP	-11.6	*dBW*	Sum of noise sources	-173.3	*dBW*
			Tx noise EIRP (in ref BW)	-10.8	*dBW*			
Downlink Frequency	10490	*MHz*						
Rx Antenna Gain	34	*dBi*						
Antenna Temp	40	*K*						
Rx Noise Figure	1	*dB*						
Received S/N	-8.8	*dB*	**Sat Tx / Local Noise**	-7.2	dB			
			Total Noise Floor Elevation	0.8	dB			

This proved to be the case when transmitting from a car with the QFH antenna on a mag-mount on the roof. Decoding of the beacon transmission was consistent and reliable when the vehicle was stationary for the entire transmission period of 50 seconds, and the antenna had a clear view of the sky in the satellite's direction. But not one single decode was ever achieved while moving. Even a test on a long straight road at constant speed failed. It was quite clear that the normal slow modes in the WSJT suite were completely unsuitable for mobile QO-100 operation.

Fast Modes

WSJT-X has a couple of fast modes in its armoury. These are not used in a time synchronous manner, have no need for GPS timing and are targeted at burst type communications such as meteor scatter and aircraft reflections. The two of note are MSK144 and four variants of JT9, JT9E/F/G/H-Fast. The short transmission nature of these and their wider bandwidth ought to be able to overcome the issues of Doppler spreading and fast-fading inherent with mobile operation. But a faster symbol rate leads to reduced sensitivity and needs a higher received S/N to work.

The WSJT-X user guide https://physics.princeton.edu/pulsar/k1jt/wsjtx-doc/wsjtx-main-2.5.4.html does not quote threshold S/N values for these fast modes, but values can be estimated from a knowledge of the symbol rate and by studying text book curves for S/N versus error rate for the particular modulation in use. This suggested a S/N of around 0 to +1 dB (ref 2.5kHz) would suffice for MSK144 and around -10dB for JT9G-Fast with its 100Hz symbol rate. The other JT9-fast rates scale in threshold sensitivity with their respective symbol rates.

A 10 Watt power amplifier had become available since the original tests were made, but to compensate for the now-increased power, transmission should be limited to short bursts that could lead to a low duty cycle; aiming for an averaged power consumption similar to the original slow-mode tests.

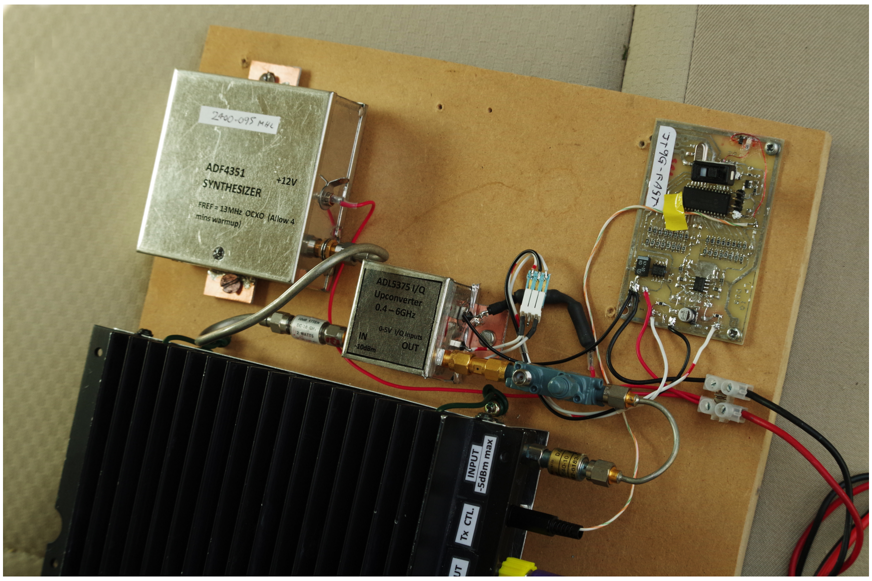
MSK144 Beacon

MSK144 using Minimum Shift Keying modulation is quite straightforward to generate in a Direct Digital Synthesizer. The frequency is shifted by exactly +/- 500Hz according the '1' / '0' pattern in the message data string at the 2000 baud data rate. 144 symbols per frame at 2000Hz takes 72ms, and frames are repeated for a whatever burst length is requested. DDS sources cannot, however, directly generate 2.4GHz.

A design for a baseband quadrature DDS using a PIC microcontroller is given in annexe A of http://g4jnt.com/PIC_DDS.pdf. This supplies dual I/Q channels at positive or negative frequencies from a Numerically Controlled Oscillator in the PIC firmware, with the audio/baseband output generated via a D/A converter made from an R-2R ladder. This can be seen at the top right of the photograph below.

Connecting the low pass filtered I/Q output to an AD8346 or ADL5375 quadrature upconverter chip with an LO at 2.4GHZ allows a signal at this frequency to be generated, modulated by programming the DDS. The simplicity of MSK144 modulation meant that only small changes to the PIC code were needed to allow the baseband DDS to generate a fixed MSK144 message from a set of pre-stored symbols. A complete 2.4GHz beacon transmitting 10 Watt bursts of MSK144 was put together into a package that could be moved around rapidly for testing. A photo of the breadboard can be seen below.

Unfortunately the satellite link budget was a bit marginal with 13dBW EIRP of MSK144. From a fixed location with a clear view of the sky, and a bit of antenna position optimising, some MSK144 bursts were decoded through QO-100. But only perhaps 30 – 50% of all those transmitted. An attempt to try this mobile with the antenna on a vehicle roof ended up as a total failure, with no decodes at all even when stationary. Clearly several more dB were needed in the link budget to overcome the 2000Hz noise bandwidth of MSK144.



Breadboard 2.4GHz Beacon Test Source, ADF4351 Synthesizer, ADL5375 Quadrature upconverter and 10W PA.

JT9 tones are generated as baseband I/Q signals in a 16F870 PIC and R-2R ladder D/A converter, low pass filtered and fed to the upconverter.

JT9-Fast

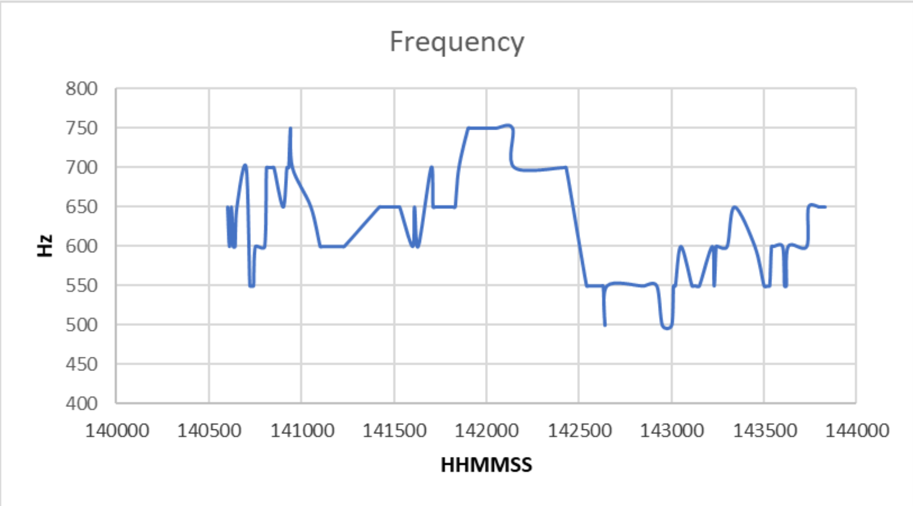
With a bit of care over optimising code and speed of execution, it was possible to rewrite the existing Baseband DDS hardware to generate JT9 at any desired speed or tone spacing, with a fixed test message from a pre-stored set of symbols. The JT9-Fast submodes E-H have symbol rates / noise bandwidths of 25/50/100/200Hz respectively and as a starting point the 100Hz spaced JT9G-Fast mode was programmed into the PIC. Free Text message format was chosen so that the WSJT software would not try to use any form of averaging during the decode process – which might otherwise distort reception tests with a message that remained unchanged from one timeslot to the next.

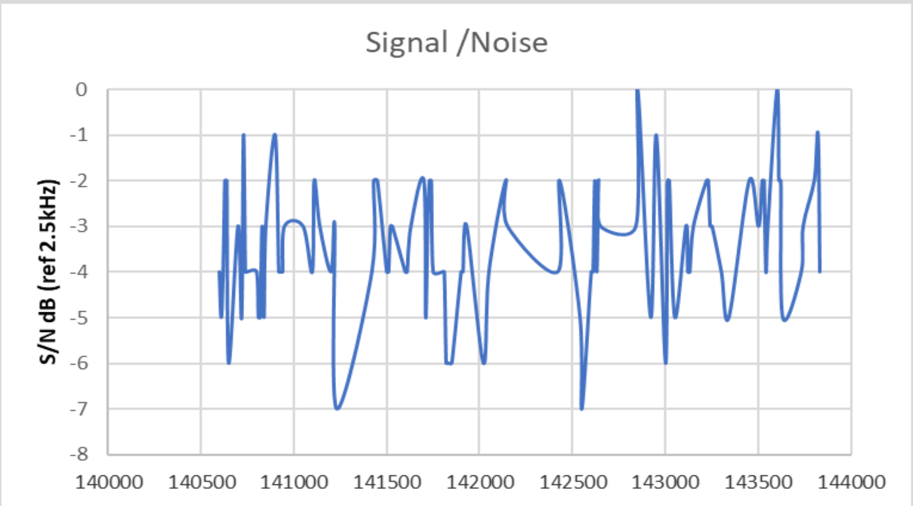
The burst length was set to be about 2.5 seconds, which means that a frame of data is transmitted four times within each burst. (JT9 has 85 symbols, so when transmitted at 100 baud it takes 0.85s per frame, with identical frames stacked end to end for each transmission period). The repeat period was set at 10s, merely in order to save having to wait too long during tests and give plenty of result sets for analysis.

Mobile Tests

The first test was an immediate success. A circular drive around suburban roads and country lanes over a period of 32.5 minutes (1950 seconds) resulted in 100 successful decodes using a 10 second decoder cycle time to match that of the transmitter. This is a success rate of 100/195 = 51%. Successful decodes were generally bunched together so it is quite reasonable to assume most of the failed decodes are caused by shading and blocking of the signal path to the satellite by trees and houses along the route.

A plot of the reported decode frequency and S/N over the test period are shown below. The measured frequency has a direct relationship to the Doppler shift on the uplink caused by relative vehicle velocity in the direction of the satellite. WSJT-X only reports this to a resolution of 50Hz for the JT9G-Fast mode; the plot clearly showing this granularity. As the drive was over meandering roads at modest speeds of no more than 40mph, and generally a fair bit slower, it is difficult to relate the Doppler pattern to the route taken. Time is shown as HHMMSS on the X axis.

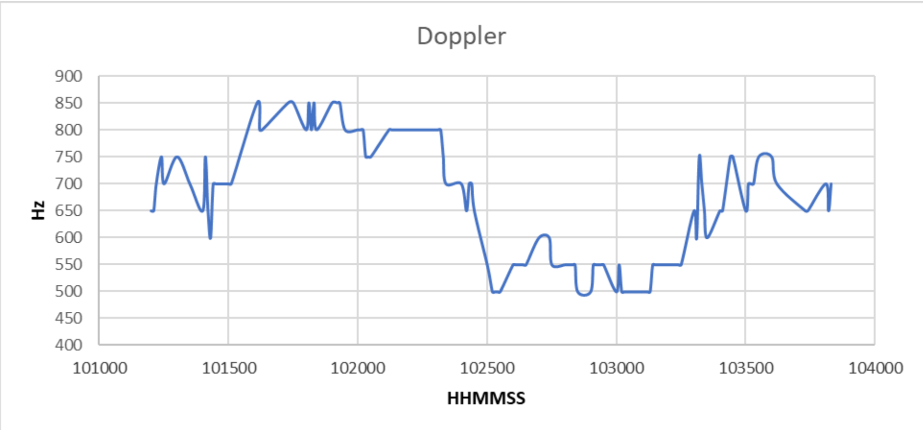


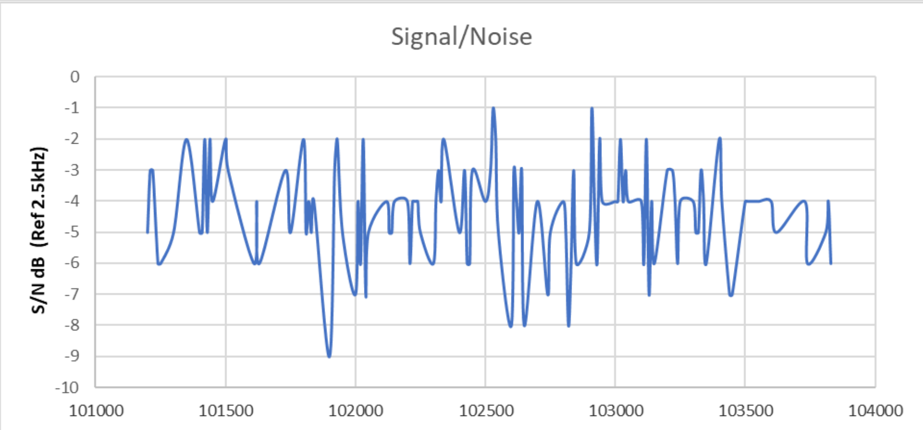


A second test was made along the M27 motorway, out and return from J8 (Hedge End) to J11 (Fareham), driving at a more or less constant 60mph. Speed limit signs were active, with all vehicles maintaining a well-behaved constant speed, very suited to this sort of test. This section of motorway is almost straight and runs on a bearing of roughly 120/240°, meaning that a significant portion of the vehicle's velocity is in a direction away from or towards the satellite at a bearing of 146°.

This time the run was 26.5 minutes or 1590 seconds, 159 time slots, from which there were 120 successful decodes; a 75% successful decode rate. The view from the M27 motorway to the satellite is significantly clear as it is almost in line with the road and no doubt leads to the higher success rate.

The Doppler and S/N plots from this run are shown below. Note how the out and return Doppler shifts are very evident, again subject to 50Hz decoder reporting granularity. The U-turn at Junction 11 was made at 102400. The small median sections at each end are from the 2 miles of local suburban roads used to access the motorway at Junction 8.





The lowest reported S/N at which a decode succeeded was around -9dB, with most lower troughs at -7 or -8dB, so the original estimate of a -10dB S/N threshold for JT4G-Fast was slightly optimistic. At this EIRP there is plenty of margin, with the best S/N report being 0dB and averaging at around -4dB.

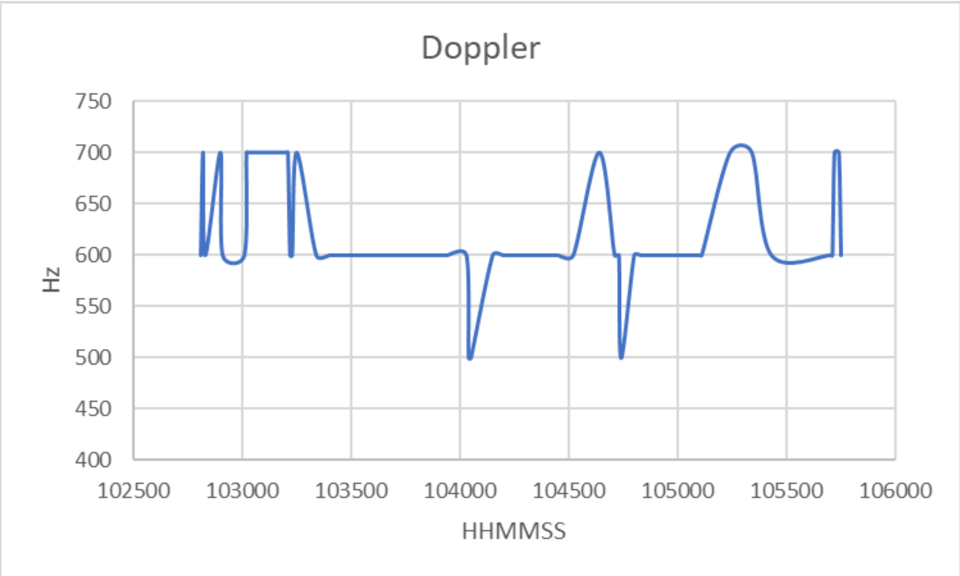
Higher Rate

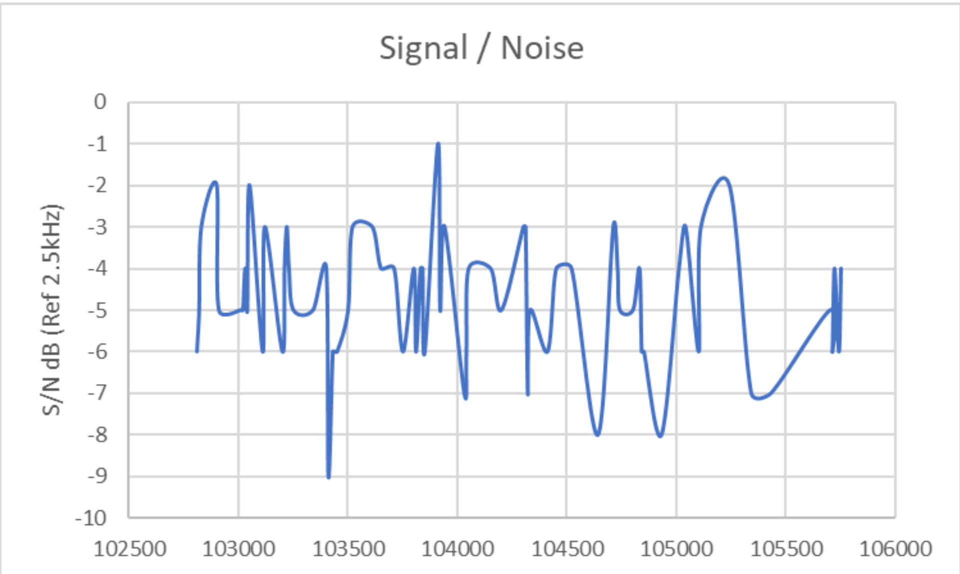
The tests at 100Hz JT9G-Fast rate showed remarkable resilience, with at least 50% of all transmission bursts decoded, so a test was made at a higher symbol rate. The source was reprogrammed for

JT9H-Fast, with 200Hz symbol rate. The burst duration was set to 1.7 seconds in order to keep the same number of frames per burst, four, as used previously but repeated at the same interval of 10 seconds. The transmission duty cycle is now lowered to 17%.

A test route over suburban and rural roads similar to that of the first run was driven, for a transmission period of 29.7 minutes (1780 seconds, 178 Tx bursts). A total of 70 of these shorter bursts were successfully decoded, a success rate of 39%.

For this higher speed mode the WSJT-X software only reports decoded frequency to the nearest 100Hz, so the Doppler plot does not add much of value. The S/N plot shows a similar mean S/N, as would be expected as the same signal strength is normalised to the same bandwidth. A slightly higher minimum value shown reflects the higher minimum threshold S/N for the faster symbol rate, although interestingly both symbol rates did result in a decode at the same minimum S/N of -9dB





WSJT-X and Frequency Settings

The WSJT-S software requires that an Rx tone frequency be set, corresponding to the lowest tone of those transmitted. The default is 700Hz when the fast modes are selected by ticking the 'Fast' checkbox with JT9E – JT9H selected. A frequency tolerance around this value over which the decoder will search also needs be specified. This 'Tol' setting has to be made wide enough to accommodate the maximum expected Doppler shift likely to be expected, plus any tuning discrepancy or frequency drift. A value of 300Hz was used for these tests. The transmitter was locked to an oven controlled oscillator and stayed within a few tens of Hz of nominal. The Receive system used a fully locked LO chain accurate to a few tens of Hz at 2.4GHz; Q0-100 exhibits about 100Hz peak to peak of diurnal Doppler shift, so for these tests all frequency uncertainties were no worse than any expected Doppler.

Conclusions

This short test has shown that using one of the fast modes within the WSJT suite allows reliable one-way messaging through the QO-100 satellite from a moving vehicle at motorway speeds, from a small fixed antenna at a power level commensurate with readily available Wi-Fi power amplifiers. Such message bursts are useful for tracking, telemetry and warning / alerting purposes.

Both JT9G-Fast and JT9H-Fast show a quite acceptable level of reliability of burst decodes, 50% and 39% respectively on urban / rural roads with shadowing. The theoretical 3dB reduction in sensitivity of the H mode over G does not appear to be borne out on this single test, other than in a slightly reduced decode rate, 50% to 39%. This could be due to the shorter individual frame length making the faster version more resilient to fast fading and fluttering. Doppler shift does not appear to be an issue, at least up to 60mph with the slower JT9G-Fast when used with a Rx tolerance of 300Hz. JT9H-Fast was not tested at speed on the motorway as, to be a worthwhile test, speeds up to 100mph really need to be used here! For slower vehicle speeds combined with lower power operation the 25 and 50Hz variants might be worth investigating.

A fixed message was used for these tests for simplicity of source hardware. Encoding of JT9 into the 13 character free text format is a straightforward process and has been demonstrated in the older 16F family of PIC processors used here. With the high reliability of decodes, multiple repeats of messages are not necessary and longer messages could be built up by splitting into multiple 13-character message formats.