FreeDV Digital Voice on HF

Chris G7LWV

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Introduction to digital voice modes

- Amateur radio voice modes such as D-Star, C4FM (Fusion), DMR and M17 all use some form of 4-FSK modulation
- These are effectively digital baseband signals modulated as FM and mostly used on VHF and UHF
- Voice coding is often AMBE or AMBE2 or in the case of M17 open source Codec2
- Some professional voice and audio modes use PSK or OFDM modulation and various other codecs
- FreeDV uses OFDM (Orthogonal Frequency Division Multiplex) as a baseband signal that is then modulated on SSB
- FreeDV can use a range of codecs, initially Codec2 and now RADE
- FreeDV is optimised for HF but can be used on higher bands

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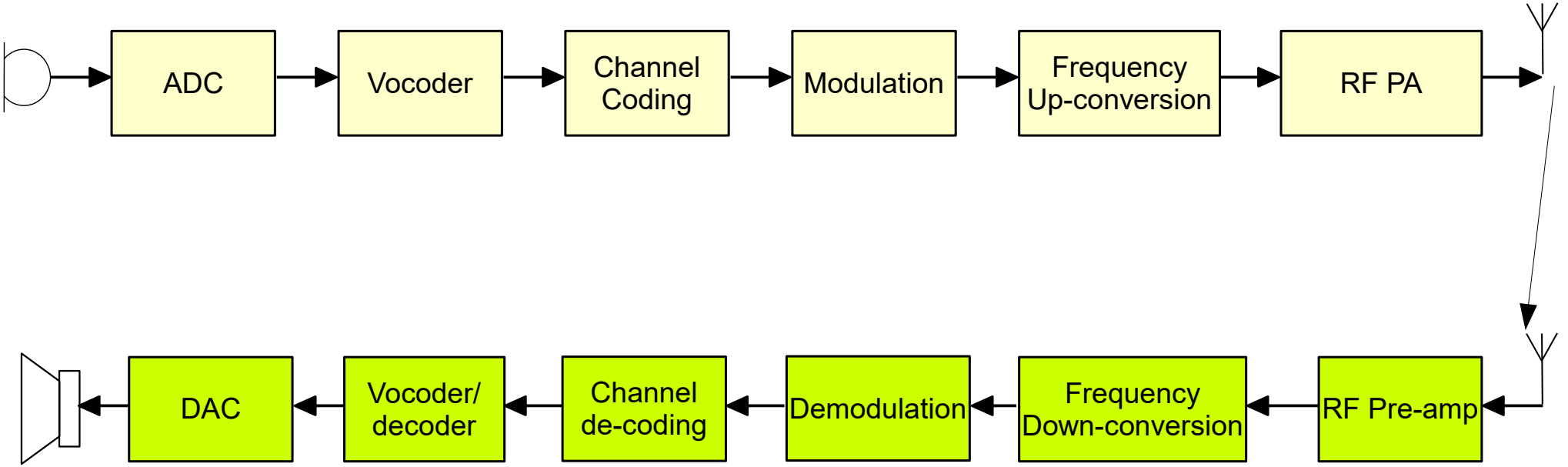
Typical digital voice signal chain

- Standard digital voice mode block diagram showing voice input, voice coding (Vocoder), error protection and modulation
- FreeDV uses software to do the first four stages and forms a baseband signal that is 'up-converted' as SSB



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OFDM modulation

- Orthogonal carriers overlap perfectly without causing interference to each other
- The peak of each carrier occurs exactly at the point where all other carriers cross zero. This zero-crossing point is the mathematical definition of orthogonality
- Allows the receiver to demodulate individual specific carriers without interference from its neighbours
- Voice data is spread across many carriers, with some carriers used as 'pilot tones' to help the demodulator lock to the signal and provide a degree of automatic channel equalisation
- OFDM reduces data loss during selective fading of the RF path

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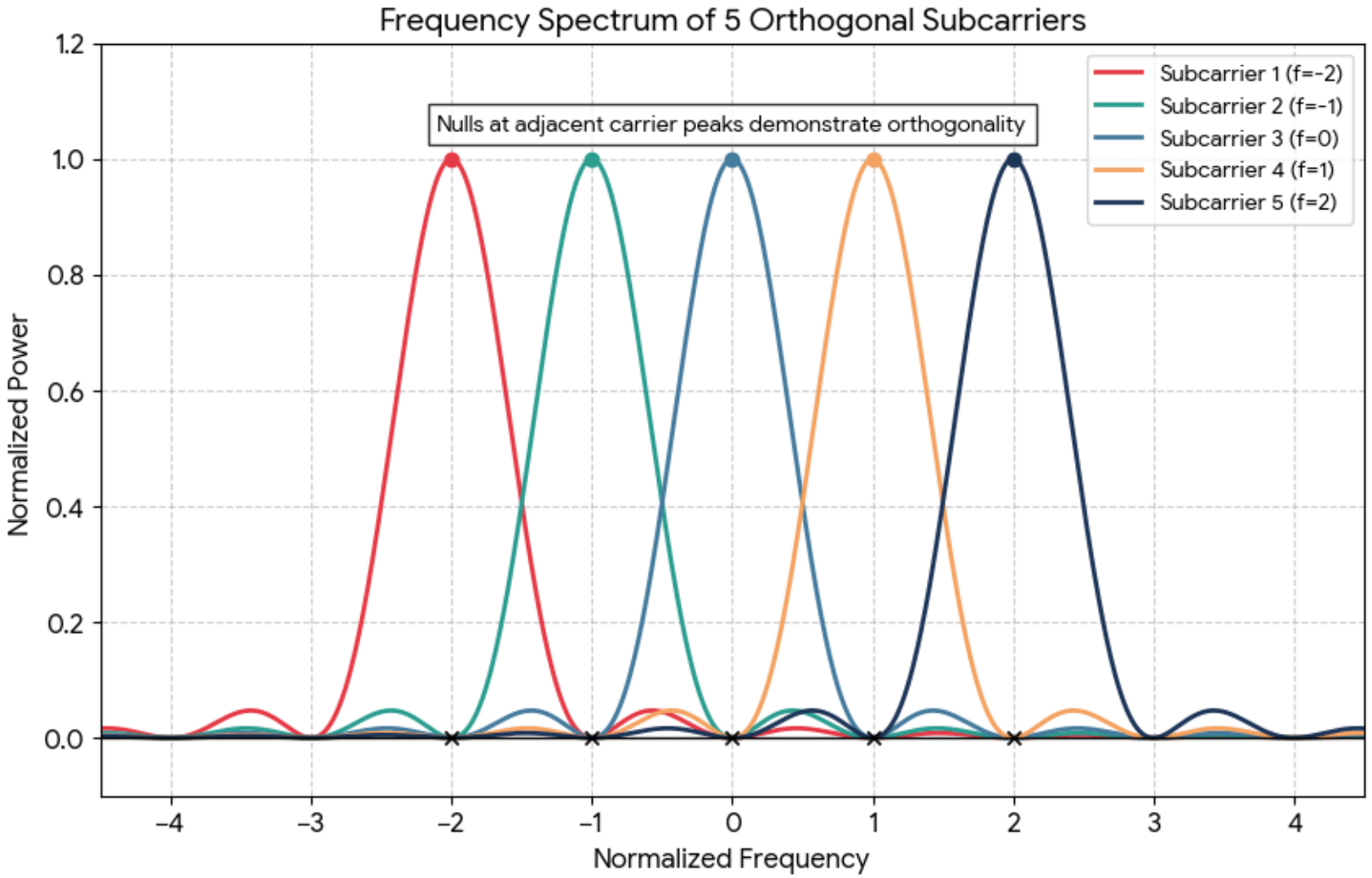
OFDM modulation carriers

- An example showing just five orthogonal carriers, FreeDV has up to 31 carriers (depending on the mode)



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OFDM modulation details

- In time domain the modulating pulse needs to be created such that it produce a sinc function (sin(x))/x in the frequency domain to achieve orthogonality
- And the duration of the symbol period needs to the reciprocal of the carrier spacing, so Fs = 1/T (where T is symbol duration and Fs is carrier spacing)
- FreeDV also has a cyclic prefix (CP) as a 'guard interval'
- Each carrier is modulated with QPSK or QAM
- Some carriers can be defined as 'pilot tones' to help the receiver lock and equalise the signal before demodulation
- All created digitally to produce a baseband signal that is fed as a multiple tone audio signal to a SSB transceiver

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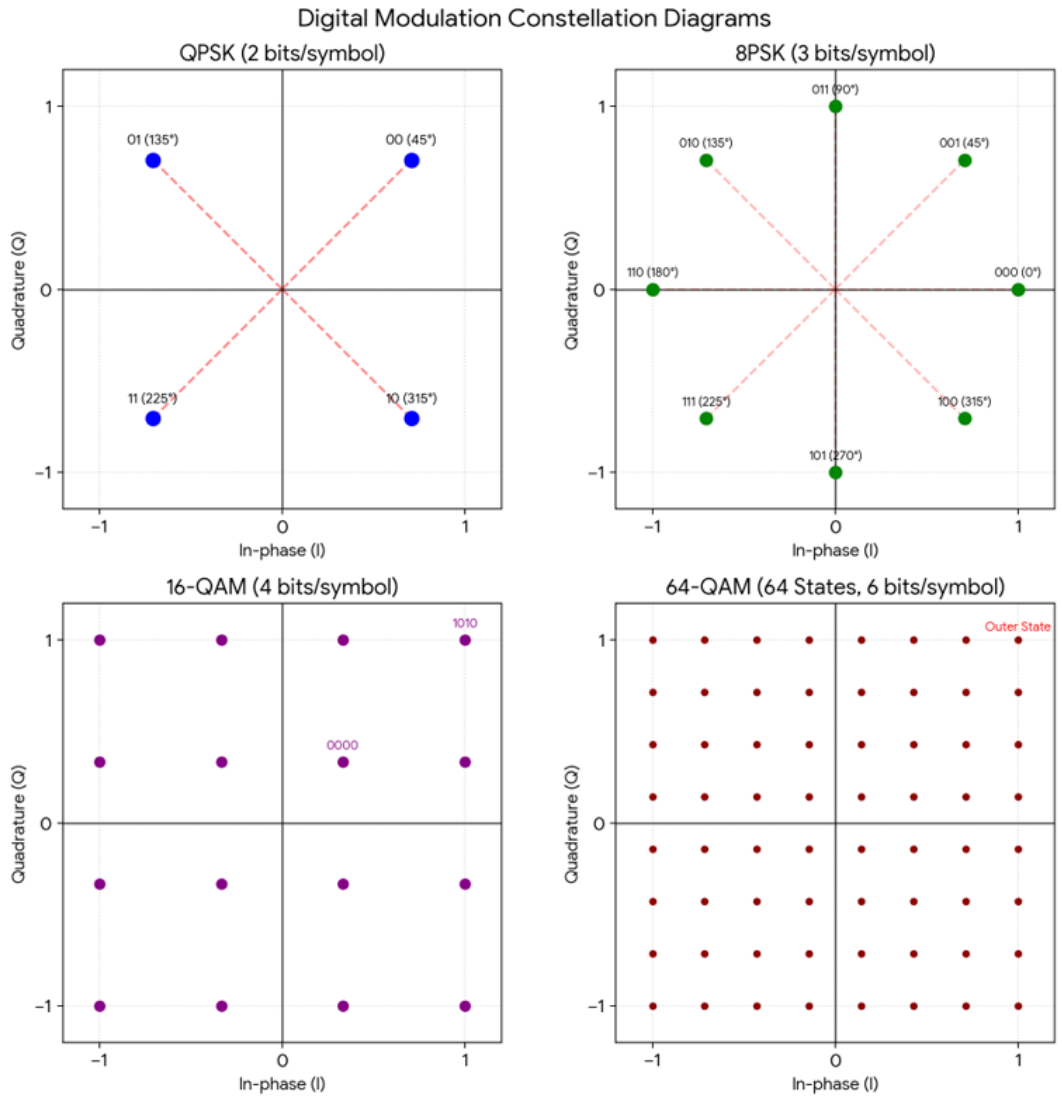
Individual carrier modulation

- Each OFDM carrier is modulated separately
- Some typical digital modulation schemes are shown below



Scheme	Bits / Symbol	Total States
QPSK	2	4
8PSK	3	8
16-QAM	4	16
64-QAM	6	64

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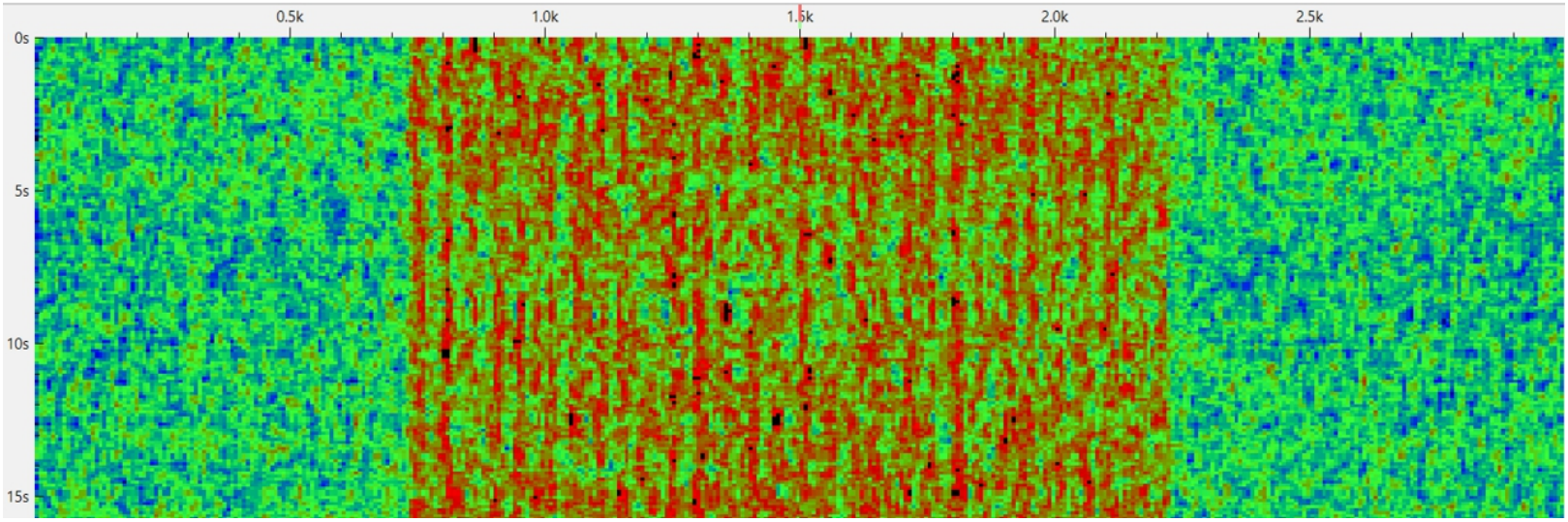
FreeDV OFDM bandwidth

- Bandwidth of FreeDV signals
- Number of carriers depends on FreeDV mode, 17 were used for an earlier mode (700D), current RADEv1 mode has 30
- RADEv1 mode shown below has spectrum of 1.5kHz, in overall 2.1kHz bandwidth channel



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FreeDV original audio codecs

- Original FreeDV vocoder (Codec 2) was developed by Dave Rowe (VK5DGR)
- With some early work on modulation modes by Bill Cowley (VK5DSP)... what a great callsign!

FreeDV Mode	Vocoder Technology	Audio Sample Rate	Native Codec Bitrate	Sound Characteristic
FreeDV 1600	**Codec 2**	8 kHz	1300 bps	Slightly robotic, high clarity
FreeDV 700D	**Codec 2**	8 kHz	700 bps	Intelligible, communication-grade
FreeDV 2020	**LPCNet** (Neural Text-to-Speech)	16 kHz	1733 bps	Broad, high-fidelity studio sound

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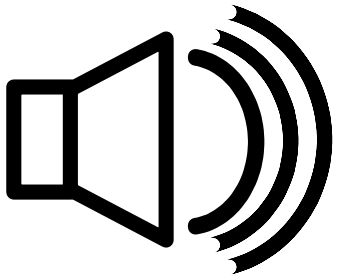
FreeDV 700D audio clip

- What does FreeDV 700D using Codec 2 sound like?



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FreeDV RADE audio codecs

- Work to improve audio quality led to the development of RADE (originally called RADAE)
- ML trained using recordings of HF signal chains
- RADE – stands for 'Radio Autoencoder'

FreeDV Mode	Vocoder Technology	Audio Sample Rate	Native Codec Bitrate	Sound Characteristic
RADE (V1)	**FARGAN** (Deep Learning AI)	16 kHz	Analogue Continuous	Highly natural, clean background
RADE (V2) *	**FARGAN** (Deep Learning AI)	16 kHz	Analogue Continuous	Highly natural, clean background

* not yet fully released (Sept 2026), work underway to add it to the FreeDV 3.0 GUI

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RADE development included OFDM

- RADE has no distinct separation between audio codec and modulation/demodulation stages
- Machine Learning (ML) included both stages in the development of the new algorithms
- Also included the demodulation and decoder stages in the new algorithm development
- The audio is mathematically processed to extract vocal 'features' (but only what is absolutely necessary to relay intelligible meaning) and modulated as 'analogue' waveforms into multiple carriers
- Discrete symbol periods are kept, so that orthogonality is maintained but the modulation of each carrier is 'continuous QAM' instead of 'discrete QAM or QPSK' as used in previous modes (uses floating point values rather than fixed constellation values)

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FARGAN Vocoder

- Based on research into **FARGAN Vocoder**
- FARGAN (Framewise Autoregressive Generative Adversarial Network), a machine learning vocoder
- Speech is initially analysed by an algorithm called LPCNet to characterise it's 'features'
- Features represent vocal traits like pitch, tone, and spectral shape and are converted to a continuous stream of floating-point numbers
- FARGAN feature or 'vectors', compresses them further, maps them directly to the continuous OFDM carriers
- Important feature of this Vocoder is that the speech degrades gracefully as received S/N increases (unlike most other Digital Voice modes)

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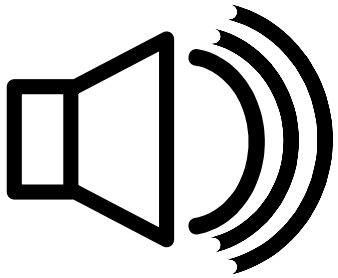
RADE audio clips

- RADE example audio with various levels of added noise
- Use encoded audio files into the FreeDV application (v 2.4.0)

- Demonstrate how these sound when receiving SSB



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RADE ML training

- RADE was developed and optimised using Machine Learning (ML)
- A physical radio propagation model was used directly with a deep learning training loop
- ML was given strict global constraints for bandwidth and power performance
- Primary objective to reconstruct 8 kHz wide, natural-sounding voice audio using 1.5kHz of RF bandwidth
- To provide intelligible speech at -2dB SNR
- Also given target to achieve the lowest peak to mean ratio for better power amplifier performance (PAPR)
- Many hundreds of hours of speech recording used for the training and over 900 different voices
- Resulted in an optimised and self-contained neural network that handles all the voice encoding and decoding (as Python library)

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RADE v2 enhancements

- RADEv2 **no pilot symbols** on the OFDM signal
- 14 carries rather than 30
  - Narrower working bandwidth of 860Hz (RADE is 2100Hz)
- Better SNR than RADEv1 (theoretically around 3.8dB)
- Estimated up to 20dB improvement over voice SSB on HF
- Improved PAPR (Peak-to-Average Power Ratio) to 1dB – it was good anyway (4dB) but will often be limited by transceiver SSB filters
- To be added to the FreeDV v3.0 GUI soon for a 'big change-over'
- FreeDV v3.0 update to include a change to USB only, currently LSB is used on bands that use this mode for analogue voice
- FreeDV v3.0 will drop 'legacy' modes and this may include RADEv1
- Improved callsign decoding using lower rate LDPC code, better than the current 2dB SNR requirement

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RADE future developments?

- ARDC grant of $420K for 'Enhancing HF Digital Voice with FreeDV' but the grant money is now coming to an end
- Need to see RADEv2 in the wild
- Operating standardisation to use USB (this will be the default setting in the new release of the app
- C libraries to lower the processing overhead, originally written in Python
- Which radio manufacturer will be the first to offer native support for RADE? (Ans. FlexRadio - integration and testing was done as part of the grant)

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Final comments

- Daily net on 60m, 5.368,5 MHz (or 5.371,5 MHz) at 15:30, plus Sundays after GB2RS news and at 18:30
- Net protocol is to add a number prefix to your name in Reporter
- Digital mode where the 'strongest station wins' hence leave gap between overs for others to join
- Spot frequencies are programmed into the software, but can enter manually (or tune from the rig)
- Found that noise from my laptop PSU degrades received SNR by up to 5dB (need to investigate this)
- Inter-G on 20W is possible
- High duty cycle mode - so in common with other digital modes don't run at 100W using standard 100W SSB transceiver (35W is generally adequate)
- Additional settings for getting Kenwood TS-590S to work with FreeDV SW – I made some notes!

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