Small Station EME at 10 and 24 GHz:

GPS Locking, Doppler Correction, and JT4

Rex Moncur, VK7MO, and Joe Taylor, K1JT

Abstract

GPS frequency locking and automatic Doppler correction, together with a recently improved JT4 decoder make it possible for small portable stations (40 W and 80 cm dishes) to work the larger (3 meter dish) home stations on 10 GHz EME, even with libration spreading in excess of 100 Hz. While 24 GHz JT4F EME signals from a home station (100 W, 2.4 m dish) have been received and decoded using a 47 cm dish, a two way QSO is still a challenge.

1. Background

The digital mode JT65C has been widely used for EME on the lower microwave bands, but not at 10 or 24 GHz. Doppler shifts on these bands can be as large as 50 kHz and can change by more than 200 Hz in a minute. Such frequency excursions are well beyond the capability of the AFC system currently programmed in *WSJT*; moreover, at 10 and 24 GHz libration-induced Doppler spreading can be as large as several hundred Hz, much more than the 10.8 Hz tone spacing of JT65C.

WSJT provides a mode called JT4 that offers a range of tone spacings up to 315 Hz. The submodes with wider spacings are especially appropriate for EME on the higher microwave bands. JT4 spreads its energy evenly over 4 tones, and does not have an easily identified synchronizing tone like the one in JT65C. As a consequence, very weak JT4 signals can be hard to find by tuning across the band. For these and other reasons, making EME contacts is greatly facilitated by accurate frequency control and automatic real-time Doppler correction.

Several years ago VK7MO experimented with JT65C on 1296 and 2301 MHz using GPS locking [1] and Doppler correction controlled by software written by Glen English, VK1XX [2]. The VK1XX program obtains Doppler information from a file written by *WSJT* and applies corrections automatically to the IC910-H transceiver at VK7MO. After many hours of testing with other GPS-locked stations, it has been found that EME signals reliably stay locked to within a few Hz.

In 2010 Charlie Suckling, G3WDG [3], drew attention to the existence of predictable times of minimum libration on a specified EME path and how to calculate the libration spreading on own echoes and between stations. The necessary calculations were soon incorporated into *WSJT* and also *Moonsked*, a program by David Anderson, GM4JJJ and *EME Planner* and *LibCalc* by Doug McArthur, VK3UM. Using *Moonsked* VK7MO was able to find predicted times of libration spreading as small as a few Hz at 10 GHz, suitable for use with JT65C [4]. Tests were arranged with Alan Devlin, VK3XPD (75 W, 3 m dish) and after a few attempts a JT65C EME QSO was completed using the VK7MO portable 10 GHz station — a 64 cm offset dish and 7 watts at the feed [5]. The deep libration minima last only a few minutes, and it was surprising at first to discover that VK7MO could copy VK3XPD's 75 watt transmissions even when spreading was as large as 150 Hz, well beyond the 10.8 tone spacing of JT65C. The explanation is contained in a paper by K1JT, presented at the 2010 International EME Conference [6] (see especially Figures 6 and 7 of that paper, and associated text). While the limb-to-limb spreading may be over 150 Hz, much of the received energy falls within a quasi-specular peak reflected from the central part of the moon, with much lower spreading. An example of this effect is shown in Figure 1, the spectrum of a 10 GHz EME signal received at a time when limb-to-limb libration spread was around 90 Hz, as indicated by the horizontal bar. The half-power width of the spectrum is only 19 Hz, and nearly half of the power falls within ± 5 Hz. JT65C can decode such a signal by taking advantage of the narrow central peak.

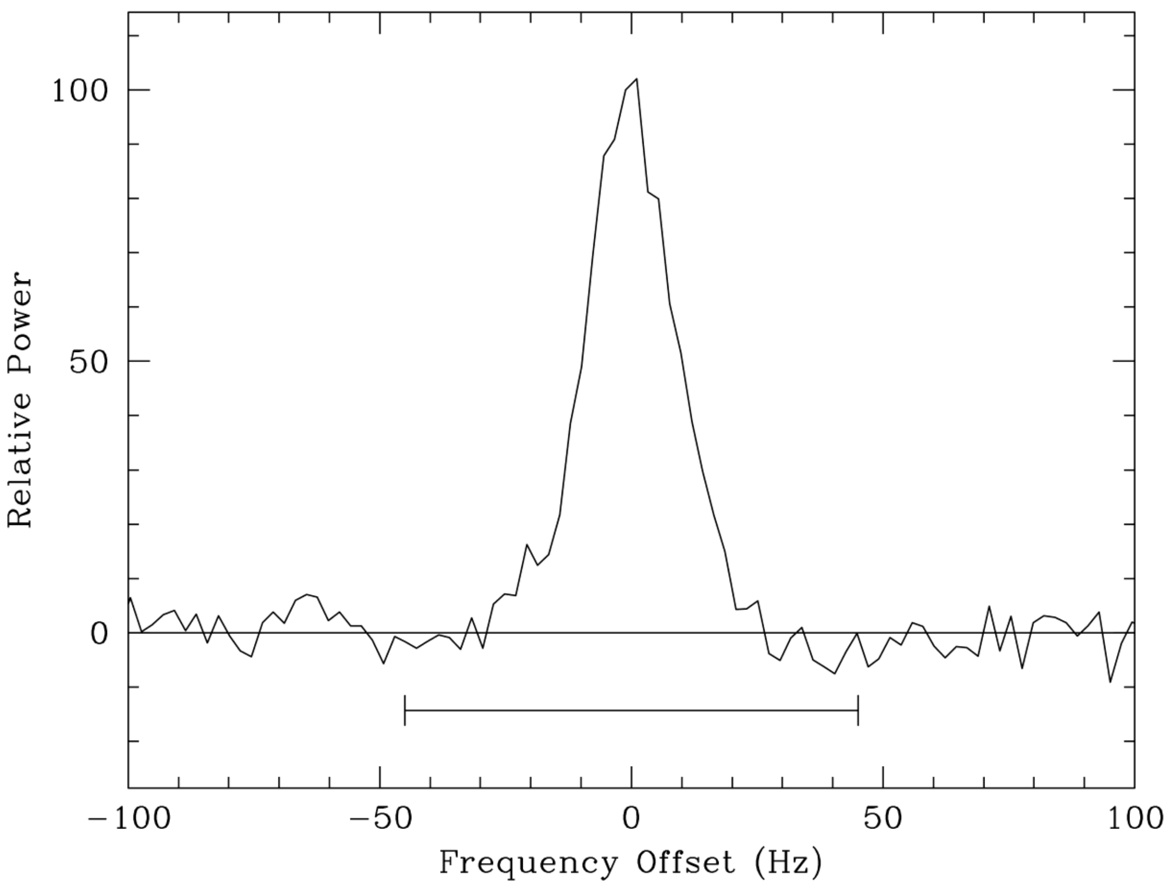

Fig. 1 — Measured spectrum of the VK7MO EME signal at 10 GHz as received by G3WDG. The width of the central peak is much less than the total limb-to-limb libration spreading, about 90 Hz at this time.

Given this success in using JT65C with wide spreading (albeit one way with higher power) VK7MO improved his portable station to a 77 cm prime focus dish and a 45 watt DB6NT power amplifier (Figure 2). After this upgrade it was no longer necessary to wait for the few minutes of low libration that occur only two or three days a month; it became possible to complete QSOs with VK3XPD on about half of all days, at times when the libration spreading was less than 150 Hz.

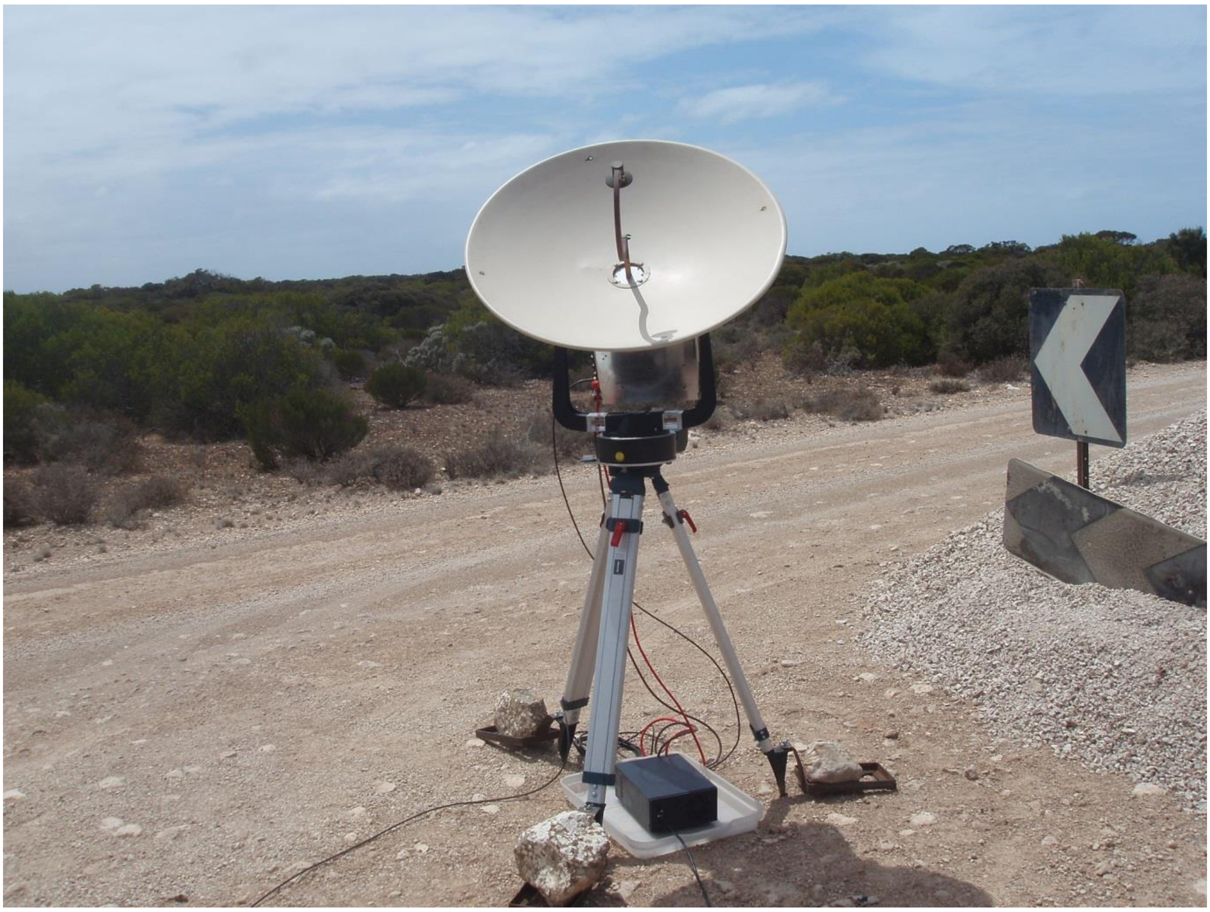

Fig. 2 — The VK7MO portable setup for 10 GHz EME.

VK7MO then examined *Moonsked* predictions to find times of low libration spreading between Australia and either Europe or North America. On such paths, times of extremely low spreading were not found; nevertheless, there are many opportunities with spreading well below 100 Hz. Tests were arranged with Vlada Masek, OK1DAK and Tonda Jelinek, OK1DAI at the OK1KIR club station, and with Al Ward, W5LUA. EME QSOs at 10 GHz were completed easily with these stations from the small VK7MO portable station, using JT65C.

In November 2012 VK7MO set off on a grid square tour across Australia, working from 25 different locators. Many contacts were made with OK1KIR, W5LUA, VK3XPD, and VK3NX [7].

On returning home VK7MO set his mind to what could be done on 24 GHz with his very small portable station (4 W, 47 cm offset dish). Initial 24 GHz tests with W5LUA (100 W, 2.4 m dish) showed clear evidence of his single tone signals (see Section 4 below). After improving the feed illumination it was occasionally possible to gain synchronization, a necessary prerequisite to successful JT65 decoding. However, no decodes were achieved despite signal levels and total limb-to-limb spreading at a level that would have decoded on 10 GHz. A likely cause for decoding failure was evident in the appearance of single-tone transmissions on the waterfall display. The signal was much more evenly distributed over the full range of Doppler spread, with little evidence of the narrow central peak seen at 10 GHz (cf. Figure 1).

Having pushed JT65C to its limit, VK7MO made some tests with W5LUA using the JT4E mode (78.75 Hz tone spacing). Sync was achieved on nearly all transmissions, but again there were no decodes. Some of the test files were sent to K1JT, to see what he could do with them. Within a few days the files were decoded — we had confirmed that it's possible to copy W5LUA's EME signal on 24 GHz using a 47 cm offset dish.

2. Development and Description of JT4 modes

K1JT has viewed design of the various *WSJT* protocols and their decoders as a learn-as-you-go process. Some features have been tried and abandoned, while others have been retained and built upon. JT65 uses a low-rate (high redundancy) code, with 63 six-bit symbols transmitted to convey just 72 bits of information, and it devotes half of the transmitted energy to a synchronizing tone. This approach helps the mode to perform well under conditions of QSB and intermittent QRM or QRN, and the sync tone provides a handy visible marker on a waterfall spectral display. A well-designed JT65 decoder often succeeds even on a signal with deep fades or dropouts, or when two or more signals overlap in both frequency and time. But JT65's ratio of occupied bandwidth to information rate is rather large, and arguably devoting half the transmitted energy to the synchronization is overkill. For amateur radio use, another downside is that the soft-decision Reed Solomon decoder uses a patented algorithm [8] and its source code is not "open". The soft-decision Koetter-Vardy decoder distributed in executable form with *WSJT*, *MAP65*, *JT65-HF*, and several other programs yields a 2 dB advantage over hard-decision decoding for steady signals, and even more under conditions of Rayleigh fading. For long-term viability of the JT65 mode, it's a pity that the source code is not openly available. The patent expires in 2020.

JT4 was created in 2007 to facilitate experiments with a structured, time-sequenced digital mode offering more bandwidth flexibility than JT65. For educational reasons, JT4 was built to use a non-patented, soft-decision sequential decoding algorithm by Fano [9], with open-source code and a very different synchronizing scheme. JT4 and JT65 both use efficient source-encoding of basic QSO information (callsigns, grid locators, signal reports, and acknowledgments) in a fixed-length 72-bit message. Both modes include strong forms of error-control coding (ECC) — a Reed Solomon (63, 12) code for JT65, and a long-constraint convolutional code (constraint length K=32, rate r=1/2) for JT4. In both cases the ECC is strong enough that decoders nearly always produce exactly the message that was transmitted, or otherwise a flag indicating that decoding has failed. The modulation for both modes is continuous-phase frequency-shift keying: JT65 uses 65 tones, JT4 uses 4. With just 4 tones, JT4 can use tone spacings up to 315 Hz to cope with wide libration spreading and still fit within a standard SSB passband. In both JT65 and JT4 the transmitted signal has a constant envelope, so full "key down" power is present at all times during a transmission. A detailed description of the JT65 protocol was published in *QEX* in 2005 [10].

Generation of a JT4 signal starts in the same way, by source-encoding the user's message into 72 bits. With a "zero tail" of 31 bits (effectively making a continuous code into a fixed-length block code), the rate-1/2 convolutional encoding increases the number of data bits to (72+31) × 2 = 206. These bits are scrambled in order by bit-reversing their indices, and the re-ordered bits are merged with those of an equal length pseudo-random synchronizing vector to form two-bit channel symbols, as follows:

$$\text{Symbol}[i] = 2 \times \text{Data}[i] + \text{Sync}[i] \qquad \text{where i is an index running from 1 to 206.}$$

The channel symbols have values 0 to 3. Multiplied by N, a parameter that defines the tone separation for each JT4 submode, the symbols control the transmitted audio frequency for each tone interval, using the equation

$$\text{Frequency}[i] = 118 \times 11025/1024 + (\text{Symbol}[i] - 1.5) \times 4.375 \times N.$$

Values of expansion factor N, the tone separation, and total occupied bandwidth for the JT4 submodes are summarized in Table 1. For comparison, we note that JT65C has tone spacing 10.8 Hz and total bandwidth 711 Hz.

Table 1. — Expansion factors N, tone spacings, and total bandwidths of the JT4 modes.

Mode	**Expansion Factor N**	**Tone Spacing (Hz)***	**Bandwidth (Hz)**
JT4A	1	4.375	17.5
JT4B	2	8.75	35
JT4C	4	17.5	70
JT4D	9	39.375	158
JT4E	18	78.75	315
JT4F	36	157.5	630
JT4G	72	315.0	1260

* The four tones are spaced around a centre frequency of 1270 Hz

The EME experiments at 10 and 24 GHz described in this paper motivated several improvements to the implementation of JT4 in *WSJT*. Capability for message averaging has been added, providing opportunities for decoding a signal 1 to 3 dB below the threshold for a single transmission. A correlation-type decoder has also been added, similar to the one in JT65. The correlation algorithm can help to determine which message (from a list of plausible or likely messages) has been received, even when the signal is several dB too weak to be decoded by the fully general convolutional algorithm. Of course, this approach works only if the received message is one of those in the list; but there's no reason why a decoder must be equally sensitive to all possible received messages.

Inverted sync vectors (0 replaced by 1, and vice-versa) are now used for messages that include two callsigns and a signal report. As with JT65, the decoder now marks most synchronized messages with "*", but those including reports with "#". As described in section 4, this scheme helps the receiving operator to decode messages for which averaging is required.

Regrettably, the prospect for further coding and modulation improvements useful for microwave EME is not very bright. Phase-coherent techniques are out of the question; the rough lunar surface ensures that EME signals on these bands will always have arbitrary, rapidly varying phases. One could use GPS-based timing and calculated EME delays to do away with the need for signal energy devoted to synchronization. Such an approach could gain another 2 dB, approximately [11]. If receiver bandwidths as large as 10 to 20 kHz were available — perhaps by using special equipment similar to that used for *MAP65* — a wide-spaced JT65-like mode with 65 tones (perhaps called JT65G ?) could be used, yielding maybe another 2 dB from the more efficient modulation [11]. These approaches would require special hardware, as well as a number of software changes.

3. Results achieved with JT4, and Comparisons with JT65

WSJT and JT4 have now been thoroughly tested with EME signals on both 10 and 24 GHz. Among highlights of these tests are the following:

- VK3XPD (12 W, 3 m dish) worked W5LUA (100 W, 2.4 m dish) for a 24 GHz World record distance for any mode, 14496 km.

- VK3XPD (6 W, due to longer waveguide run when working to his Moonset, 3 m dish) worked OK1KIR (21 W, 4.5 m dish) to extend the 24 GHz World record to 15874 km.

- VK7MO (45 W, 0.77 m dish) worked G3WDG (15 W, 3 m dish) for a 10 GHz VK distance record of 17410 km. G3WDG was copied when using as little as 8 watts.

- VK7MO (0.47 m dish) copied W5LUA (100 W, 2.4 m dish) under good conditions on 24 GHz. Usually this required averaging of several transmissions. (W5LUA did not detect the 4-watt signal of VK7MO.)

- Subsequently VK7MO upgraded his 24 GHz portable station to a 77 cm dish and 10-watt DB6NT PA. With this arrangement VK7MO could decode W5LUA reliably on 24 GHz, mostly without need for averaging. Averaging was still required when absorption was high due to cloud cover or elevations less than 10 degrees. (W5LUA still did not detect the 10 watt signal of VK7MO.)

- OK1KIR (4.5 metre dish and 21 watts) was copied on 24 GHz by VK7MO (77 cm dish and 10 watts). OK1KIR was able to detect single tones from VK7MO but not decode signals.

Revisions 3021 and higher of *WSJT* include a facility to add noise to a recorded signal so you can determine the amount of S/N you have "in reserve". This feature is activated by entering (for example) $-3 in the Tx6 message box, where the -3 indicates a 3 dB degradation in S/N. Using this facility, VK7MO established that there was a 5 to 6 dB reserve on W5LUA's signal under good conditions. W5LUA has 10 dB more power than the VK7MO portable setup and receives additional moon noise on his bigger dish; the difference in system performance is around 12 dB. So even with 6 dB in reserve, another 6 dB is required to achieve a QSO with a small dish and 10 watts.

Four days of 24 GHz tests between VK7MO and W5LUA showed that the median frequency error after Doppler correction was less than 20 Hz. On a few occasions the W5LUA antenna drifted off moon centre toward the limb, and the signal shifted in frequency by around 100 Hz. The total limb-to-limb spreading at the time was 200 Hz, so it's clear that this shift was caused by the differing Doppler shifts at the centre of the moon and the limb. When tracking was accurate, apparent frequency variations were always less than 40 Hz at 24 GHz — a clear demonstration of the value of GPS locking and automated Doppler correction.

Atmospheric absorption by water vapour can add several dB of attenuation at 24 GHz, especially when the moon elevation is low and the atmospheric path longer. The atmosphere holds much less water vapour in winter, so winter conditions are generally best. Of course, for trans-equatorial paths it cannot be winter at both ends, and for Australia to Europe or North America elevations will always be rather low. Atmospheric absorption will then be more of an issue.

On-the-air tests with the latest versions of *WSJT* show that for narrow signals the sensitivity of JT4 is only 1 to 2 dB worse than JT65C. As Doppler spreading increases beyond 10 Hz the wide-spaced JT4 submodes lose around 1 dB of sensitivity for each doubling of spreading, while JT65C loses more like 3 dB — the exact amount depending on shape of the Doppler-spread profile. Thus, as spreading increases JT4 becomes the preferred mode. In practice at 10 GHz, where the spreading has a significant central peak, the crossover point is around 50 – 80 Hz. At 24 GHz, where the spreading is more evenly distributed, the crossover is more like 20 – 40 Hz and there would rarely be any advantage in using JT65c. For very small 10 GHz stations working a station at the same longitude it is sometimes possible to choose a time when the spreading is low enough (say, < 40 Hz on 10 GHz) to give the advantage to JT65C; but most of the time JT4 is preferred. In general we recommend using submode JT4F: its 157.5 Hz tone spacing is usually enough, and its total bandwidth of 630 Hz is small enough to fit comfortably within a SSB receiver's passband, with some reserve to accommodate possible frequency-control issues. Finally, we note that another advantage of JT4 over JT65C is that its wider tone spacing allows nearly smooth Doppler corrections on radios such as the FT-817 with 10 Hz incremental tuning steps. For JT65C, it's important that Doppler corrections be done with 1 Hz tuning steps.

4. Procedures for Microwave Doppler Corrected EME

The latest version of the *WSJT* software can be downloaded from a link posted at

http://physics.princeton.edu/pulsar/K1JT/wsjt.html

In JT4 mode the program works similarly to JT65, but there are some significant differences.

Single Tones: JT65 offers two-tone shorthand messages for the common EME information RO, RRR and 73. With GPS locking and automatic Doppler correction we can use frequency offset of a single tone to convey such simple information. A single tone is easier to see on the waterfall, since the full Tx energy is focused in one place. JT4 has therefore adopted the following meanings for single-tone messages:

@1500 Hz = RRR
@1700 Hz = 73

Single tones are sent by using the @ symbol followed by a number representing frequency of the tone. As described below, single-tone messages for RRR and 73 usually appear in Tx message boxes 4 and 5. For a station that is not fully GPS locked (for example, the IF radio is free-running) it is important to establish the centre frequency as a reference against which to measure other tones such as RRR and 73. For this purpose a 1270 Hz tone may be transmitted at the start of a QSO. If a station appears slightly off frequency you can click on the waterfall to centre the green tick on the received 1270 Hz tone; the two red ticks to the right then respectively represent RRR and 73. The @1270 tone can be manually added in place of the CQ message in Tx6. It is also possible to replace the CQ message with @1270 in the Tx6 message template, on the Setup screen.

@1000 Hz: Often when working portable it is impossible to align on the moon visually due to cloud. As moon noise is too weak on a small dish the best way of alignment is to peak on the single tone being sent from the other station. In order that the other station knows that you have completed alignment and are ready to receive messages, the recommended procedure is to start with a 1270 Hz tone for both frequency and pointing alignment; when you are ready to receive messages you send a 1000 Hz tone. The change can be done in the middle of a transmission: indeed, it proves to be more positive if the other station sees such a frequency discontinuity within a single transmission.

@2000 Hz: The 2000 Hz single tone is used to represent QRT so that a portable station can let people know that they are closing.

Yellow Graph to help identify weak single tones: The Setup menu includes a new option "Plot average JT4 spectrum". If this is ticked, a yellow curve will be displayed in the graphical section of the main window. This can be used to identify the frequency of single tones too weak to show up on the waterfall. Moving the mouse cursor vertically along the line of the yellow peak will activate a highlighted yellow box showing the frequency difference from the nominal 1270 Hz. Thus if you see a highlighted DF of 230 Hz this identifies an RRR tone and 430 Hz identifies a 73 tone. A starting @1270 Hz tone will show up close to DF=0. If the starting @1270 is slightly off you will need to do some mental arithmetic to check the RRR and 73 tones. But if the tones are sufficiently strong to see on the waterfall and the green tick is on @1270 then the correction is automatically done and you just read below the red markers.

Signal Reports: We recommend using numerical signal reports for microwave digital EME. Among other obvious advantages, such reports ensure that you exchange some unknown information as well as identifying the callsigns of both stations, thereby complying with the original 1957 Tilton VHF definition of a minimal QSO [12]. Message generation is made easier by setting message templates on the Setup/Options screen, as follows:

Tx 1: %T %M %G
Tx 2: %T %M %R
Tx 3: %T %M R%R
Tx 4: @1500 (RRR)
Tx 5: @1700 (73)
Tx 6: @1270 (START)

If you double-right-click on the other station's callsign in the decoded text window, *WSJT* will automatically generate messages with the correct report. If you achieve a decode only after averaging, estimate a dB value, insert it manually into the Rpt box, and click Gen Msgs. It's probably best to insert a report the first time you get a good signal in the average (good DT and DF) and then click Gen Msgs so you're ready to send a report as soon as you get an average decode. Once having started to send a report you should stick to it, since the other station may need to use averaging and that requires a constant message.

Message Averaging: Averaging has always been a feature of JT65, but in our tests it rarely came into play even at 10 GHz. We have found that at 24 GHz averaging is the norm. In part this is because our signals have been weaker, but the diffuse 24 GHz reflections also give a more consistent signal level. When averaging is likely to be important you should clear the average as soon as the other station starts sending messages. The first message sent by both stations will include callsigns and grid locators. This message is accompanied by a "*" sync indicator. Once one station copies the other they move to Tx2 and the message will change to a "#" sync. As soon as you see the "#" sync, click on Clr Avg to start a new average and press the Decode button again. The use of averaging requires you to pay attention to the values of DT and DF, rejecting inconsistent transmissions with the Exclude button. Effective use of averaging requires some practice, but it can help you to pick up that last 1 or 2 dB.

Sync Setting: The default setting of *WSJT*'s Sync control is 1, which may help to limit the number of false decodes. In practice on 10 and 24 GHz there are few birdies to trigger false decodes, and our operational experience is that it‘s best to set Sync to 0, so as to see and evaluate the weakest signals.

MinW control: The JT4 decoder starts by assuming minimum frequency spreads comparable with the setting of the MinW control, using the same labels A–G as those for the JT4 submodes, see Table 1. If decoding fails, it proceeds to the next higher width. By this means the decoder optimises the bin-width to match the spreading of the signal. To speed up the decoding process and avoid the picking up false syncs at lower widths, experience suggests it is best to set the starting width just one or two steps below the predicted spreading. For example, if the predicted limb-to-limb spreading is 200 Hz you might set MinW at the "E" level, representing a bin-width of 78.25 Hz. The final column in a line of decoded text will contain a letter representing the bin-width actually used.

Freeze and Tolerance: When you have identified your QSO partner's signal, limit the frequency range over which decoding is attempted by using the Freeze and Tol (tolerance) controls. We find that Tol = 50 is generally sufficient for Doppler corrected signals, even with spreading in excess of 200 Hz. Freeze can be set at the time you see the initial @1270 Hz tone, and reset if you should see DF drifting, for signals that are otherwise correct — for example, they decode or have DT consistent with previous transmissions.

5. Prospects for a 24 GHz Portable Station

We have shown that it's possible for a 24 GHz portable station with a 47 cm dish to copy a good home station such as W5LUA (100 W TWT, 2.4 m dish). However nothing has been copied from the portable station even when running 10 watts to a larger 77 cm dish. As discussed in Section 3 it seems that at least another 6 dB will be required to complete a QSO with a small portable station, and then only under good conditions.

In Section 2 we argued that the prospects for improving system performance with better coding and modulation are limited. Making up 6 dB by increasing antenna size would require a dish of 1.6 metres, which is a practical upper limit for convenient portable operation. Another option is to increase power. High power TWTs run at around 12000 volts; the necessary HV supplies are heavy and susceptible to breakdowns with humidity in open air. They are hardly good candidates for portable operation. Some amateurs, for example JA8CMY [13], are home brewing up to 38 watt solid state amplifiers based 8 TGA4915 modules giving almost 6 dB over the 10 watt DB6NT amplifier used to date. Alternatively 21 watts solid state has been achieved by OK1KIR with a pair of DB6NT PAs. It seems that a viable portable operation able to cope with more-than-minimum atmospheric and libration losses will require improvements in both dish size and power — perhaps an increase in dish size to around 1.6 m and a home-built 30 watt PA. It will be a challenge.

6. Conclusions

We have shown that small-station, portable 10 GHz EME is feasible by taking advantage of GPS frequency locking, automatic Doppler correction, and recent improvements in the JT4 decoder. Achieving similar capability at 24 GHz is the next challenge, but it will not be easy. We recommend using digital mode JT4F for amateur EME communication with small stations at 10 and 24 GHz. It's worth noting that JT4F, with the improved decoder, should also work well for rain scatter at 10 GHz.

7. Acknowledgments

The developments and advances reported here owe much to the efforts of the following stations who provided on-the-air test signals and contributed to discussion of results within a small email group: The OK1KIR club station operated by Vlada Masek, OK1DAK and Tonda Jelinek, OK1DAI, Al Ward W5LUA, Alan Devlin VK3XPD, Charlie Suckling G3WDG, and Gerald Williamson, K5GW (who has also developed a separate version of the Doppler correction program for use with the Flex Radio). Thanks also to Glen English, VK1XX for writing the original Doppler correction program for the IC-910-H, and adding capability for the FT-817. His program should be useful on most modern ICOM and Yaesu rigs that have CAT control.

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