How Good Were the EME Systems of the 1960s and 70s?

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Working with Doug VK3UM on his *EME Calculator* software [1], I found myself thinking how useful this system analysis tool would have been in the early years of amateur moonbounce. That is not to imply that we didn't know how to calculate the basic parameters, there were published papers that carried a full analysis of the signal budget and the Radar Equation was well known. But one area about which we had much less information was antenna characteristics – the sort of information that W1GHZ and SM6FHZ have provided in recent years [2, 3] and will be updating at this Conference.

Knowing that I had quite good records of many of the early tests, I thought it would be interesting to apply some of the modern analysis tools to the systems of the 1960s and 70s to see how good they actually were. The paper is mainly about 432 and 1296 MHz but there is some reference to the 144 MHz work.

Of course there were many things we didn't have in those days, so we had to develop them. Even today, EME continues to be the driving force behind new developments in LNAs, power amplifiers, frequency stability and weak-signal operating techniques that most VHF/UHF/microwave amateurs take for granted.

Why 432 MHz and 1296 MHz?

Looking at the curve of sky noise against frequency (Figure 1) we see that the noise from the galactic background contribution falls rapidly with increasing frequency, levelling off to a low-noise window starting at about 1 GHz. Because technology for the microwave bands was much more difficult in the early days, the first developments in amateur EME were mostly at the lower edge of this window, on 432 and 1296 MHz.

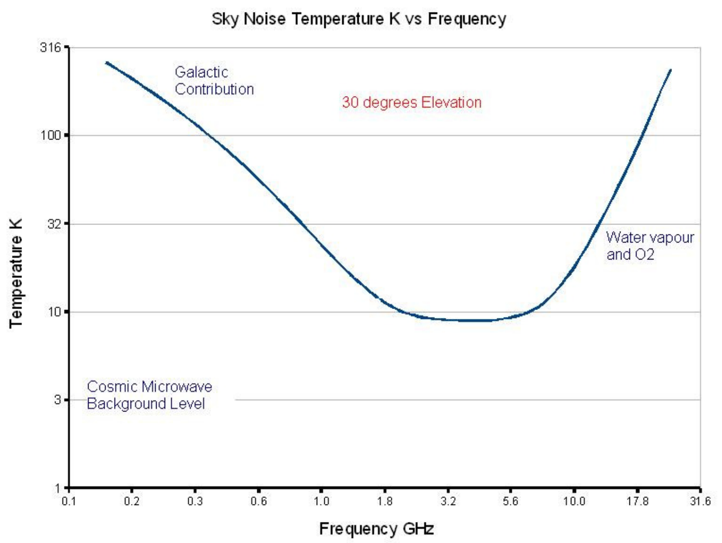

Figure 1: The sky noise 'window' between 1 GHz and 10 GHz

The 1950s were a time of tremendous progress in microwave technology and the emergence of high quality varactor diodes made it possible to achieve noise figures of about 1 dB within the low noise window by using a parametric amplifier. The 144 MHz EME efforts were pretty much unaffected by this but the UHF and microwave community got a big boost.

The Early Years, 1953–1980

The first amateur signals detected after moon reflection were on 144 MHz and were received in July 1953 by W3GKP and W4AO. Several groups tried to build on this and make a QSO but without success. In July 1960 the first amateur EME QSO was made on 1296 MHz by W1BU and W6HB – 'amateur' in name, but in fact supported by two major US corporations. In essence, Microwave Associates had paramps and Eimac had power klystrons, so by swapping one for one, and after an enormous amount of hard work with dishes and mounts, the QSO was made.

At this distance in time, it is hard to convey the impact of this news. VHF/UHF enthusiasts everywhere opened their *QST* for September 1960 (Figure 2) and immediately thought: **"How can I copy that? What do I need?"**

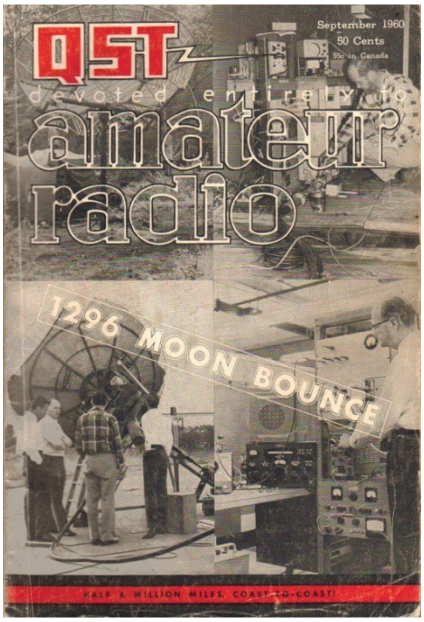

Figure 2: Inspirational QST *cover of September 1960*

Over the next twelve months, several stations built dishes of between 16 and 26 ft diameter and some of these copied transmissions from W1BU; but the next full QSO was not until March 1962 when W1BU worked W2CXY. Soon afterwards, in August 1962, W1BU worked KH6UK, extending the 1296 MHz distance record again. The 144 MHz workers had not given up, of course, and the first QSO on 2 m was made in April 1964 by W6DNG and OH1NL.

The small number of 1296 MHz QSOs actually completed in the three years since the initial W1BU effort was principally due, I believe, to the real problems of generating sufficient power on 1296 MHz using only amateur resources. As a result, several people (including me) had turned to 432 MHz and EME on this band was about to get a tremendous boost. Following the lifting of the 50 W power restriction in the USA, W5SDA and K5KDN heard the first echoes on 432 MHz in January 1963 but the first QSO on this band was again between W1BU and KH6UK.

On June 13th 1964 the 1000 ft radio telescope at Arecibo was activated on 432 MHz as KP4BPZ by a team including Sam Harris W1FZJ (the driving force behind W1BU). Six stations were worked, and HB9RG and I were the only non-US stations. This was my first EME QSO using my 15 ft wood frame dish (Figure 3).

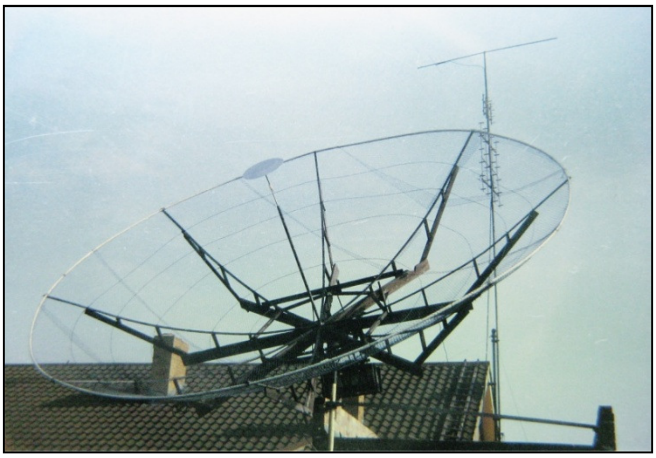

Figure 3: G3LTF 4.6 m dish, 1964

The next day, June 14th, the Arecibo dish was used on 144MHz with another host of firsts, including the first EME QSO on 144 MHz from G by G2HCG. In September 1964, HB9RG and W1BU finally made it on 1296 MHz for the first NA-Europe QSO on that band.

KP4BPZ was the first of the ‘big dish’ operations that characterized the 1960s and 70s, and it achieved several things: it gave a tremendous boost to stations who already had systems under way; it generated wide publicity for EME operations; and it even provided the opportunity for near-random QSOs, just like tropo! When KP4BPZ came on 432 MHz again in July 1965 there were far more stations ready for them, and in addition they were on SSB. They made 28 QSOs. Several stations also heard WA6LET which was the Stanford 150 ft dish (Figure 4) and so in September 1965 WA6LET ran their own big dish test and worked 12 stations (all in NA except for me). In October 1965 the 60 ft Crawford Hill dish of Bell Labs at Holmdel, NJ (Figure 5) was activated for the first time on 432 MHz as K2MWA/2, working W1BU, W9HGE and W3SDZ.

Meanwhile on 144 MHz, VK3ATN had erected a massive 3-stack rhombic array, 342 ft each leg, and in November 1966 he worked K2MWA/2 for the first NA-VK EME contact. VK3ATN also worked K6MYC. The first *EME Newsletter* also started at this time, compiled and distributed by Vic, W3SDZ; I think it ran to about 10 issues.

Figure 4: WA6LET, 150 ft dish at Stanford, CA

Figure 5: W2IMU/2, 60ft dish at Crawford Hill, NJ

A group led by Dick Turrin W2IMU then started to activate the Crawford Hill dish two or three times a year on 432 or 1296 MHz in a series of pre-advertised tests or “activity weekends” and this bought an increasing number of stations onto the bands. Tests then started between smaller stations who could just about hear each other during the Holmdel dish tests. One of these was WB6IOM in Los Angeles who had a very well developed 1296 MHz system, and in April 1969 I made a QSO with him which set a new distance record for that band.

The Crawford Hill operations started on April 15th 1967 on 432 MHz and K2MWA/2 worked HB9RG and G3LTF. On April 12-14th 1968 W2NFA was on 1296 MHz, and made QSOs with HB9RG, G3LTF and WB6IOM. Between then and December1973 their 1296 MHz system was gradually improved and QSOs were made with a number of stations including PA0SSB, VK3AKC, WA6LET, OZ9CR and probably others such as K4QIF, VK2AMW, W9GAB, W9HGE and W5LGW. Then in December 1973 the operation closed down and the dish was dismantled and sold. Dick W2IMU produced an excellent set of technical notes at this time. They are still highly relevant and a useful source for data and designs (reproduced in the Proceedings of the Dallas 2010 EME Conference).

In early 1973 the 150 ft dish at the US Naval Research labs was used for a series of receiving tests on 144, 432 and 1296 MHz, with about 25 stations participating (see *QST* January 1973).

Meanwhile the number of stations equipped for 432 MHz had been steadily growing and in early 1973 Cor VE7BBG started to produce a monthly sked list on 432 MHz with K2UYH, W9WCD, W6FZJ (later W1JR) F8DO VK2AMW and G3LTF. By early 1974 the list had grown to about 10 stations and Al K2UYH had taken over the monthly distribution – together with the first, handwritten, EME NL in June 1974! In February 1975 WA6LET came up on 432 MHz again and worked 15 stations. The list of active stations on 432 MHz now totalled 50, and in November 1975 another WA6LET activation worked 84 stations. VE7BBG was already testing with circular polarization and in Sept 1977 the first amateur SSTV QSO took place on 432 MHz between KP4RF and K3NSS (who used an 85ft dish).

1976 had also seen the first EME DXpedition to HK1TL. This was also the first EME activation from SA, and allowed K2UYH to complete the first EME WAC on 432 MHz.

432 MHz EME was now well and truly established and in April / May 1978 the ARRL organised the first EME contest. 1296 MHz activity levels still lagged a long way behind but in early 1980 the first monthly CQ periods were started with PA0SSB, W6YFK and VE7BBG.

So much for the early EME activity. Now, what about the early EME technology?

Early EME Technology

Low noise amplifiers

Amateur EME could not have started without the parametric amplifier. 'Low noise' tubes like the 416B and 417A were available but the NF was nowhere near low enough for amateur EME, and low noise VHF/UHF transistors were still a distant dream.

The principle of parametric amplification was understood from the pre-electronics era but it was the emergence of varactor diodes with cutoff frequencies above 100 GHz that made the technology feasible at microwave frequencies. The diode is 'pumped' by a frequency Fp that is much higher than the signal frequency Fs, and the difference ('idler') frequency Fi must also be present. There are thus three resonant circuits to be arranged around the diode. Losses in the signal and idler circuits have to be kept to a minimum for low noise amplification.

The absolute minimum noise figure is given by $F = 10 \log_{10}(1+ Fs/Fi)$, so Fp and Fi must both be as high as possible. The paramp is a two-terminal device and so to avoid noise from the output port limiting the noise figure, the output had to be much more loosely coupled than the input. This meant running the whole paramp at a much higher gain which made it even more tricky to tune... and so on. A circulator solves those problems but they certainly were not readily available for amateurs in those days.

The first amateur paramp designs, by W6AJF, appeared in *QST* in 1959 and these were for 144-432 operation. Pump frequencies were 600-1400MHz but these designs were really hard to get working as they depended on multiple resonances in the line, and a series of traps to contain the pump and idler frequencies. We struggled with them because – when they worked – they were better than tubes. In January 1961 an infinitely better design for a 1296 MHz paramp was published in *QST*. This used a 3 cm klystron for the pump, and had separate cavities for the pump and idler with a coaxial line for the signal.

I built two of these, for 432 and 1296 MHz, but added radial chokes at pump and idler to completely isolate the signal line which was made in an adjustable coaxial form. This arrangement worked extremely well. I fired up the 1296 MHz version (Figure 6) recently and it measured 1.5 dB NF with about 20 dB of gain… not bad at all, and superb by the standards of those days. These paramps were followed directly by a trough line or cavity diode mixer, typically with a 7 dB NF.

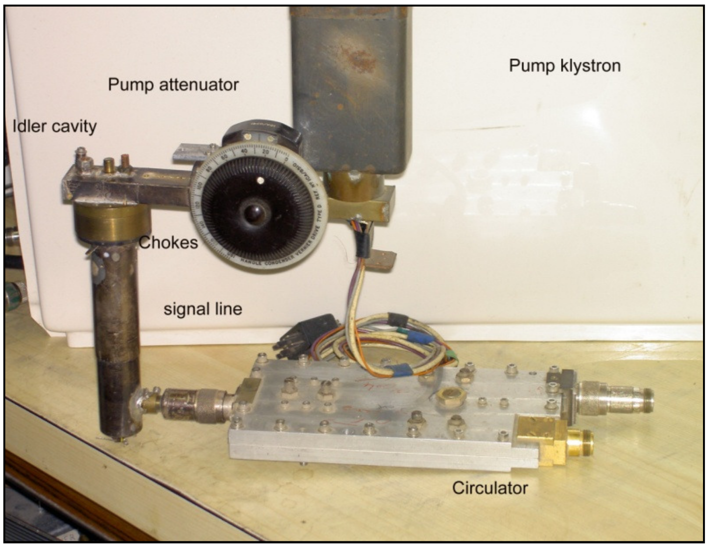

Figure 6: G3LTF 1296 MHz paramp, used from 1965 to 1974

So parametric amplifier technology was just about possible in those days, but by no means easy. In 1969 Rusty K4QIF had a paramp mounted at the edge of his 10 ft dish, which was hugely impressive – most people had enough problems with running them in the shack! The unavoidable feedline losses associated with paramps gave a head start of at least 1 dB to the next emerging technology: transistor LNAs that could be installed directly at the feedpoint itself. At the time of the first EME contacts there were no transistors that could approach a paramp, but progress was rapid.

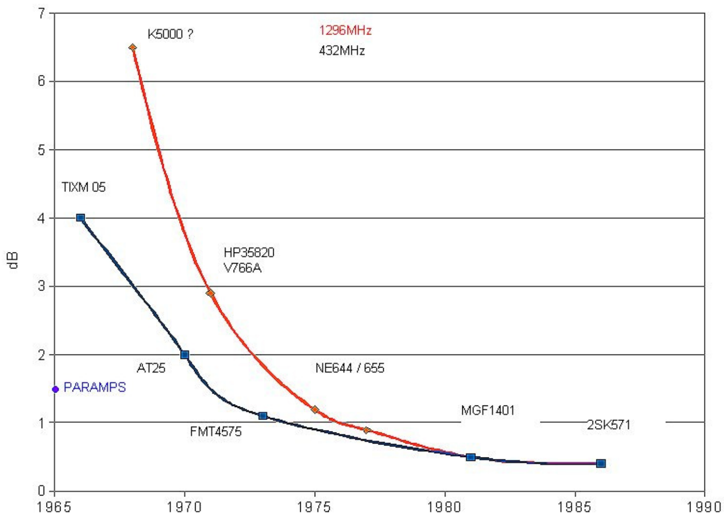

Figure 7: Noise figures, 1960-1986

Figure 7 shows the noise figure of transistor preamps over the period 1960-1986 taken from the archive material. Several of these data points are from designs by professionals like W1JR and WB5LUA with access to proper measuring equipment, and they also agree with the data sheets. By 1970-72 a transistor LNA at the feedpoint could outperform a paramp at the bottom of the feedline… but only if you could obtain (and afford) the precious transistor. By the mid-1980s 0.5 dB was obtainable on both 432 and 1296 MHz and noise figures have continued to fall to the 0.2 dB region today.

Transmitters and moon tracking

Generating RF power on 432 MHz in the 1960s was not easy. Only a few large tubes were around, for example the 7213 and the GL6942, both 1.5 kW tetrodes. In 1972 K2RIW published his wonderfully simple parallel 2 x 4CX250B design. Compact and efficient, it delivered 800-900 W and was used by many EMEers. On 1296 MHz it was even more difficult. Apart from a few klystrons in the USA the only other tube was the 100 W ceramic 3CX100A5 triode. Lack of transmitter power was the principal reason that the early W1BU 1296 MHz EME QSOs were not followed through. In early 1968 WB6IOM designed a 2 x 3CX100A5 using a sheet metal box cavity delivering >150 W. Combining two with ring hybrids and driving with a third amplifier generated 300 W, enough for 1296 MHz EME.

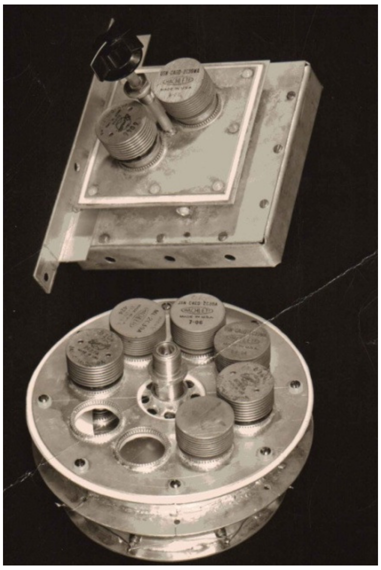

Figure 8: WB6IOM 2- and 8-tube PAs for 1296 MHz

WB6IOM also designed and published in 1968 an 8-tube ring using 3CX100A5s. This brute would deliver 800 W. The UPX4 units then appeared with a 6-tube ring of 3CX100A5s delivering >600 W. The dimensions were published in the W2IMU Notes and OZ9CR manufactured several. K4QIF produced a 4-tube design and W2IMU an improved 2-tube version. These designs fuelled 1296 MHz EME from 1968-80 and beyond. The tube's voltage limits had to be stretched a bit to 1.5-2 kV while the use of water cooling, pioneered by K6MYC, improved cooling and reduced tuning drift.

Moon Tracking was also a major problem. Until PCs arrived in the early 1970s, ephemeris data had to be obtained from almanacs. Many stations used polar mounts as published in *QST*, along with articles on how to obtain el /az data graphically.

Antennas

This section is going to be predominantly about dishes because in the early days they were very much the antennas of choice. In early 1973 there were six stations active in the 432 MHz sked lists, and all used dishes. By April 1974 that list included 47 stations, of which 75% used dishes; but a year later the list had 81 calls with 63% using dishes. In both lists there were a few colinear arrays. The smallest dish was 4.8 m and the majority were 6-9 m. The reasons for this mix were (a) that good Yagi designs at 432 MHz were not yet well established; (b) signals were weak at best, and Faraday rotation easily wiped them out, so rotatable or switchable polarization was considered almost essential; and (c) as power and LNAs became available on 1296 MHz, EMEers wanted to be able to work that band as well.

At the start the predominant driver of dish design was to maximise efficiency. Simple dipole type feeds were the first choice and so we looked at the WW2 reference books (especially *Microwave Antennas* by Silver in the MIT Radiation Lab series) and went for f/D ratios of 0.3 or thereabouts. On 1296 MHz the W2IMU Crawford Hill operation moved to circular polarisation in 1968 with crossed dipoles and a 90 degree hybrid with a relay to switch, but a lot of the early work was done with fixed circular polarisation, reversed at each end to cope with the Moon reflection. As echoes to begin with were non-existent, reversing polarisation was an unnecessary complication but there were a few nail-biting moments when you weren't really sure that you'd got it the right way round. By measuring the field distribution across the dish surface we soon realised that dipoles were not the best choice and very quickly moved to the 150 mm (6 in) circular waveguide feed (literally a coffee can) with probe excitation. Selecting the guide diameter to optimize illumination was the next step, and the first choke to minimize surface current on the outside of the guide was fitted in 1971. As soon as good transistors arrived, which had noise figures better than a paramp at the end of about 1dB of feeder, the preamp moved up to the feedpoint at the output of the hybrid. This first happened in about 1970-71.

In 1970 Dick Turrin W2IMU published a design for a relatively shallow 6 m (20 ft) dish with an associated feed – the now famous W2IMU dual-mode horn. Before the days of really low noise transistors the best dish to build for this horn was one with an f/D of 0.5 to 0.6 and a lot of stations followed that design. A few months later Dick came up with a waveguide polarizer which could be added to the horn and eliminated the need for the comparatively lossy hybrid coupler. Many of these W2IMU horns are still in use and in 2008 the design was updated by N2UO with a septum polarizer section instead of the original with multiple adjustable posts.

On 432 MHz the feed situation has progressed much less, starting with single dipoles and then moving to the dual dipole design around about 1970, after this had been published by the EIA as a gain standard having equal E- and H-plane patterns. Most 432 MHz dish stations had fully rotatable feeds from the very early days. 432 MHz also benefited from the concept of the stress dish pioneered by K2UYH and first described in *QST* in 1966.

With the relatively poor 'low noise' amplifiers of those days, the only way to further increase the received signal was to increase the antenna gain – or in other words, to increase the dish diameter. In the USA there seemed to be a supply of Kennedy 28 ft dishes but in most cases it was very much 'build your own'. In a following section I will give more details of some home-built dishes.

But by the 1970s a large Yagi array was becoming a serious alternative to a dish for 432 MHz (and of course for 144 MHz). F9FT's 1975 system comprised 16 x21 element Tonna Yagis and Jan DL9KR had 16 Quagis with a precision low loss phasing system. By the late 1970s, stations with big antennas (both dishes and Yagis) were making contacts with two-Yagi and even single-Yagi stations, the latter perhaps with some help from ground gain.

Finally we should mention colinear arrays. The notable ones were built by W6FZJ (later W1JR) and ZE5JJ. They had 64 one-wavelength driven elements with reflectors, end fed with open wire feeders, and were about 4.2 x 4.5 m with a gain about the same as a 5m dish. W6FZJ's array was also rotatable in polarization.

Using archive data together with estimates from VK3UM's *EME Calculator* [1] I have put together a chart (Figure 9) showing how the typical system noise temperatures changed between 1960 and 1980 due to the combined effect of improvements in LNAs and feed systems. The advent in the early 1970s of the W2IMU feed horn and transistors at the feedpoint is very obvious in the 1296 MHz curve.

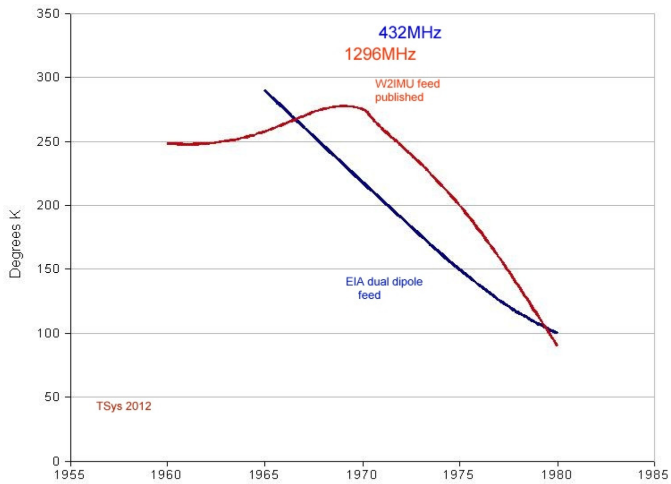

Figure 9: Typical system noise temperatures, 1965-1980

Station Profiles

In this section I will briefly describe some of the best known 432 and 1296 MHz stations of the 1960-1980 era. The System Temperature data in Figure 9 has been obtained by analysis of their performance with the help of VK3UM's *EME Calculator* [1] and references [4] and [5]. These are all estimates, but where possible I have also tried to verify with Sun noise data and received signal strengths. I am very grateful to Paul W1GHZ for modelling some of the older feeds.

Only a few examples can be mentioned in this short version of this paper. Many more examples are given in the longer version on the Conference DVD.

1296 MHz stations

W1BU, 1960: 18 ft Kennedy dish (Figure 10) estimated 0.4 f/D, feed was L-band waveguide with flange, feedline loss 0.5 dB; Microwave Associates paramp MA2-1000B 1.5 dB NF; Tx power 400W. Estimated Tsys 248 K, echoes +3 dB in 300 Hz, G/T +11 dB.

KH6UK, 1962: 28ft Kennedy dish, other details the same as W1BU. Estimated G/T +15 dB. Reported that "KH6UK's signals run 15-18 dB over noise in 30 Hz at W1BU"; the predicted level is 18 dB.

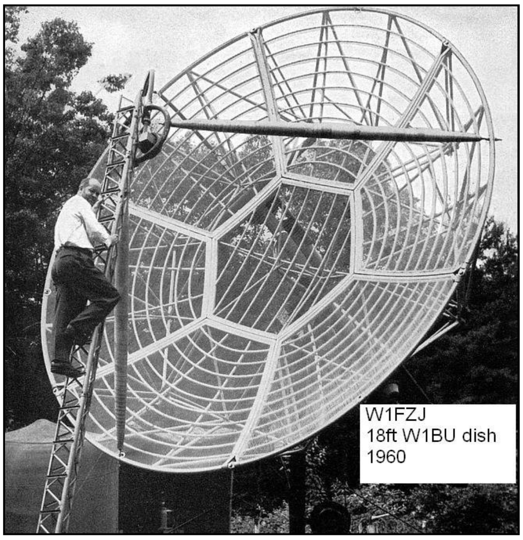

Figure 10: Sam Harris W1FZJ with the W1BU 18 ft dish, 1960

WB6IOM, 1968: 10 ft dish, 0.375 f/D, 6 in (0.66 λ) coffee can feed, 0.6dB feedline loss; paramp 1.5 dB NF; Tx power 500 W. Estimated Tsys 267 K, G/T +6 dB.

WB6IOM, 1969: 16ft dish, 0.525 f/D, same feed as 10 ft dish, 0.8 dB feed line; paramp 1.5 dB NF. Estimated Tsys 300K, G/T +7 dB. Figure 11 shows both of WB6IOM's dishes. The 16ft dish at the rear was made from honeycomb off-cuts glued together on a massive concrete mould; it was on a polar mount with a fixed declination and a movable feed. Unfortunately the feed was never optimized.

Figure 11: WB6IOM 10 ft and 16 ft dishes, 1969

G3LTF 1968-70: 15 ft dish (Figure 3), 0.3 f/D, 0.83 λ circular guide feed, 0.7 dB feedline; paramp 1.8 dB NF; Tx power 280 W. Estimated Tsys 280 K, G/T +8.6 dB. In 1970 this was replaced by a 19 ft dish, made with marine ply ribs. 0.5 f/D, W2IMU feed + hybrid; transistor 1.5 dB NF. Estimated Tsys 200 K, G/T +12 dB.

PA0SSB, 1972: 20 ft dish, 0.6 f/D, W2IMU feed; Tx power 480 W. Estimated Tsys 200 K, G/T +14 dB. Figure 14 shows this beautifully constructed dish with 48 ribs, which could slide down the tower to protect it from the winds.

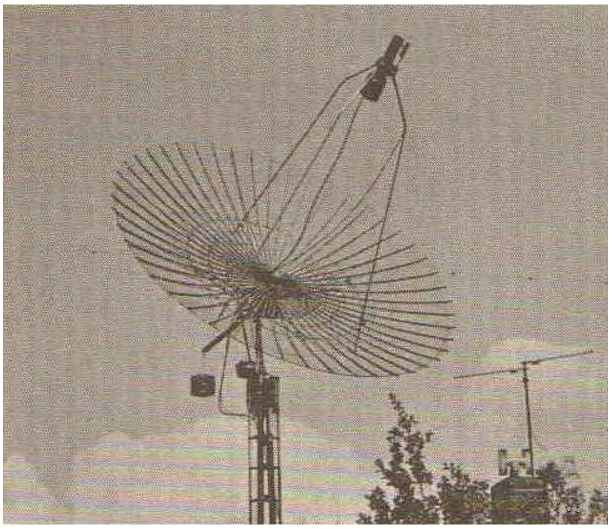

Figure 12: PA0SSB 20 ft dish in elevated position

432MHz stations

Most of the larger dishes were also used on 432 MHz, but many other operators used Yagi arrays.

VK2AMW, 1975: 30 ft dish (Figure 15), 0.4 f/D, dipole feed; MT4578 transistors. Estimated Tsys 140 K, G/T +8 dB.

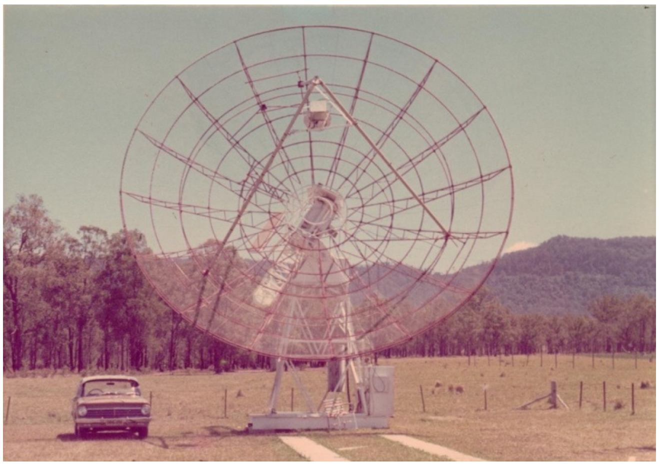

Figure 13: VK2AMW 30ft dish

F9FT, 1975: 16 x 21 element Yagis, 33 dBi gain. Estimated Tsys 150 K, G/T +6 dB. This antenna (Figure 14), which was in use from 1975 until 1992, is typical of the big Yagi arrays of the 1970s and 1980s.

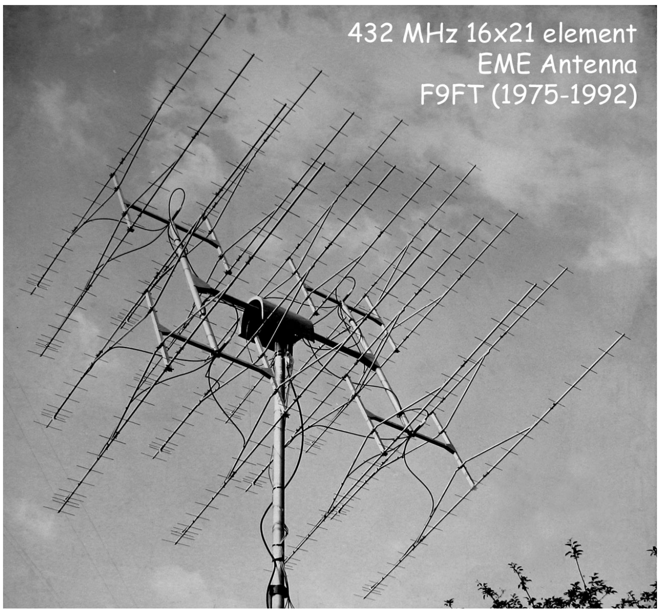

Figure 14: F9FT 16 x 21 element Yagi array

Finally, it must be mentioned that **DL9KR** set the standards for low-noise Yagi arrays on 432 MHz using open-wire feedlines to reduce internal losses. With modern computer optimized Yagi designs, those techniques are still state of the art.

Conclusions

So… how good ***were*** the EME systems of the 1960s and 70s?

It is quite hard to provide a simple answer the question that I asked myself when I thought of putting together this paper. It has been quite difficult to extract the data from the archives and to come up with some meaningful trends, but fortunately the early EMEers were reasonably good at recording their results and describing their systems and nearly all of their communication was by letters (which I have kept).

On both 432 and 1296 MHz the major change from 1960 to 1980 has been in the LNAs, from paramps to germanium transistors, followed in turn by silicon bipolars and then FETs. But at the same time there was also a change to better, more complex, feed systems as the improvements in LNAs forced us towards a better appreciation of the effects of spillover and the benefits of more uniform illumination. I have tried to show this with extracted data in the curves of noise figure and system temperature.

One other issue comes through as I have gone back through the data and the letters: that of antenna aiming. The margins for many of these early contacts were extremely small, for example the W9WCD-G3LTF contact on 1296 MHz was made with signals of around 4-6 dB over noise in 100 Hz, quite a typical level for that time. The -3 dB beam-width of the dishes was about 3.5 degrees so you needed to point within 2 degrees at least. This implies an update every 8 minutes, and we used to run 10-minute Tx/Rx periods to give plenty of time for searching. And as someone so memorably said, there was also a very big difference between listening to your own tiny echoes and searching for someone else’s signals while at the same time scrambling to keep everything work-ing, tuned up and pointed correctly!

As 1980 arrived, there were a lot of developments just around the corner which would transform the capabilities of our EME systems on 432 and 1296 MHz: much better low-noise transistors, the evolution of Yagis with much improved G/T, the availability of powerful modelling tools and the wider availability of large tubes for both bands.

Looking back, I conclude that with limited budgets (many of us were then comparative youngsters bringing up families!) and with mainly homebuilt test equipment, we did build stations which were pretty close to the state of the art. The homebuilt antennas of those days, especially DL9KR's Yagi arrays, were truly amazing, while PA0SSB's dish construction and performance stands comparison with any of today’s big dishes.

And finally: you can find much more information about the early days of EME, with many more EME station profiles and archive photographs, in the longer version of this paper on the Conference DVD.

References

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