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The Journey to EME on 24 GHz

Part 2—On August 18, 2001 VE4MA and W5LUA completed the first 24-GHz Earth-Moon-Earth (EME) QSO. As you're about to read, the struggle for this achievement required resourcefulness and patience.

The recent improvements in low noise microwave transistors allow good low noise amplifiers to be created, although this still takes a great deal of skill and patience to achieve. The commercial satellite industry at 14 GHz has created efficient parabolic antenna reflectors that might be useful with reduced efficiency at 24 GHz. Obtaining high transmitter power still represents the biggest individual challenge, however. High-power traveling wave tube amplifiers (TWTs) are not commonly available, and low frequency units are hard pressed to produce the gain and output power needed. As all the radio technologies are challenged to perform well at this frequency, strict attention to details are necessary.

Beyond the technology challenges, the high path loss adds a further barrier. The minimum EME loss to the Moon at 24 GHz is approximately 297 dB! Furthermore, the 24 GHz band is also severely affected by water vapor absorption in the atmosphere. What would it take for amateurs to bridge this formidable gap?

Antenna Systems and Moon Tracking

At VE4MA, the initial plan was to use an Andrew 3.0-meter dish (see Figure 1) that has been operational from 1296 to 10,368 MHz. This dish was made for 14/12 GHz satellite terminals, but it had some surface inaccuracies that could be a performance problem at 24 GHz. The theoretical gain at 24 GHz was expected to be near 55 dB over an isotropic radiator—and with a beamwidth of 0.28 degrees! Antenna pointing is a significant problem as the dish has a 1 dB beamwidth of 0.16 degrees and the Moon moves across the sky at a rate of 15 degrees per hour. This means that the antenna pointing must be updated about every 60 seconds!

Antenna peaking is accomplished manually and is assisted by a "noise meter" that displays the relative value of the Moon's thermal noise being received. The Moon, being at an average temperature of 250 kelvins (273 K = 0°C), radiates thermally generated radio noise and is quite bright compared to the 4-degree background temperature of space. After careful adjustment of the feedhorn position, approximately 0.6 dB of Moon noise was seen on the dish with the receiving system of the time at 24 GHz (more about this later). The General Radio GR-1236 noise meter has a 1 dB full-scale deflection, so the movement is quite dramatic. Larger dishes would not see more noise because the Moon illuminates the whole antenna beamwidth and this thermal Moon noise actually limits the ultimate sensitivity of the receiving system. More antenna gain from a larger dish would help on transmit, but antenna pointing becomes very critical because you must hit the center of the Moon to ensure that the reflection comes straight back to the Earth.

Barry was able to acquire a Prodelin 2.4-meter offset-feed dish originally intended for 14/12 GHz remote broadcast uplinks. Looking like one of the direct broadcast mini-dishes, this reflector is very flat and in theory might provide very high efficiency and perhaps even as much gain as the larger 3-meter center fed Andrew dish (see Figure 1). Linear actuators are used for both azimuth and elevation control. A fringe benefit of the offset fed dishes is the ability to locate all the electronics at the feed point without introducing blockage of the dish's capture area. Using one of W1GHZ's computer programs[1] a W2IMU feedhorn was created and built using plumbing parts and sheet copper. See Figure 2. With the W2IMU feedhorn carefully optimized in front of the reflector the Moon noise was 2.3 dB (previously 0.6 dB) and Sun noise was 15 dB.

The transverter is homebuilt and mounted at the feed of the dish. The present transverter uses a 1.55 dB noise figure DB6NT LNA driving an isolator, filter and surplus downconverter. The LO is a surplus Frequency West local oscillator. The IF is at 432 MHz, which is fed to a separate 432-to-28 MHz receive converter used to drive an HF receiver and the noise meter for peaking on Moon noise.

Initial tests were performed using homebrew waveguide input low noise amplifiers, as shown in Figure 3. The WR-42 waveguide input also provides a convenient method of tuning for lowest noise figure with screws at the appropriate positions. The amplifier uses a printed circuit

[1]Notes appear on page 47.

Figure 1—The 3-meter Andrew prime focus and 2.4-meter offset feed dishes at VE4MA.

board design by W5LUA[2] and modified for waveguide input and output by VE4MA.[3] The LNA makes use of two Agilent Technologies ATF-36077 PHEMT devices producing a 2.3-dB noise figure. This preamplifier was used with the initial tests with the 3-meter dish.

At VE4MA the manual dish aiming method remains, but a TV camera with a telephoto lens is used to provide operator feedback. This avoids having to pause during the middle of a 2.5-minute transmit period to re-peak on received Moon noise.

At W5LUA a 5-meter fiberglass dish is used for EME from 902 through 10368 MHz, while a 3-meter Andrew aluminum dish is used on 24 GHz (see Figure 4). In order to improve the surface accuracy of the 3-meter dish, an adjustable back structure was added to aid in mechanically tuning the surface of the dish. The eight points of the back structure allowed optimization of the dish's surface. In the March 2001 timeframe, when VE4MA first received W5LUA's echoes, Al was receiving 12.5 dB of Sun noise and 1.3 dB of Moon noise. The Sun noise is a 3-dB improvement over what Al was obtaining prior to optimizing the dish surface. His system noise figure at the time was 2.25 dB. Al's feed is a scalar design optimized per the "W1GHZ On-Line Antenna Handbook."[1]

The Andrew Corporation manufactured the original W5LUA az-el positioner. However, it was only designed to rotate test antennas for pattern measurements and was quite worn out. After a quick look, Gerald, K5GW, concluded that with some rework, Al's original az-el positioner could be rebuilt. The heart of the original positioner was a pair of 70:1 right-angle gearboxes, but they were driven by some high-RPM 24-V dc motors. Needless to say, the motors swung the antenna excessively fast. Al managed to find a pair of 5-RPM dc motors. With some sprockets and chain he was able to attach the motors to the gearboxes. The resultant antenna speed was now reduced to about 0.5 degrees per second. The positioner had a precision transducer for the azimuth readout, which has a 0 to 8-V output for 0 to 360 degrees azimuth rotation. For elevation, Al uses a precision 270-degree potentiometer with a 4 to 1 reduction obtained using small sprockets and plastic chain. The output voltages from both positioners are fed to an old IBM A/D board that he installed in his old HP Vectra 486 computer. Al is able to track a 0.1-degree change in both azimuth and elevation. With the new tracking system, he is able to update the dish in 0.1-degree increments while transmitting.

In order to minimize the amount of metal used at the focal point of the dish a piece of PVC pipe is used to support the

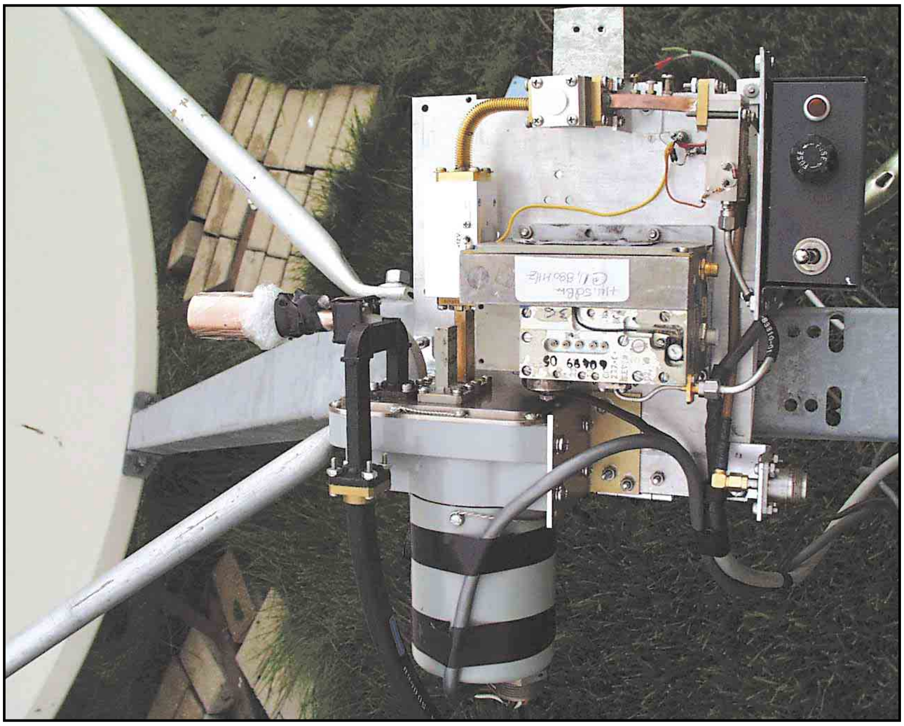

Figure 2—A 24-GHz feed assembly (receive converter and waveguide switch) and W2IMU feedhorn.

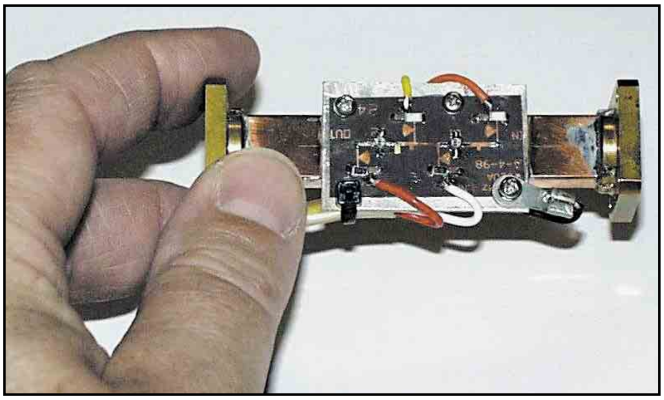

Figure 3—The VE4MA 24-GHz waveguide 2-stage preamplifier.

Figure 4—3- and 5-meter dishes at W5LUA.

feed and relay/LNA combination. The PVC pipe is guyed back to the dish in four directions by the use of insulated Phillystrand cable. Al attempted to keep as much metal and conductive material away from the feedhorn as possible. See Figure 5.

The transverter at W5LUA is also homebrew and uses a surplus DMC LO and a DMC power amplifier providing 50 mW on transmit. He uses cascaded homebrew LNAs to set the system noise figure. The LNA used on 24 GHz is a homebrew two-stage W5LUA[2] design using a pair of Agilent Technologies PHEMT devices that provided a 2.25 dB system noise figure. Al has since acquired some lower noise figure devices that have produced a 1.75 dB system noise figure.

The transverter is dual conversion with a first IF of 2304 MHz and a second IF of 144 MHz. Al's IF radio is an ICOM IC-271. He samples some of the 2-meter IF signal and downconverts even further to 28 MHz. The 28 MHz signal feeds both a GR-1216 IF amplifier for measuring Sun and Moon noise, and a Drake R7 receiver. Although Al has used his IC-271 for nearly every EME and tropo QSO he has made through 10 GHz, he says that the R7 receiver produced an easier to copy signal off the Moon on 24 GHz. The Drake R7 receiver was originally used by W4HHK for his IF on 2304 MHz EME so it is carrying on the EME tradition.

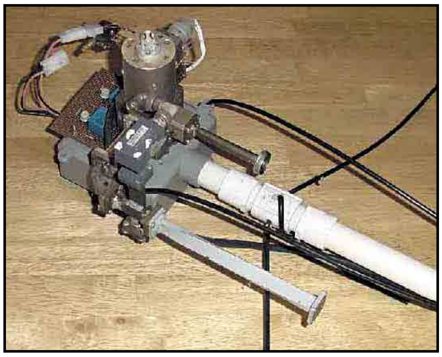

Figure 5—The waveguide relay, LNA and feed assembly at W5LUA.

At W5LUA a combination of rigid and flexible waveguide is used to connect the output of the TWT to the waveguide relay. The TWT and transverter are mounted on a shelf, which is attached to the back of the dish. There is an advantage of a low 0.3-f/d dish, i.e. short length from feed to back of dish! Regardless of what type of antenna is used, every effort must be made to minimize transmit feedline loss by keeping it as short as possible and even putting the transmitter out by the dish if practical.

Transmitter Power Amplifiers

Transmitter power is the most difficult thing to achieve at microwave frequencies. Modern solid-state amplifiers are available on the surplus market up to about a watt, but above that one must rely on TWTs. Most 24-GHz-rated TWTs that become surplus are instrumentation units that at are only rated at 1 W output, while lower-frequency TWTs (e.g. 12-18 GHz) are usually rated to about 25 W. All TWT amplifiers are usually capable of considerably more power if the focusing voltages are optimized for the specific frequency of interest.

At VE4MA, the initial power amplifier work focused on trying to get Varian and Hughes 18-GHz instrumentation amplifiers to move up to 24 GHz. Unfortunately, these amplifiers are often surplus because the power supply and/or the TWT itself are defective. Barry has spent many weeks time in reverse engineering switching power supplies, only to find that the tubes are also bad. The best results were obtained with a Hughes 1177 amplifier driving a Logimetrics 10-W 8-18 GHz amplifier (ITT tube) to achieve 11 W on 24 GHz. Since 11 W was considered marginal for the trip to the Moon and back, the quest for more power continued.

At W5LUA, the initial success in generating power on 24 GHz came after re-tuning his VTU-6191 TWT. The VTU-6191 TWT is a 14.5-GHz 80-W tube that works very well at 10368 MHz, producing 100 W with some additional waveguide tuning. See Figure 6. Al decided to see if this tube could be pushed to 24 GHz. Most TWTs can be coaxed up in frequency by lowering the helix voltage. Unfortunately, lowering the helix voltage down towards the lower specified limit of the tube will generally raise the helix current and cause trip-outs if you're not careful. With generous use of small "refrigerator magnets" and some waveguide tuning, Al was able to generate nearly 10 W at 24 GHz with 50 milliwatts of drive. When a friend of his, John, K5ZMJ, heard that Al was tuning the tube with magnets, John indicated that he had some larger magnets (2.5 × 4 × 0.6 inches) that Al could try.

After careful positioning of the magnets near the input waveguide connector, Al was able to get nearly 20 W output, a gain of 3 dB over his previous best. At this power level, he was able to hear his first echoes off the Moon in March 2001. Also note the band switch arrangement between 10 and 24 GHz as shown in Figure 6. When Al operates 10 GHz, he has to remove the large magnet!

Barry was fortunate to acquire four Varian 100-W 28-GHz TWTs and power supplies. These TWTs proved to be narrow-band "cavity-coupled" tubes that produced no output at 24 GHz. Cavity-coupled TWTs actually have tuned sections within the tube that can be very difficult to tune externally, especially if the tube is of a multiple-cavity type. Although the tubes themselves proved to be unusable at 24 GHz, the hefty power supplies were still usable by Barry after considerable modifications.

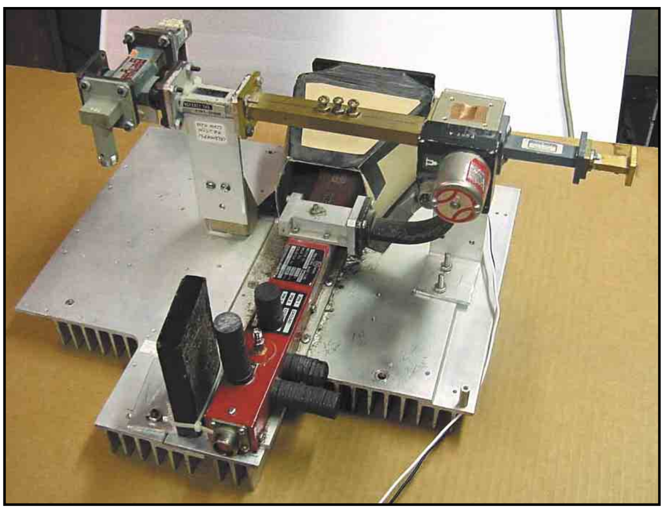

Figure 6—A VTU-6191 TWT band switched for 10 and 24 GHz.

Figure 7—An 80-W 32-38-GHz Varian TWT; a Hughes 10-W TWT and glass 2C39 tube.

After the original tubes did not work out, Barry and Al were able to acquire four different 100-W 26-30 GHz TWTs that were wideband Helix based tubes. Paul Drexler, W2PED, donated these tubes to the EME effort. Many thanks to Paul for his generous donation! Barry was able to modify the 23- and 12-kV sections of the big TWT power supply to create 15 and 6 kV, and make filament and control anode voltage changes. Barry used a Varian TWT unit that is rated at 80 W output from 32-38 GHz to achieve 75 W. See Figure 7. This was achieved after the addition of external waveguide tuners and extensive use of extra magnets for refocusing and dramatic adjustment of the Helix voltage from 13.6 up to 14.7 kV. Presently, Barry is using an NEC LD7235A producing 110 W output in the shack and the resultant power at the feedhorn is approximately 70 W after a 25-foot run of EW-180 waveguide. EW-180 is used at VE4MA for the transmit feed lines from the feedpoint of the dish to inside the ham shack in order to avoid exposing transmitter equipment to extreme weather. The high-voltage TWT power supplies do not like high humidity, while the tubes themselves do not take well to cold temperatures.

For his part, Al was able to bring up a Thompson TH-3864C TWT, designed for the 28 GHz band, to produce 80 W at 24 GHz without additional waveguide tuning. The only problem encountered with the tube was high helix current. The normal no-drive helix current was very near the 5 mA absolute maximum limit. Al was able to place a magnet about the size of a domino at a location very near the input waveguide flange, which reduced the helix current in half without adversely effecting output power.

Working with high voltage TWT power supplies is certainly not without excitement. Several weeks prior to the first QSO, Barry and Al had a sked during which Barry was Q5 at W5LUA when he was running 55 W. Al had just remoted his TWT power supply out near the dish and was excited about making their first QSO. Upon application of the standby-to-transmit push-button, the power supply proceeded to arc! Up until this time, Al had no problems with high-voltage arc-over in the shack, but due to the 75 to 80% humidity that existed in his part of Texas at 0700 in the morning, the power supply decided to act up. It took Al three weeks to disassemble and rebuild the transformer.

First Echoes at W5LUA

Al was first able to copy his 24-GHz echoes on March 6, 2001. They were weak, but CW readable and not just "imagination." System noise figure was 2.25 dB and the power level at the feed was 18 W. Al was able to use the AF9Y DSP software to get a picture representation of his first echoes (Figure 8). The black area represents the time in which he was transmitting. The blue noise represents the receive passband. The white area within the red oval shape shows the received echoes. They are most pronounced during the last 30 seconds of the minute time slot beginning at 0848Z. The S meter on the right hand side of the DSP plot shows the echoes to peak at about 8 dB over the noise in a 50 Hz bandwidth as they slowly drift downward in frequency as the Moon sets in the western sky.

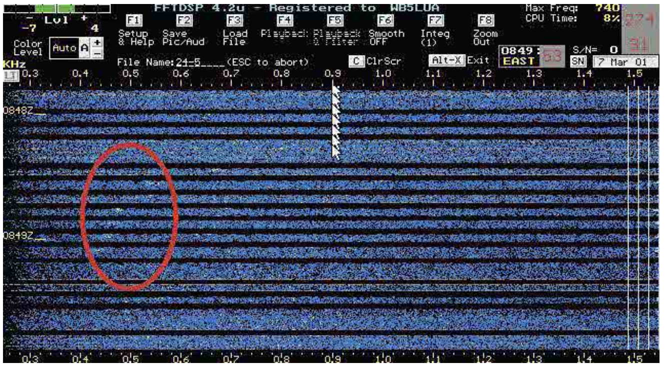

Figure 8—AF9Y DSP software used to document W5LUA's first 24 GHz lunar echoes.

Early tests between VE4MA and W5LUA

For the next several months, Barry and Al ran numerous one-way transmit tests as both were able to get their high-power systems up and running. Hearing each other's signals off the Moon for the first time was certainly a high point. A significant problem early on had been frequency co-ordination and Doppler shift. This is especially troublesome when tuning slowly for a weak signal combined with the dish aiming problems. Al now has a calibrated Rubidium source that is used as a reference for an HP signal generator. At the time of their first QSO both stations were within a few kHz of where they expected to find each other. As with all narrowband microwave work, frequency calibration and stability is a detail that cannot be overlooked.

There is a maximum of +/- 70 kHz of Doppler shift at this frequency and this is easily predicted, but there are significant differences in the values predicted by different programs. Mike Owen W9IP's old *RealTrack* program seems to be within 500 Hz. With the difference in latitude between VE4MA and W5LUA, the Doppler shift between them differed by a maximum of approximately 12 kHz. Frequency setting can be confusing, although it is easiest if the first receiving station corrects the transmit frequency for their echoes to fall on the echoes of the first transmitting station. Keep in mind that for a 10 or 24 GHz EME schedule between two stations on a scheduled frequency, a third observer will not hear both stations on the same frequency due to the difference in Doppler shift from each location.

The First 24-GHz EME QSO

After several years of hard work Barry and Al were able to complete the first 24-GHz EME QSO on August 18, 2001. They exchanged M reports both ways. Al was running 70 W at the feed while Barry was running 60 W. The weather was cool and clear in Manitoba; it was cloudy, hot and humid in Dallas. As it turns out, August is probably the worst time to run on 24 GHz via the Moon because of higher atmospheric absorption.

Since the First 24-GHz EME QSO

As tough as it was to make the first 24 GHz QSO in August of 2001, QSOs have become quite routine since then. Barry and Al have made skeds just about every month since then and they have since worked each other a total of 10 times with "O" copy signals most of the time. They used this time to test improvements to their systems, encourage other stations to listen and learn more about 24-GHz EME conditions. Between August 2001 and March 2002, they were heard by G3WDG, RW3BP, VE7CLD and AA6IW.

In April of 2002, RW3BP, AA6IW and VE7CLD made their first EME QSOs on 24 GHz. The QSO between RW3BP and AA6IW is noteworthy since it sets a new distance record of 9514 km between grids KO85ws and CM87vi.

WA7CJO and G3WDG are expected on the air shortly. Other stations with listening capability include LX1DB, CT1DMK, OH2AUE, OK1UWA and G4NNS.

Power-Level Testing

Barry and Al ran power-level tests in January that helped give some insight as to how high above threshold their signals are. For reference, both Barry and Al run about 70 W at the feed. They ran a one-hour sked and proceeded to reduce power every 15 minutes. The first 15 minutes was easy "O" copy at the 70 W level. The next 15 minutes was using 35 W output. Signals were still "O" copy. The third 15-minute period was run at the 17 W level. Signals were "M" copy and about at the same level as Al's echoes were in March 2001. "M" copy is about the minimum level required to hear a complete set of calls. They did not lower the power level further. Al speculated that at 10 W at the feed, signals would be identifiable especially if one were to place their echoes on top of the stronger signal. Hunting for a 10-W station calling CQ at 24 GHz would still be a challenge.

Signal Spreading

At 24 GHz the rough texture of the Moon's surface produces spreading of a signal. The effect varies with the band. For example, at 2.3 GHz the loss of symbols within a character can make copy of an otherwise strong signal very difficult. Progressing up to 5.7 GHz, a CW signal sounds quite musical and is easy to copy with several discrete carriers being heard close together. At 10 GHz it is somewhat like aurora on 2 meters. The big question was, will 24 GHz be worse than 10 GHz? The answer is "no." The narrower antenna beamwidth, being less than the subtended angle of the Moon (i.e. less than 0.5 degrees), seems to actually produce less spreading than at 10 GHz. The characteristic buzz always sounds like 10 GHz EME (or 2-meter aurora), but is less severe. The musical notes heard on 5.7 GHz have not appeared at 24 GHz. The spreading (or smearing) of the signal is at a minimum near the horizon (when the Doppler is at a maximum) and increases to a maximum as the Moon passes directly south (Doppler minimum).

To illustrate the spreading of signals please see Figure 9, which is a spectrum display received from Charlie, G3WDG. Clearly the CW signal shown from VE4MA is widely spread. The horizontal scale is 3.5 kHz. The Moon at the time was about 30 degrees above the horizon at both ends, so that the spreading is probably about what can be normally expected. As the Moon gets closer to directly south the spreading is much more severe and readability is severely affected. Conversely, at Moonrise/set the spreading is at a minimum. Sergei, RW3BP, has copied signals off his setting moon (approximately 7.5 degrees elevation) from both VE4MA and AA6IW. At the time the moon was due south at VE4MA and just rising in the eastern sky at AA6IW. Sergei

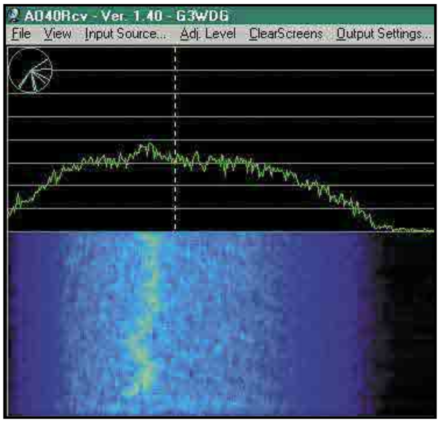

Figure 9—An example of 24 GHz EME signal spreading.

noted almost no spreading (a very sharp signal) from AA6IW, while VE4MA was very distorted. At this time VE4MA observed a high amount of spreading on all signals.

Effect of Seasons and Elevation Angle on System Performance

There is a large water absorption peak (resonance) in the atmosphere just below 24 GHz. As a result, the loss through the atmosphere will vary with the amount of water vapor, which is related to the ambient temperature and the weather. In the colder atmosphere at VE4MA you'd expect the water vapor level, and hence absorption, to be significantly less than at W5LUA (Dallas area). The absorption in the atmosphere has two effects: pure path attenuation and an increase in sky temperature. A receiver looking at a 4 K cold sky will see a sky temperature increase from the "temperature" of the path attenuation as well as perhaps some back scattering from the warm Earth.

The high values of Moon noise achieved in winter dropped dramatically to as low as 1.2 dB (vs 2.3 dB) at VE4MA and down to 0.8 dB (vs 1.3 dB) at W5LUA. The receive performance had dropped in summer due to the combined effects of increased atmospheric absorption and the rise in ambient operating temperature. Consider that for the winter tests the ambient temperature at VE4MA was ~ –30° C vs +25-35°C in summer! For Al, W5LUA, the Moon noise received peaked for only a relatively short period in February and March, before the higher temperatures and water vapor returned.

Clouds were also a concern. The first reception of W5LUA by VE4MA, and also the first QSO between W5LUA and VE4MA occurred through high-altitude clouds at VE4MA that were thick enough to obscure visual tracking of the Moon, but had no apparent effect on reception.

Some time earlier on the occasion of the first Sun/Moon noise checks at VE4MA, tests were conducted during a hot summer day with low, thick cloud cells that produced local rain showers. As the clouds passed the Moon noise was observed to be very erratic with significant drops. This weather is unusual at VE4MA, but served to show the effects.

The local elevation angle of the Moon was found to be very important. All stations have observed that the Moon noise is reduced below about 30 degrees elevation. This is surely due to the effect of the atmosphere discussed earlier and perhaps some ground noise pickup from sidelobes of the dish. Even at lower frequencies, the antenna temperatures increase with elevation angles less than 30 degrees.

Conclusion

It seems unlikely that Moonbounce operation at 24 GHz will ever become as routine as on the lower VHF, UHF and microwave frequencies, but now that several additional stations have become operational, regular repeated QSOs will be accomplished. The preparation work that is required for these 24 GHz QSOs will remain high. The ability to generate RF power will restrict the possibility of 24 GHz EME to a small number of people fortunate enough to find 100-W TWT tubes. In the future more TWTs will likely become available and more stations will accept the challenge.

Notes

[1]W1GHZ Web page: **www.w1ghz.cx**.

[2]Al Ward, "Inexpensive Components for 24 GHz," *Proceedings of Microwave Update 1998*, ARRL, pp 246-256.

[3]Barry Malowanchuk, "A Waveguide Amplifier for 24 GHz," *Proceedings of Microwave Update 1999*, ARRL, pp 301-304.

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FEEDBACK

◊ There is a blank space where an equation should have appeared on page 70 of October 2002 *QST*. The equation should read:

$$20\log\left(\frac{49.28}{49.28+50}\right) = -6.06\text{ dB}$$