By Al Ward, W5LUA, and Barry Malowanchuk, VE4MA

The Journey to EME on 24 GHz

Part 1—The art and science of communicating throughout the world by bouncing signals off the surface of the Moon has captivated hams for decades. Advances in hardware and software have placed this aspect of Amateur Radio within the grasp of the average ham on the VHF and UHF bands, but the "high frontier" remains to be explored with microwaves.

Moonbounce or EME (Earth-Moon-Earth) has always been our ultimate goal for each of the VHF and microwave amateur bands. The primary reason for EME was to aid in achieving the ARRL's Worked All States award on bands above 6 meters. For someone who lives in the middle of North America, EME is the only way to work Alaska and Hawaii. The authors have worked each other on the 8 amateur bands from 432 MHz through 24,192 MHz—all via EME over the past 25 years. For each band, it was a matter of getting the most gain out of our antennas, the most power out of the final amplifier without producing unwanted smoke and noise, and getting the last 0.1 dB out of our low noise receive amplifiers. For years, I can remember each of us bringing our low noise preamplifiers to the Central States VHF Conference and seeing whose was better and trying to better ourselves the following year.

A Short History of EME

A team of folks at the Signal Corps Engineering Laboratories accomplished the first attempt at bouncing signals off the Moon on January 10, 1946 on a frequency of 111.5 MHz. The equipment consisted of a 64-dipole array producing 24 dBi of gain and a 3.5 dB noise figure low noise amplifier. The equivalent of very short dots were sent to the Moon at a peak power level of 3000 W. The return echoes from the Moon were both visually and audibly recorded.

The first amateur work at receiving one's own echoes was accomplished back in 1953 on 144 MHz by W4AO and W3GKP. VHF pioneer Sam Harris, W1FZJ, was also very active in the late '50s. Having heard his echoes on both 50 and 144 MHz, Sam decided it was time to switch to 1296 MHz and on July 21, 1960 made the first-ever amateur EME QSO between W1BU and W6HB. The first 144 MHz EME QSO was made on April 11, 1964 between W6DNG and OH1NL followed by W1BU making the first 432 MHz EME contact with KH6UK on May 20 in 1964. In the late '60s, we find W4HHK and W3GKP making an attempt at the first 2304 MHz EME contact. It was not until after many years of work that the first 2304 MHz EME QSO took place between W4HHK and W3GKP on October 19, 1970. The first 220 MHz EME contact took place on March 15, 1970 between W7CNK and WB6NMT (now KG6UH). A couple of years later the team of W5WAX (now K5SW) and K5WVX (now K5CM) worked the team of WA5HNK and W5SXD on 6 meter EME. Their contact took place on July 30, 1972. The first 902 MHz EME contact took place on January 22, 1988 between K5JL and WA5ETV.

EME contacts on the higher microwave bands did not take place until the mid-'80s when a group from the North Texas Microwave Society decided to undertake the task. Months of intense work paid off on April 7, 1987 when KD5RO (now K2DH) worked W7CNK for the first EME QSO on 3456 MHz. Soon thereafter on April 24, W7CNK worked WA5TNY for the first 5760 MHz EME QSO. A similar effort was underway on 10 GHz with WA7CJO and WA5VJB working diligently to make the first EME QSO on 10 GHz, which occurred on August 27, 1988. So how long would it take to make the first 24 GHz EME QSO? As it turns out, just about 13 years. For more detailed information regarding the history of EME, consult Chapter 10 of the *ARRL UHF/Microwave Experimenter's Manual*[1] and Chapter 8 of *Beyond Line of Sight.*[2]

Microwave EME

Without a doubt, the most activity off the Moon in recent years has been on

[1]Notes appear on page 32.

2 meters and 70 cm. The "Big Guns" on these bands have worked in excess of 1000 different stations on each of these bands. A kilowatt amplifier, four good Yagis and a low noise amplifier and you're on with a station that can hear its own echoes and is capable of working all states and many countries. The EME career at W5LUA started on these two bands and I certainly have a lot of fond memories. However, my goal has been and always will be to go up in frequency. For me the excitement was conquering a new band both terrestrially and via the Moon.

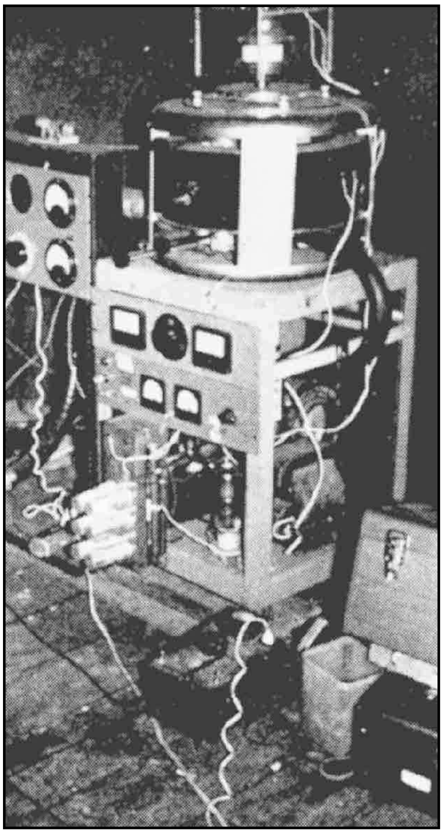
The sections that follow discuss the activity levels on the various microwave EME bands leading up to the first EME QSO on 24 GHz. The various bands will be listed by wavelength with the present US allocation listed by frequency.

33 cm (902-928 MHz)

The 33 cm band experienced a surge in EME activity shortly after the band was opened to amateur use. The 33 cm band represents the lowest frequency at which the parabolic reflector or dish is the primary antenna of choice. Rarely are multiple Yagi arrays used on 33 cm and 23 cm EME. When one considers the number of Yagis required to achieve gain similar to that of a 3-meter dish, one finds that the dish is an easier solution. Since the 33 cm band is a Region 1 allocation only, the only activity has been from the US and Canada. Weak signal work both terrestrially and via the Moon generally starts at 902.000 MHz and in some areas 903.000 MHz. The only stations known to have been active on 33 cm EME include K5JL, WA5ETV, W5LUA, K2DH, W0RAP, WB0TEM, VE4MA, NU7Z, WA8WZG and AF1T. All stations used dish antennas ranging from 3 meters in size to 8 meters. A dish antenna requires a feed system designed for the specific frequency of operation. Most stations use their dish antennas on multiple bands making multi-band operation with a single dish quite a challenge. Most amateurs just swap out feeds and T/R systems for each band. Scheduling of activity periods then becomes very important.

23 cm (1240-1300 MHz)

Interest in the 23 cm band seems to have gained significant momentum. Both terrestrial weak signal work and EME activity occurs near 1296.000 MHz. One of the main reasons for the increased popularity is the apparent greater consistency of signals compared to the lower frequencies. The use of circular polarization on 23 cm minimizes fading due to Faraday rotation and also minimizes the problem of spatial offset between two



The klystron amplifier used in the 1296-MHz EME station at W1FZJ/W1BU. It delivered 300 to 400 W output.

stations on different continents.

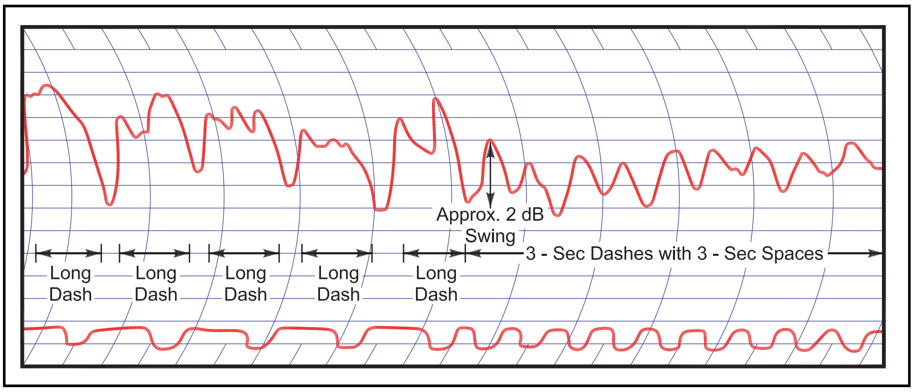
Faraday rotation randomly twists the incoming (and outgoing polarization) based on the condition of the ionosphere. This variation of a linearly polarized signal at 50 MHz through 432 MHz makes it necessary for operators to wait out the variations until the rotating polarity becomes aligned closely enough to permit completion of a QSO. More recently 144 MHz operators have realized a big improvement through the use of switchable polarity antennas. Polarity adjustment has long been a common practice on 432 MHz since Yagi antennas can be rotated easily and parabolic dish antennas are popular. In the case of dish antennas, only the feed antenna needs to be adjusted. This polarization change due to the Faraday effect is non-reciprocal so that the optimum received polarization is often not optimized in the reverse direction.

Spatial offset can be best described by the following example. When one is working Europe from the US, the difference in longitude between the two continents is nearly 90 degrees, causing a horizontally polarized signal coming from the States to the Moon to appear to be nearly vertically polarized when it is reflected off the Moon and received in Europe. This results from the geometry of the path and depends on the differences in longitude, latitude and the position of the Moon in its monthly orbit. The larger the spatial offset, the greater the polarization difference can be between two stations. This offset can be a big obstacle in completing contacts as a polarization difference of 45 degrees contributes 3 dB of loss, which increases to over 20 dB at 90 degrees.

On 1296 and 2304 MHz these problems are overcome by the use of circular polarization, so that all stations where the Moon is visible can hear each other without having to adjust polarization or suffer any loss. On the higher microwave bands the simplicity of linear polarization and relatively low number of active stations (North America and Europe only) resulted in a convention where North American stations use horizontal and European stations use vertical polarization. This worked very well until stations appeared in South Africa. Certainly there is movement toward circular polarization on 5.7 and 10 GHz.

The normal convention on both the 23 and 13 cm bands is to transmit a right-hand circular polarized signal to the Moon. Upon reflection from the Moon, the signal now appears as a left-hand circular polarized signal, which is then received as a left-hand polarized signal anywhere on Earth.

There are numerous big signals on the 23 cm band and many loud enough to



A reproduction of the chart recording made by W4HHK of the 2304-MHz moonbounce signal from W3GKP.

carry on casual SSB QSOs. All it takes is a 3 meter dish and a couple of hundred watts and one is able to hear their own echoes and work 50 to 75 different stations without much trouble. The fact that EME is possible today with only moderately sized antennas says a lot for today's technology. There are presently more than 200 active stations in more than 40 countries on 23 cm EME.

13 cm (2300-2310 and 2390-2450 MHz)

The next higher amateur band at 13 cm poses some interesting international frequency allocation challenges. Although the 13 cm band is an international allocation, not all countries allow weak signal work to occur at one common frequency within the band. In the US, 2304.000 MHz is the recognized lower end of the weak signal portion of the 13 cm band, and this is where most of the narrowband terrestrial and EME work occurs.

Although it appears that most of the terrestrial weak signal work in Europe is centered around 2320 MHz, a good portion of the European EME activity is centered around 2304 MHz. Hams in several countries including Germany, England and Wales cannot transmit at 2304 MHz and therefore transmit near 2320 MHz. This requires that stations who cannot transmit on 2320 MHz use an auxiliary receive converter for 2320 MHz to work these stations. The US does not have an allocation between 2310 and 2390 MHz and therefore we must develop a separate receive converter for 2320 MHz.

A similar frequency allocation problem occurs in Asia. Japanese amateurs have their weak signal allocation at 2424 MHz. This requires that the rest of the world have receive capability at 2424 MHz. The Japanese must also have receive capability at 2304 MHz and 2320 MHz to receive North American, European and African stations. Since the US has the 2390 to 2450 MHz spectrum of the 13 cm band, it is possible to transmit on 2424 MHz.

The first 13 cm QSO between the US and Japan was achieved when W5LUA worked JA4BLC, both transmitting on 2424 MHz. Retuning the klystron from 2304 MHz to 2424 MHz was possible for the initial QSO but later QSOs were achieved by using the cross frequency technique. The easier solution is to build individual receive converters to allow reception of the other station's transmit frequency. This generally entails having the primary receiver set up on your own transmit frequency and a separate receiver or receive converter set up to receive the other station's transmit frequency. Operating split on 13 cm EME is very similar to working one of the amateur satellites. More than 50 stations in 22 countries are presently active on 13 cm EME.

9 cm (3300-3500 MHz)

The 9 cm amateur band has limited worldwide authorization, thereby limiting the number of amateurs who can operate EME on this band. US, Canadian, German and Luxembourg stations operate at 3456 MHz. Besides the initial contacts made by KD5RO (now K2DH), W7CNK, and K0KE, the list of stations presently operational include W5LUA, DL9EBL, VE4MA, NU7Z, OH2AXH, LX1DB and OK1CA. The contact between OH2AXH and W5LUA required that both stations transmit and receive on 3405.200 MHz. This was necessary because OH2AXH does not have a transmit allocation on 3456 MHz. My contact with OK1CA made it necessary for me to receive Franta at 3400.100 MHz while still transmitting at 3456 MHz. No doubt, the limited number of countries that have access to this band has kept the number of EME contacts down, but it does offer the opportunity to use old TVRO antennas and old TVRO LNAs as receive preamplifiers. The recent availability of 20 and 40 W surplus solid-state amplifier for this band should allow one to put a respectable 9 cm EME station on the air with relative ease.

6 cm (5650-5925 MHz)

Although the 6 cm band is an international allocation it has not gained the popularity of some of the other microwave bands both terrestrially and on EME. The boost in 6 cm activity both terrestrially and EME has been as a result of numerous surplus 6 GHz uplink microwave systems including many high power TWTs in the 15 to 200 W power range. A 4 GHz TVRO type antenna has more than enough gain for use at 5760 MHz. Since the first 6 cm EME QSOs by WA5TNY, KD5RO, W7CNK, and K0KE, about 25 stations in 15 countries have emerged with EME capable systems on 6 cm. Worth mentioning is the station at W5ZN in Arkansas. Joel has a 3-meter dish and a solid-state amplifier that produces 12 W at the feed of his dish. Joel has worked several stations off the Moon with this very modest setup. Joel is presently upgrading to a larger 5-meter dish. All activity has been near 5760 MHz with one exception. RW3BP has transmit privileges at 5670 MHz necessitating that additional receive capability be built by those who wanted to work Sergei. The typical 5760 MHz transverter uses a 5616 MHz local oscillator to convert 5760 MHz down to 144 MHz where it is received on a typical multimode 2-meter transceiver. At W5LUA, the same 5616 MHz local oscillator frequency converts 5670 MHz down to an IF of 54 MHz, which is easily received by my Kenwood TS-690.

3 cm (10,000-10,500 MHz)

The 3 cm amateur band is the most popular of the upper microwave EME bands. With today's PHEMT technology providing 1 dB noise figures, the system noise floor is controlled more by the level of Moon noise received than the noise floor of the receiver. It is not uncommon to achieve between 1 and 2.5 dB Moon noise from 3- and 4-meter dishes at 10 GHz. The reception of Moon noise is possible because of the relatively narrow beamwidth of the dish at 10 GHz versus the subtended angle of the Moon. The subtended angle of the Moon is described as the apparent width of the Moon in degrees as seen from Earth. Since the beamwidth of the 3 meter dish at 10 GHz (0.7 degree) is nearly as small as the subtended angle of the Moon (about 0.5 degree), most of the noise that the antenna sees is generated by the Moon, which is significantly hotter than the background cold sky. The Moon noise can also be used as an effective means of keeping the dish on the Moon. Maximum Moon noise indicates the dish is optimized on the Moon. A 3 meter dish coupled with a 20 W TWT and a 1 dB noise figure provides a very nice 3 cm EME station that is capable of working several dozen stations. Since the first EME QSO on 3 cm by WA5VJB and WA7CJO in 1988, upwards of 50 stations in nearly 20 countries are currently operational on 3 cm EME. The smallest station W5LUA has worked to date is Dave, N4MW. Dave runs a 2.4-meter offset fed dish and 8 W at the feed.

1.25 cm (24,000-24,250 MHz)

The next higher amateur band at 24 GHz presents an even bigger technical challenge. Parabolic reflectors quite often have very limited performance above 14 GHz due to surface inaccuracies. Low noise amplifiers are not nearly as easy to make as can be done on 10 GHz. High power is very hard to come by. Part 2 of this series will address how VE4MA and W5LUA overcame these difficulties in order to make the first ever EME QSO on 24 GHz.

Path Loss and Dish Gain

One of the most interesting phenomena I have noticed on the upper microwave bands is that it appears to take less power to receive one's own echoes as frequency is increased. The path loss to the Moon and back increases by 6 dB every time frequency is doubled. The theoretical increase in dish gain for doubling frequency is also 6 dB. However, the increase in dish gain is realized on both transmit and receive. Therefore, for a similar power output and a similar noise figure, doubling the frequency will improve the signal-to-noise ratio of one's echoes by 6 dB. This assumes there is no additional attenuation due to oxygen and water vapor absorption in the atmosphere.

Equipment

If one were to have to purchase all the equipment at new prices, very few would actually be on the air. Thanks to the vast electronics surplus market, it is possible to procure the components required to build a system at very reasonable cost. It is also possible to pick up surplus instrumentation TWTs sometimes for only hundreds of dollars versus the new market price of many thousands of dollars.

So where does one find commercial equipment for the microwave bands? Most microwave stations start with a good multimode 2-meter transceiver or HF transceiver and a transverter. A transverter is a device that can either be homebrewed or purchased and takes the 28 MHz or 144 MHz receive and transmit signals from the basic radio and converts them to higher frequencies. The design of homebrew transverters can be found in numerous ARRL publications including the proceedings of various Microwave Update and Central States VHF Society conferences held over the last several years. If one is inclined to purchase equipment, various amateur microwave equipment manufacturers, such as Down East Microwave and SSB Electronic, supply transverters and low noise amplifiers in either kit form or already built and tested. eBay is also a goldmine of various electronic equipment that is up for sale or bid.

Signal Distortion and Signal Reports

The Moon's surface is very rough and as a consequence the reflected signals can suffer distortion as the multiple reflections combine. The effect varies with the frequency band and the particular motions of the Moon relative to the Earth at any particular time. With rapid fades on top of already weak signals, parts of characters can be lost and thus "dots" in characters tend to be lost. With marginal EME stations, this makes successful reception of an RST report and calls difficult at best. The distortion effect tends to increase with frequency, reaching a peak at 2304 MHz where at times a signal can be quite strong but readability very poor. On the bands above 2304 MHz the tones become almost musical at times on 5760 MHz and spread into a hiss or buzz at 10 and 24 GHz.

An EME signal reporting convention was adopted early on by the amateur community. The convention uses the letters T, M or O for reporting. Being long characters, they tend to survive the distortion. Transmission sequences are normally 2 minutes on 2 meters and 2.5 minutes on 432 MHz and higher. The last 30 seconds of each transmit period is normally reserved for the signal report. Calls are normally sent repeatedly for either 1.5 or 2 minutes depending on the length of the sequence. This gives the receiving station time to find the frequency, optimize the tuning and receive enough good messages to be sure of the content. If calls are correctly received then the next transmission sequence should include either an "M" or "O." The "M" is the minimum acceptable signal report signifying the correct reception of calls and an "O" report indicates that the signal is well above that required for minimum reception. Most often an "O" report is accompanied with an RST report. On 432 MHz and higher, the report of a "T" signifies the detection of a signal, but not enough to put together complete calls. As an example, on 432 MHz, the reception of a "T" report may be an indication that Faraday has rotated the polarity of one's signal, making it difficult to copy at the other end. The 432 MHz operator might then try rotating the polarity of his Yagi array in an attempt to increase the signal level at the other end or the receive end. This offsets the effect of Faraday rotation or compensates for the spatial offset.

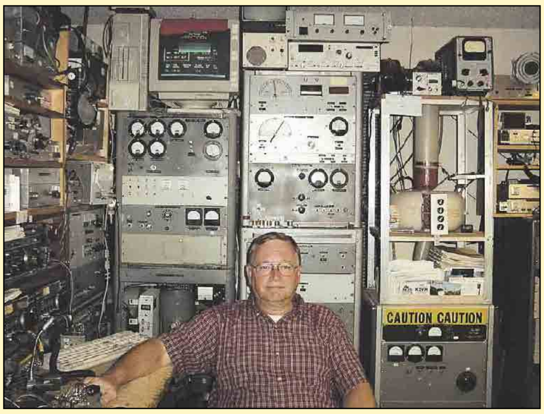
Frequency Setting and Accuracy

The shifting of the received frequency due to the Doppler effect is the result of the Moon's moving around the Earth. This relative motion of the Moon with respect to a fixed point on Earth results in a shift of the frequency of an incom-

W5LUA

I earned my amateur license in 1965 as WN9QZE and soon became WA9QZE in Barrington, Illinois. I had my first exposure to EME through a good mentor, W9YYF. From that point on, my goal was to make an EME contact on 2 meters. I envisioned taking four 8-element HyGain antennas and phasing them. I had already built a kW using a pair of 4CX250Rs while in college. While at the University of Illinois I managed to talk my advisor into letting me build a low noise preamplifier for 144 MHz. I wrote to Texas Instruments and requested samples of the new MS-175TE transistor. This new state-of-the-art bipolar transistor was capable of 1.5 dB noise figure at 2 meters so I was pretty excited. In 1973, we did not have the best equipment for measuring noise figure so the best I could do was determine that the noise figure was something less than 3 dB. As luck would have it, I managed to get a job with Texas Instruments in Dallas, Texas so 2 weeks after marrying Emily, we headed to Dallas with one stop-off on the way. The stop was at the home of W9YYF to pick up two Oliver Swan 14-element Yagis for 2 meters. These were to be the start of a 4 Yagi array for 2-meter EME.

It wasn't until we moved into our first house in Richardson, Texas in 1975 that I was able to build my "big array." I did not really learn what a "big array" was until I met a friend W5SID. W5SID, now K5GW, has certainly redefined in my mind what a big array is! Nonetheless, I still set out to hear my first echoes on 2 meters. On a cold winter night in December, I was poised and ready to "bleep" at the Moon. My four 14-element Swan antennas, 500 W at the antenna and my 1.5 dB highly optimized homebrew LNA were ready. At the sight of the Moon coming across the horizon in Richardson, I sent out three dashes and upon returning to receive, I heard dah-dah-dah! I could not believe it. I did it again and again. Every time I heard my echoes. Boy, was I in heaven! That was the best moment in my Amateur Radio career. Since my early days on 2 meters, my goal has been to make EME contacts on every VHF and higher Amateur Radio band. I am not done yet!



The microwave station of Al Ward, W5LUA. The klystron amplifier at the right is the same unit that W3GKP used to work W4HHK for the first 2304 EME QSO.

VE4MA

My father Andy was an Amateur Radio operator (VE5MA and VE4MA before me) and he introduced me to the hobby. I attended a local ham club meeting in late 1964 where Wally, W0PHD, played a tape of his reception of moonbounce signals from KP4BPZ using the 1000-foot radio telescope dish at Arecibo, Puerto Rico and I said to myself, "I want to do that someday." Being a teenager fascinated with the race to the Moon and anything related to space travel, I began my lifelong quest "to go to the Moon."

Bolstered with extra money from my father I began working on getting a high performance 432 MHz station together, building transistor preamplifiers and 4 and 8 long Yagi arrays for 432 MHz in the hope that KP4BPZ or Sam Harris, W1FZJ, would once again become active on moonbounce. I also began building a 2.2-GHz receiver in hopes of hearing Apollo astronauts visiting the Moon. Neither ever occurred, but as I went through university in the early 1970s, moonbounce became possible for normal hams such as VE7BQH and VE7BBG with the availability of low-noise microwave transistors and better antenna designs.

After completion of university in 1974, I continued my pursuit of moonbounce with the assistance of Jack, VE4JX, who having a large piece of property was willing and able to host an 8 × 13-element Yagi array initially and later a home-made 20-foot diameter dish. Jack and I made many 432 MHz EME QSOs starting in April 1975 including one with my longtime friend Al Ward, WB5LUA (now W5LUA). In 1978 I was able to put up my own 432 MHz EME station at my home, and the relentless pursuit of technology and higher frequencies began.

Barry Malowanchuk, VE4MA, at his station in Winnipeg, Canada.

ing RF carrier, upwards for a rising Moon and downwards for a setting Moon. The absolute frequency of the RF carrier determines the actual magnitude of the shift, with it being a maximum of ±300 Hz at 2 meters (144 MHz) and up to ±60 kHz at 24 GHz. Fortunately, the actual shift at any moment is calculable by the many computer programs available for tracking the position of the Moon.

The setting of the absolute frequency is not trivial. Most commercial radio equipment has relatively poor frequency accuracy and stability, so that at 1296 MHz the possible error can be as high as ±2 kHz. When combined with a maximum Doppler shift of approximately 3 kHz there can be a range of ±10 kHz required for tuning in the search for weak moonbounce signals. Fortunately the absolute frequency is not important if there are high power "beacon" stations operating. This makes finding a reference frequency much easier. Another exciting development is the availability of Global Positioning System (GPS) satellite clocks at reasonable prices that provide a frequency accuracy improvement of approximately 200,000. This translates to an accuracy of less than ±1 Hz at 10 GHz!

Activity Periods and Scheduling

In the early days of moonbounce when signals were very weak, all activity centered on a period of approximately one week when the Moon was closest to the Earth in its elliptical orbit. The point at which the Moon and the Earth are closest is called *perigee*. This provided a signal strength improvement of approximately 2 dB, which was difficult to achieve in any other manner. A few key people around the world compiled written requests (this was long before e-mail!), developed schedules and published them in monthly newsletters that were mailed around the world. So activity tended to focus on one weekend a month.

As the newsletter and moonbounce activity grew, additional people began functioning as schedule coordinators, taking the written requests and schedules passed on the 20-meter international moonbounce nets that operate on 14.345 MHz. The 70-cm-and-Above EME Net starts at 9 AM CST/CDT Saturdays and 10 AM CST/CDT on Sundays. The 2-Meter EME Net immediately follows the 70 cm net at 11 AM CST/CDT. The present Net control station for the 70-cm-and-Above EME Net is K1RQG in Maine, and for 2 Meters it is Lionel, VE7BQH, in Vancouver, British Columbia. Both of these nets are also a good source of technical information.

Many schedules are now arranged directly by e-mail and through the use of an e-mail reflector. Moonbounce activity and signal levels have increased to the point that there is activity nearly every weekend when the Moon is visible in Europe and North America on 2 Meters, 432 and 1296 MHz.

Operating Aids

Since the beginning of Amateur Radio moonbounce activity, the biggest challenge has been locating the position of the Moon and knowing when distant stations have Moon time in common so that contact is possible. Before hams had access to mainframe computers this was nearly impossible. Later in the 1980s, as personal computers became commonplace, a variety of machine language and BASIC programs became available for amateurs to use. Today these programs exist for virtually every operating system and provide such advanced features as real time operating clocks, indication of Doppler frequency shift, station polarity differences and antenna pointing information. They can even perform antenna control.

Further, these programs permit the planning of moonbounce activities by looking for mutual windows, minimum polarity difference, and prediction of signal strengths based on the position of the Moon in its orbit, station equipment capabilities and the position of celestial noise sources. Many of these programs are free or shareware. More information can be found by visiting the Web sites **www.ve1alq.com** and **www.nitehawk.com/rasmit/ws1_1.html**.

Tune in next month for Part 2 of this series. See you in the ARRL EME contest October 26, 27 and November 23, 24!

Notes

[1] *The ARRL UHF/Microwave Experimenter's Manual*, Chapter 10, ARRL, 1990. Available from ARRL (order no. 3126), toll-free 888-277-5289 or on *ARRLWeb* (**www.arrl.org/store**).

[2] *Beyond Line of Sight, A History of VHF Propagation from the Pages of QST*, Chapter 8, ARRL, 1992. Available from ARRL (order no. 4025), toll-free 888-277-5289 or on *ARRLWeb* (**www.arrl.org/store**).

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By Al Ward, W5LUA, and Barry Malowanchuk, VE4MA

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

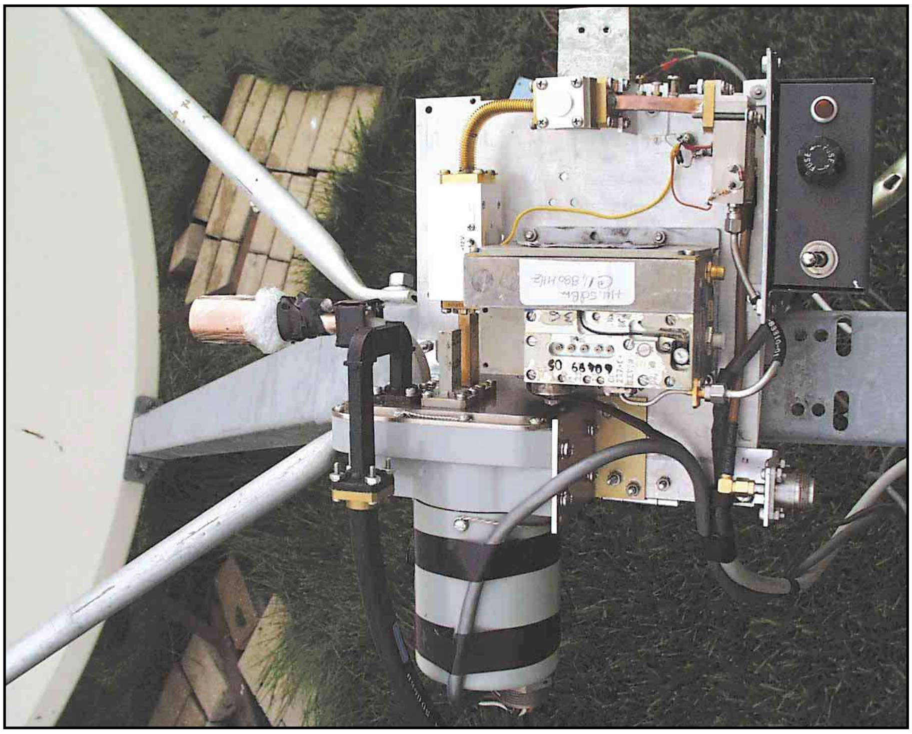

Figure 2—A 24-GHz feed assembly (receive converter and waveguide switch) and W2IMU feedhorn.

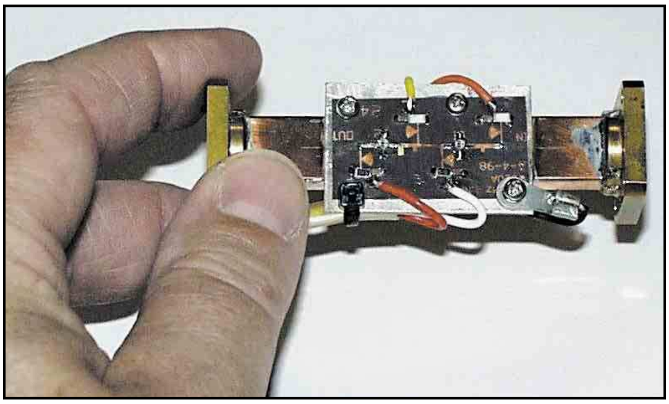

Figure 3—The VE4MA 24-GHz waveguide 2-stage preamplifier.

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.

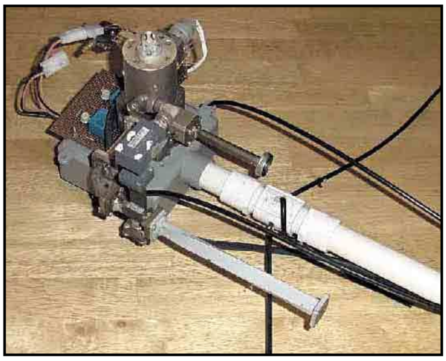

Figure 5—The waveguide relay, LNA and feed assembly at W5LUA.

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.

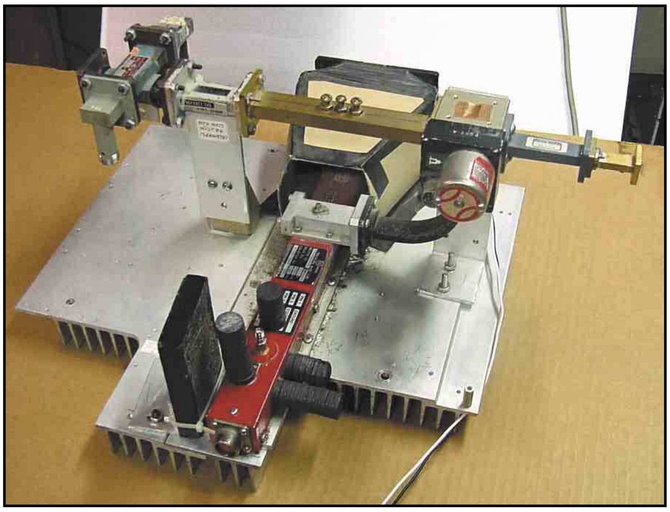

Figure 6—A VTU-6191 TWT band switched for 10 and 24 GHz.

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.

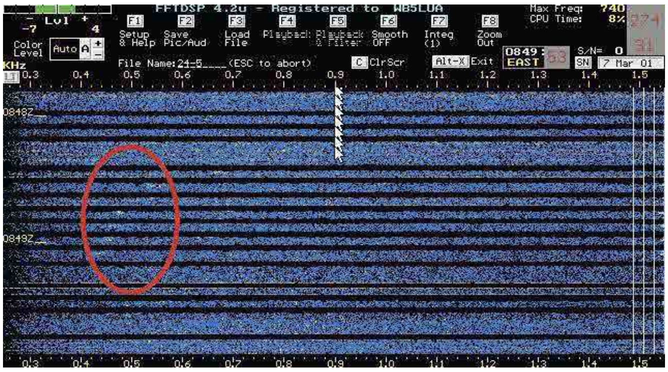

Figure 8—AF9Y DSP software used to document W5LUA's first 24 GHz lunar echoes.

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 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.

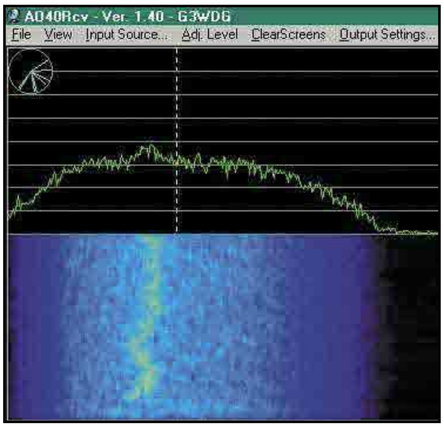

Figure 9—An example of 24 GHz EME signal spreading.

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:

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