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.

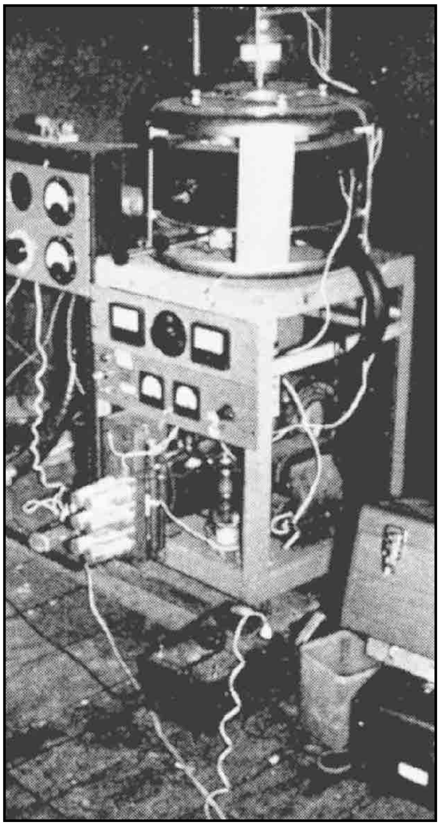
The sections that follow discuss the activity levels on the various microwave EME bands leading up to the first EME QSO on 24 GHz. The various bands will be listed by wavelength with the present US allocation listed by frequency.

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 stations on different continents.


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

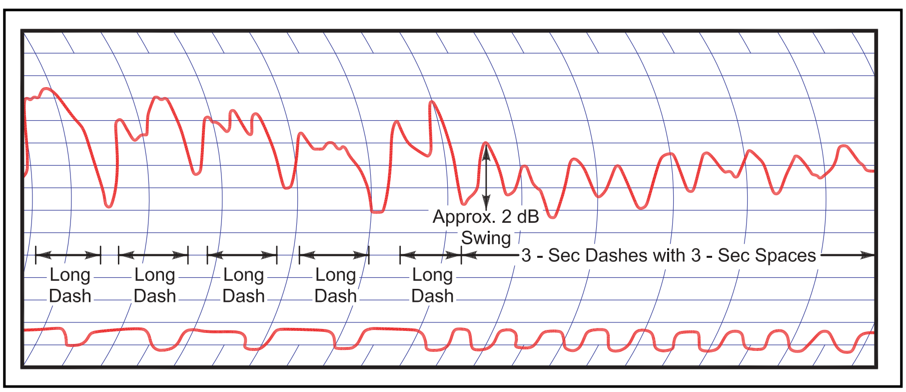
Faraday rotation randomly twists the incoming (and outgoing polarization) based on the condition of the ionosphere. This variation of a linearly polarized signal at 50 MHz through 432 MHz makes it necessary for operators to wait out the variations until the rotating polarity becomes aligned closely enough 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.

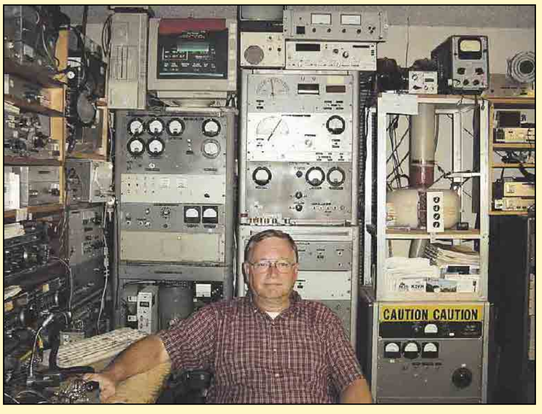
Frequency Setting and Accuracy

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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